



UNIVERSITY OF  
BIRMINGHAM

**MODELLING THE DYNAMICS OF TEAM  
SITUATION AWARENESS**

by

**JOANNE CLAIRE KITCHIN**

A thesis submitted to

The University of Birmingham

for the degree of

**DOCTOR OF PHILOSOPHY**

School of Engineering  
Department of Electronic, Electrical and Systems Engineering  
The University of Birmingham  
August 2018

UNIVERSITY OF  
BIRMINGHAM

**University of Birmingham Research Archive**

**e-theses repository**

This unpublished thesis/dissertation is copyright of the author and/or third parties. The intellectual property rights of the author or third parties in respect of this work are as defined by The Copyright Designs and Patents Act 1988 or as modified by any successor legislation.

Any use made of information contained in this thesis/dissertation must be in accordance with that legislation and must be properly acknowledged. Further distribution or reproduction in any format is prohibited without the permission of the copyright holder.

# ABSTRACT

For decades both industry and academia have been interested in situation awareness, from individual situation awareness to system situation awareness of dynamic collaborative systems. Several theories and definitions exist for situation awareness and although considerable research has been conducted in this domain no definitive consensus has been reached. Therefore, the purpose of the research in this thesis is not develop new theories or definitions, but to explore how situation awareness presents itself in teams and systems in terms of team cognition. The methods used in this thesis include simulating team tasks using agent-based modelling, analysing team knowledge using concept maps and analysing team processes using entropy. In order to remove the risk of intrusion on the tasks being explored, the communications of team members are recorded and used as the primary data for the analyses conducted. Visually presenting knowledge of agents using concept maps made it easier to understand how the information was stored and transferred throughout the teams. An interesting result showed that it was not important for all agents to have the same information when key decisions were made and that when information is not shared the team performed better and with greater accuracy than when there was a focus on information sharing. Visually presenting team processes using entropy and process distribution allowed for patterns of behaviour to be identified. Results show that while individuals within teams feel confident with the amount of knowledge they have they will focus on working independent up until the point they can no longer achieve results on their own, at that point the team shifts to teamworking. The differences between teamwork and taskwork are related to the theories of shared and distributed situation awareness, concluding that shifts in team processes represent shifts in the two types of situation awareness.

## ACKNOWLEDGEMENTS

To my best friend, companion and husband Sebastian Kitchin. Thank you for your continued loving support, encouragement and late-night tea breaks. Without you none of this would have been possible.

I am also very gratefully for my father, John Homer, who has always believed in me and encouraged me to continue along this academic path. Thanks to you the last four years have been some of the best in my life, and you're right, I would have been a fool not to do it.

A special mention to my PhD supervisor, Chris Baber. My PhD has been an amazing experience and I thank you from the bottom of my heart for your tremendous academic and moral support. I hope we get the chance to network again at conferences in the future.

To everyone I shared the office with throughout the PhD, thank you for being so kind and open. Waldo Cervantes, Natan Moran, Sandra Starke, Megan Field and Laurence Hanes, each one of you kept me sane throughout the PhD and I'm proud to call you all my friend.

Martin Read, you have provided considerable insight both emotionally and academically, probably more than you think. Without your words of encouragement and support I don't think I would be where I am today. Thank you, my friend.

To Maisy and Daisy, you have both given me more emotional support than any human possibly could. Thank you for coming into my life.

Finally, I want to thank DSTL for their financial support and for giving me the opportunity to continue researching the very important field of human factors.

Thank you all!

# TABLE OF CONTENTS

<b>ABSTRACT</b> .....	<b>II</b>
<b>ACKNOWLEDGEMENTS</b> .....	<b>III</b>
<b>TABLE OF CONTENTS</b> .....	<b>IV</b>
<b>LIST OF FIGURES</b> .....	<b>IX</b>
<b>LIST OF TABLES</b> .....	<b>XX</b>
<b>LIST OF APPENDICES</b> .....	<b>XXI</b>
<b>JOURNAL PUBLICATIONS &amp; CONFERENCE PAPERS</b> .....	<b>XXV</b>
<b>CHAPTER 1 INTRODUCTION</b> .....	<b>1</b>
1.1 INTRODUCTION .....	1
1.2 RESEARCH QUESTIONS .....	4
1.2.1 <i>Question 1: How can the use of agent-based modelling help explore humanlike behaviours and the distribution of knowledge throughout a system?</i> .....	4
1.2.2 <i>Question 2: How can the analysis of communication give insight into team situation awareness and team behaviour?</i> .....	8
1.3 THESIS STRUCTURE .....	9
1.3.1 <i>Chapter 2 – Situation awareness in teams</i> .....	9
1.3.2 <i>Chapter 3 – Modelling the HMS Dryad Operations Room</i> .....	9
1.3.3 <i>Chapter 4 – Communication as Knowledge: A Study of Team Working</i> .....	9
1.3.4 <i>Chapter 5 – Communication as Knowledge: Modelling Teams</i> .....	10
1.3.5 <i>Chapter 6 – Communication as Action: A Study of Team Processes</i> .....	10
1.3.6 <i>Chapter 7 – Discussion</i> .....	10
<b>CHAPTER 2 LITERATURE REVIEW</b> .....	<b>11</b>
2.1 LITERATURE REVIEW METHOD .....	11

2.1.1	<i>Reasons for Conducting a Literature Review</i> .....	11
2.1.2	<i>Choosing a Literature Review Method</i> .....	11
2.2	TEAM COGNITION .....	14
2.2.1	<i>Information processing</i> .....	14
2.2.2	<i>Team holistic ecology and dynamic activity</i> .....	14
2.2.3	<i>Neurodynamics</i> .....	15
2.3	TEAM SITUATION AWARENESS.....	16
2.3.1	<i>Distributed Decision Making (Wellens, 1993)</i> .....	18
2.3.2	<i>Framework of Team SA (Salas et al., 1995)</i> .....	18
2.3.3	<i>Team SA (Endsley, 1995a)</i> .....	18
2.3.4	<i>Situated Situation Awareness</i> .....	19
2.3.5	<i>Distributed Situation Awareness</i> .....	20
2.4	MEASURING SITUATION AWARENESS IN TEAMS .....	21
2.5	ANALYSING TEAMS .....	27
2.5.1	<i>Social Network Analysis</i> .....	27
2.5.2	<i>Communication</i> .....	29
2.6	AGENT BASED MODELLING .....	36
2.6.1	<i>Choosing an Agent Based Modelling Package</i> .....	37
2.6.2	<i>NetLogo</i> .....	41
2.7	SUMMARY .....	44
<b>CHAPTER 3 SIMULATING THE HMS DRYAD OPERATIONS ROOM.....</b>		<b>45</b>
3.1	CASE STUDY: AN AGENT BASED MODEL OF THE HMS DRYAD OPERATIONS ROOM .....	45
3.1.1	<i>HMS Dryad</i> .....	45
3.1.2	<i>Model Design</i> .....	53
3.2	SIMULATION RESULTS .....	68
3.2.1	<i>Analysis of Performance Data</i> .....	68
3.2.2	<i>Social Network Analysis of Agent Interactions</i> .....	71

3.2.3	<i>Analysis of Agent Knowledge</i> .....	88
3.3	DISCUSSION .....	95
3.4	SUMMARY .....	100
<b>CHAPTER 4 COMMUNICATION AS KNOWLEDGE: STUDY OF TEAMWORKING .....</b>		<b>101</b>
4.1	INTRODUCTION.....	101
4.2	HYPOTHESES .....	103
4.3	METHOD.....	105
4.3.1	<i>Experiment Design</i> .....	105
4.3.2	<i>Participants</i> .....	106
4.3.3	<i>Procedure</i> .....	106
4.3.4	<i>Task Development</i> .....	107
4.3.5	<i>Concept Map Application</i> .....	111
4.3.6	<i>Experimental tasks</i> .....	114
4.3.7	<i>Creating Concept Maps from Participant Messages</i> .....	115
4.3.8	<i>Data Analysed</i> .....	117
4.4	RESULTS.....	118
4.4.1	<i>Performance</i> .....	119
4.4.2	<i>Total Comments</i> .....	120
4.4.3	<i>Task Relevant comments</i> .....	121
4.4.4	<i>Comments against performance</i> .....	122
4.4.5	<i>Comparing Scores for High and Low Performance Teams</i> .....	126
4.4.6	<i>Review of high and low performing teams' transcript content</i> .....	128
4.4.7	<i>Information Held within the Network</i> .....	132
4.5	CONCLUSIONS .....	137
4.6	EXPERIMENT CRITIQUE .....	139
4.7	SUMMARY .....	141
<b>CHAPTER 5 TEAM TRAFFIC MODEL: COMMUNICATION AS KNOWLEDGE.....</b>		<b>142</b>

5.1	AGENT BASED MODEL OF TEAMWORKING .....	142
5.2	METHOD .....	143
5.2.1	<i>Program Structure</i> .....	143
5.2.2	<i>Export - Illegal Characteristic Identification</i> .....	154
5.2.3	<i>Export – Interval Agent Knowledge</i> .....	155
5.2.4	<i>Export – Total comments made, and task relevant comments made</i> .....	155
5.2.5	<i>Model Concept Maps</i> .....	155
5.3	RESULTS .....	156
5.3.1	<i>Performance</i> .....	156
5.3.2	<i>Communication</i> .....	160
5.3.3	<i>Comments against performance</i> .....	168
5.3.4	<i>Information Held within the Network</i> .....	176
5.4	DISCUSSION .....	178
5.4.1	<i>Concept Map Critique</i> .....	182
5.5	MODEL CRITIQUE.....	184
5.6	SUMMARY .....	184
<b>CHAPTER 6 THE DYNAMICS OF DISTRIBUTED SITUATION AWARENESS .....</b>		<b>185</b>
6.1	INTRODUCTION .....	185
6.1.1	<i>Entropy &amp; Thermodynamics</i> .....	186
6.1.2	<i>Entropy &amp; Team Cognition</i> .....	188
6.2	HYPOTHESIS.....	190
6.3	METHOD .....	190
6.3.1	<i>Application of Entropy Method</i> .....	196
6.4	RESULTS .....	212
6.4.1	<i>Coherence</i> .....	212
6.4.2	<i>Interaction</i> .....	221
6.5	DISCUSSION .....	223

6.6	METHOD CRITIQUE .....	225
6.7	SUMMARY .....	226
<b>CHAPTER 7 DISCUSSION .....</b>		<b>227</b>
7.1	INTRODUCTION .....	227
7.2	RESEARCH QUESTIONS .....	228
7.2.1	<i>Question 1: How can the use of agent-based modelling help explore humanlike behaviours and the distribution of knowledge throughout a system? .....</i>	<i>228</i>
7.2.2	<i>Question 2: How can the analysis of communication give insight into team situation awareness and team behaviour? .....</i>	<i>229</i>
7.2.3	<i>Understanding SA in teams .....</i>	<i>230</i>
7.3	USING AGENT BASED MODELLING IN RESEARCH .....	231
7.3.1	<i>Benefits of using Agent Based Modelling .....</i>	<i>231</i>
7.3.2	<i>Limitations using Agent Based Modelling .....</i>	<i>233</i>
7.4	ENTROPY AS A MEASURE OF TEAM ACTIVITY .....	234
7.4.1	<i>Benefits of using entropy as a measure of team activity.....</i>	<i>234</i>
7.4.2	<i>Limitations of using entropy as a measure of team activity.....</i>	<i>235</i>
7.5	INTEGRATING THE ENTROPY OUTPUTS INTO A DISPLAY.....	236
7.6	CONTRIBUTIONS OF THE RESEARCH.....	241
7.7	FUTURE RESEARCH .....	242
<b>REFERENCES.....</b>		<b>243</b>
<b>APPENDICES.....</b>		<b>260</b>

# LIST OF FIGURES

Figure 1 – Hierarchy of the types of situation awareness.....	17
Figure 2 - Timeline of SA measurement techniques .....	21
Figure 3 - An excerpt from Wheelan & Williams (2003) showing patterns of the verbal interaction sequence .....	34
Figure 4 - Excerpt from Wiltshire et al. (2017) showing entropy time series for a team with vertical black lines representing transition points between team processes .....	35
Figure 5 – Netlogo: Code View.....	42
Figure 6 – NetLogo: Interface View.....	43
Figure 7 - Agent interactions and information flow directions in the distributed without sharing version of the model .....	50
Figure 8 - Agent interactions and information flow directions in the distributed with sharing version of the model .....	50
Figure 9 - Screenshot of the distributed without sharing version of the model.....	52
Figure 10 - Screenshot of the distributed with sharing version of the model.....	52
Figure 11 – Flowchart of the model code.....	54
Figure 12 - Summary of agent rules, how they are activated and carried out in the distributed tasks model .....	58
Figure 13 - Summary of agent rules, how they are activated and carried out in the shared tasks model .....	59
Figure 14 – Performance data output, example .csv file .....	66

Figure 15 – Agent Interaction data output, example .csv file.....	66
Figure 16 – Agent Knowledge Data output, example .csv file .....	67
Figure 17 – Performance results for both versions of the model.....	69
Figure 18 – Performance results for both versions of the model.....	69
Figure 19 – System workload results for the distributed without sharing version of the model .....	70
Figure 20 – System workload results for the distributed with sharing version of the model...	70
Figure 21 – Directed agent networks at the end of the model trial for the distributed with sharing and distributed without sharing versions of the model .....	73
Figure 23 - Degree centrality value results for both the distributed with sharing and distributed without sharing versions of the model.....	75
Figure 24 - Density value results for both the distributed with sharing and distributed without sharing versions of the model.....	75
Figure 25 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 500 tick intervals .....	76
Figure 26 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 1000 tick intervals .....	76
Figure 27 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 2000 tick intervals .....	77
Figure 28 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 10000 tick intervals .....	77

Figure 29 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 500 tick intervals .....	78
Figure 30 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 1000 tick intervals .....	78
Figure 31 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 2000 tick intervals .....	79
Figure 32 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 10000 tick intervals .....	79
Figure 33 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 500 tick intervals .....	80
Figure 34 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 1000 tick intervals .....	80
Figure 35 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 2000 tick intervals .....	81
Figure 36 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 10000 tick intervals .....	81
Figure 37 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 500 tick intervals .....	82
Figure 38 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 1000 tick intervals .....	82
Figure 39 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 2000 tick intervals .....	83

Figure 40 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 10000 tick intervals .....	83
Figure 41 - Interval Density Values During the Shared HMS Dryad ABM Task: 500 tick intervals .....	84
Figure 42 - Interval Density Values During the Shared HMS Dryad ABM Task: 1000 tick intervals .....	84
Figure 43 - Interval Density Values During the Shared HMS Dryad ABM Task: 2000 tick intervals .....	85
Figure 44 - Interval Density Values During the Shared HMS Dryad ABM Task: 10000 tick intervals .....	85
Figure 45 - Interval Density Values During the Distributed HMS Dryad ABM Task: 500 tick intervals .....	86
Figure 46 - Interval Density Values During the Distributed HMS Dryad ABM Task: 1000 tick intervals .....	86
Figure 47 - Interval Density Values During the Distributed HMS Dryad ABM Task: 2000 tick intervals .....	87
Figure 48 - Interval Density Values During the Distributed HMS Dryad ABM Task: 10000 tick intervals .....	87
Figure 49 – Concept map of the distributed without sharing and distributed with sharing networks .....	89
Figure 50 – Concept map with coloured rings showing agent knowledge for the distributed with sharing network .....	93

Figure 51 – Concept map with coloured rings showing agent knowledge for the distributed without sharing network .....	94
Figure 51 - Excerpt from Stanton et al. (2008) showing the Social Network Analysis of the HMS Dryad Operations Room .....	98
Figure 52 - Comparing Shared and Distributed knowledge .....	103
Figure 53 - Screenshot of the traffic animation used in the experiment .....	107
Figure 54 – Screenshots of the separate displays created from the animation code .....	108
Figure 55 – Video display and chat window .....	109
Figure 56 – Layout of computers and participants .....	110
Figure 57 – Concept maps of condition 2 and 3 created using data from the transcript analysis .....	113
Figure 58 - Example of one of the raw transcript files for group 6.....	115
Figure 59 - A .txt file of knowledge from group 6.....	116
Figure 60 – Concept map using knowledge extracted from the group 6 transcripts.....	117
Figure 61 - Comparison of Mean Performance Over the Three Experimental Conditions....	119
Figure 62 - Comparison of Mean Overall Comments Over the Three Experimental Conditions .....	120
Figure 63 - Comparison of Mean Task-Relevant Comments Over the Three Experimental Conditions.....	121
Figure 64 - Relationship Between Overall Comments and Performance for Condition 1 .....	122
Figure 65 - Relationship Between Overall Comments and Performance for Condition 2.....	123

Figure 66 - Relationship Between Overall Comments and Performance for Condition 3 .....	123
Figure 67 - Relationship Between Task Relevant Comments and Performance for Condition 1 .....	124
Figure 68 - Relationship Between Task Relevant Comments and Performance for Condition 3 .....	125
Figure 69 - Relationship Between Task Relevant Comments and Performance for Condition 2 .....	125
Figure 70 - Comparison of scores between high performing and low performing groups ....	127
Figure 71 – Comparison of comments made between high performing and low performing groups .....	127
Figure 72 – Team 4 transcript for condition 2 and 3 .....	129
Figure 73 - Team 6 transcript for condition 2 and 3.....	130
Figure 74 - Team 6 transcript for condition 2 and 3 continued.....	131
Figure 75 - Concept map example for Group 6 in Condition 2.....	133
Figure 76 - Concept map example for Group 8 in Condition 2.....	134
Figure 77 - Concept map example for Group 6 in Condition 3.....	135
Figure 78 - Concept map example for Group 8 in Condition 3.....	136
Figure 79 - The OODA principles in the model.....	145
Figure 80 – Flowchart of the model code for the distributed model .....	146
Figure 81 - Summary of agent rules, how they are activated and carried out during the task	149
Figure 82 – Model interface .....	151

Figure 83 - Comparison of Mean Performance Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display .....	157
Figure 84 - Comparison of Mean Performance Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display .....	158
Figure 85 - Comparison of Mean Performance Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model .....	159
Figure 86 - Comparison of Mean Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display .....	161
Figure 87 - Comparison of Mean Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display .....	162
Figure 88 - Comparison of Mean Communication Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model .....	163
Figure 89 - Comparison of Mean Task-Related Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display .....	164
Figure 90 - Comparison of Mean Task-Related Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display .....	166
Figure 91 - Comparison of Mean Task-Related Communication Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model.....	167
Figure 92 - Relationship Between Overall Comments and Performance for the Calibrated Model in Separate Display Condition .....	168

Figure 93 - Relationship Between Overall Comments and Performance for the Novice Model in Separate Display Condition.....	169
Figure 94 - Relationship Between Overall Comments and Performance for the Expert Model in Separate Display Condition.....	169
Figure 95 - Relationship Between Overall Comments and Performance for the Calibrated Model in Common Display Condition .....	170
Figure 96 - Relationship Between Overall Comments and Performance for the Novice Model in Common Display Condition.....	171
Figure 97 - Relationship Between Overall Comments and Performance for the Expert Model in Common Display Condition.....	171
Figure 98 - Relationship Between Task-Relevant Comments and Performance for the Calibrated Model in Separate Display Condition.....	172
Figure 99 - Relationship Between Task-Relevant Comments and Performance for the Novice Model in Separate Display Condition .....	173
Figure 100 - Relationship Between Task-Relevant Comments and Performance for the Expert Model in Separate Display Condition .....	173
Figure 101 - Relationship Between Task-Relevant Comments and Performance for the Calibrated Model in Common Display Condition.....	174
Figure 102 - Relationship Between Task-Relevant Comments and Performance for the Novice Model in Common Display Condition .....	175
Figure 103 - Relationship Between Task-Relevant Comments and Performance for the Expert Model in Common Display Condition .....	175

Figure 104 – Concept map results for the model for sperate and same videos, calibrated for expert agents .....	177
Figure 105 - Changes of states of matter of water.....	187
Figure 106 - Ordered (low entropy) communication content and disordered (high entropy) communication content.....	189
Figure 107 - Excerpt from Wiltshire et al (2017) showing the collaborative problem-solving process codes and categories .....	191
Figure 108 – Continued excerpt from Wiltshire et al (2017) showing the collaborative problem-solving process codes and categories.....	192
Figure 109 – Excerpt from Wiltshire et al (2017) showing how the category codes were assigned to the communication transcripts in their study.....	193
Figure 110 – Excerpt from Wiltshire et al (2017) showing the results of applying the entropy analysis and smoothing algorithm to the communication transcripts in their study .....	195
Figure 111 - Excerpt from Group 6’s communication transcript from condition 1, with the first 5 calculated coherence entropy values .....	202
Figure 112 – Raw entropy team process values. Group 6, condition 2.....	203
Figure 113 – Raw entropy team process values with overlaid most common processes. Group 6, condition 2 .....	205
Figure 114 - Raw entropy team process values with overlaid will all present processes. Group 6, condition 2.....	205
Figure 115 – Excerpt from Group 6’s communication transcript from condition 2, with the first 5 calculated interaction entropy values .....	207

Figure 116 – Raw entropy interaction values. Group 6, condition 2 .....	209
Figure 117 – Raw entropy interaction values with overlaid most common processes. Group 6, condition 2 .....	211
Figure 118 - Raw entropy interaction values with overlaid will all present processes. Group 6, condition 2 .....	211
Figure 119 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series .....	214
Figure 120 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and coloured regions representing the most common process code. The moment a characteristic was identified is also shown. ....	216
Figure 121 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and stacked bars showing the distribution of processes. The moment a characteristic was identified is also shown.....	218
Figure 122 – Amount of teamwork processes compared to taskwork processes per region for groups 4 and 6 in conditions 1, 2 and 3 .....	220
Figure 123 - Raw entropy interaction values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series .....	222
Figure 124 – An example interface for Team 4 and Team 6 during the “Current Task”, which was condition 3 in the experiment in Chapter 4 .....	238
Figure 125 – An example interface for Team 6 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4 .....	239

Figure 126 – An example interface for Team 4 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4 .....	240
Figure 127 – Behaviour Composer: Compose View.....	269
Figure 128 – Behaviour Composer: Run View .....	269
Figure 129 – Scratch: Interface .....	271

## LIST OF TABLES

Table 1 - Summary of Agent Based Models .....	40
Table 2 - Roles and responsibilities of agents in Model 1 and Model 2 .....	46
Table 3 - Summary of data variables from the model .....	68
Table 4 – Information held by each agent when a decision is made in the distributed without sharing version of the model .....	91
Table 5 - Information held by each agent when a decision is made in the distributed with sharing version of the model .....	91
Table 6 – Team process codes adapted from Wiltshire et al’s (2017) chosen process codes	198
Table 7 - Transcripts of Group 5 in Condition 1 with accompanying process codes.....	199
Table 8 - Transcripts of Group 6 in Condition 1 with accompanying process codes.....	200
Table 9 – Entropy process for window 1 with a window size of 6 and the 6 team process codes for group 6 in condition 2.....	201
Table 10 – Entropy process for window 1 with a window size of 6 and the 6 interaction codes for group 6 in condition 2.....	208

# LIST OF APPENDICES

Appendix A – Summary of Situation Awareness Measurement Techniques .....	260
Appendix B – Comparison of alternative ABM packages.....	268
Appendix C - Page 1 of the participant information sheet used in the experiment.....	272
Appendix D - Page 2 of the participant information sheet used in the experiment	
Appendix E - Page 1 of the participant information sheet used in the experiment.....	272
Appendix F - Page 2 of the participant information sheet used in the experiment .....	273
Appendix G - Page 2 of the participant information sheet used in the experiment.....	273
Appendix H - Descriptive Statistics for the Performance Results of Teams in Chapter 4.....	274
Appendix I – Boxplots for the Performance Results of Teams in Chapter 4 .....	274
Appendix J - Friedman Test of Performance in Chapter 4.....	275
Appendix K - Wilcoxon Signed Ranks of Performance in Chapter 4.....	275
Appendix L - Descriptive Statistics for Communication Results of Teams in Chapter 4.....	276
Appendix M – Boxplots for the Communication Results of Teams in Chapter 4.....	276
Appendix N – One-way ANOVA of Total Comments and Paired Samples Statistics in Chapter 4 .....	277
Appendix O - Descriptive Statistics for Task-Relevant Communication Results of Teams in Chapter 4 .....	278
Appendix P – Boxplots for the Task-Relevant Communication Results of Teams in Chapter 4 .....	279

Appendix Q – One-way ANOVA of Task-Relevant Comments and Paired Samples Statistics in Chapter 4 .....	280
Appendix R - Correlation results for total comments and performance in Chapter 4.....	281
Appendix S - Correlation results for task-relevant comments and performance in Chapter 4 .....	282
Appendix T - Condition 2: Separate Display, Group 2 .....	283
Appendix U - Condition 2: Separate Display, Group 3.....	284
Appendix V - Condition 2: Separate Display, Group 4.....	285
Appendix W - Condition 2: Separate Display, Group 5.....	286
Appendix X - Condition 2: Separate Display, Group 6.....	287
Appendix Y - Condition 2: Separate Display, Group 7.....	288
Appendix Z - Condition 2: Separate Display, Group 8 .....	289
Appendix AA - Condition 2: Separate Display, Group 9.....	290
Appendix BB - Condition 3: Same Videos, Group 2 .....	291
Appendix CC - Condition 3: Same Videos, Group 3 .....	292
Appendix DD - Condition 3: Same Videos, Group 4.....	293
Appendix EE - Condition 3: Same Videos, Group 5.....	294
Appendix FF - Condition 3: Same Videos, Group 6.....	295
Appendix GG - Condition 3: Same Videos, Group 7 .....	296
Appendix HH - Condition 3: Same Videos, Group 8.....	297

Appendix II - Condition 3: Same Videos, Group 9 .....	298
Appendix JJ – Normal distribution stats for the performance scores of each model (calibrated, expert and novice) for both the shared and common display .....	299
Appendix KK – Kruskal-Wallis Test for the performance scores of each model (calibrated, expert and novice) for both the shared and common display .....	300
Appendix LL - Mann-Whitney Tests for the performance scores of each model (calibrated, expert and novice) for both the shared and common display .....	301
Appendix MM - Paired Samples t-test comparing the performance scores for each model (calibrated, expert & novice) using the shared and common display.....	305
Appendix NN - – Normal distribution stats for the total comments made in each model (calibrated, expert and novice) for both the shared and common display .....	306
Appendix OO – One Way ANOVA comparing the total comments of each model (calibrated, expert and novice) for both the shared and common display .....	307
Appendix PP – Independent samples t-tests comparing the total comments of each model (calibrated, expert and novice) for both the shared and common display .....	308
Appendix QQ - Paired Samples t-test comparing the total comments for each model (calibrated, expert & novice) using the shared and common display.....	314
Appendix RR – Normal distribution stats for the task relevant comments in each model (calibrated, expert and novice) for both the shared and common display .....	315
Appendix SS – One Way ANOVA comparing the task-relevant comments of each model (calibrated, expert and novice) for both the shared and common display .....	316

Appendix TT – Independent samples t-tests comparing the task relevant comments of each model (calibrated, expert and novice) for both the shared and common display .....	317
Appendix UU - Paired Samples t-test comparing the task relevant comments for each model (calibrated, expert & novice) using the shared and common display.....	323
Appendix VV - Pearson Correlations for total comments and performance for the separate display.....	324
Appendix WW - Pearson Correlations for total comments and performance for the common display.....	325
Appendix XX - Pearson Correlations for task relevant comments and performance for the separate display.....	326
Appendix YY - Pearson Correlations for task relevant comments and performance for the common display.....	327



**Conference paper**

The Dynamics of Distributed Situation Awareness  
(Kitchin and Baber, 2017)

*Author Contribution*

<b>Conception and design of the work</b>	Joanne Kitchin
<b>Data collection</b>	Joanne Kitchin
<b>Data analysis and interpretation</b>	Joanne Kitchin
<b>Drafting the article</b>	Joanne Kitchin
<b>Critical revision of the article</b>	Chris Baber
<b>Final approval of the version to be published</b>	Joanne Kitchin & Chris Baber

**Conference paper**

Exploring Workload and Performance Through  
the use of Visual Analytics (Kitchin and Baber,  
2018)

*Author Contribution*

<b>Conception and design of the work</b>	Joanne Kitchin
<b>Data collection</b>	Joanne Kitchin
<b>Data analysis and interpretation</b>	Joanne Kitchin
<b>Drafting the article</b>	Joanne Kitchin
<b>Critical revision of the article</b>	Chris Baber
<b>Final approval of the version to be published</b>	Joanne Kitchin & Chris Baber

# CHAPTER 1 INTRODUCTION

## 1.1 INTRODUCTION

It is rare for people to work totally independently, and there is ever growing appreciation for the importance of teams and teamwork in many industrial domains. There have been many catastrophic events which have hit the headlines; the Donner Party disaster (Patton, 2011), Three Mile Island accident (U.S. Nuclear Regulatory Commission, 1979), the Challenger shuttle disaster (Rogers et al., 1986), the Bhopal gas tragedy (Browning, 1993) and the Deepwater Horizon oil spill (United States. National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling., 2011), to name a few. In a review of 32 major disasters in the UK, Pollock (2013) identified how serious teamwork failures were repeated time and again. This recurrence is in part due to the challenges of learning from past events and implementing improvement recommendations. When these events happen however, research into investigating why they happened follows with the goal of preventing the same incident occurring again. During these investigations, it is crucial to study what happened on the run up to the event rather than just the outcomes. Thus, as part of these investigations, it is also crucial to study how teams work together to achieve shared goals and detect where team breakdowns arise or where teamwork can be improved to prevent serious incidents repeatedly occurring.

In order to study teams and teamwork, it is important to understand what a team actually is and how a team conducts the process of teamwork. Salas and colleagues (1992) define a team as “a set of two or more individuals interacting adaptively, interdependently and dynamically towards a common and valued goal”, and this definition remains prominent in the literature (Salas et al., 2000). Additionally, teams are seen as having three-stages, the first where they

utilise resources (input), the second where they maintain internal processes (throughput) and thirdly where they produce a specific product (output) (Mickan et al., 2000). Due to this three-stage system, time becomes an important aspect when assessing teams, not only in terms of how long a task may take but also concept of tasks requiring time to be completed. Without this allocation of time, teams could not function. Simply put, time matters in teams (McGrath, 1990).

Many evaluations of teams focus on the output, the product created by the team and the quality of this product. For example, Hackman (1987) conceptualised performance as the evaluation of the outcomes of team processes relative to a set of predetermined standards.

This focus on team output evaluation has its benefits: it gives a way of evaluating the product that the teams create and the effectiveness of the team, be it in terms of time taken or resources used. However, evaluating team outputs do not give insight into how teams reach the end goal, how they produce the end product. They do not take time into account or look at the processes that take place over the course of the team task. The dynamic nature of teams is ignored and the answer to understanding why the outcome occurred the way it did is lost.

Fortunately, there has been a increase in research looking into how teams solve tasks over the past decade (Bierhals et al., 2007; Cooke et al., 2008; Fiore et al., 2010a, 2010b, 2007; Fiore and Wiltshire, 2016; Fischer et al., 2013; Letsky et al., 2008; Newton et al., 2018; Parker and DeCottis, 2013; Quesada et al., 2005; Rosen, 2010; Salas and Fiore, 2004; Turner et al., 2014; Wiltshire et al., 2017, 2014). Just like individuals, teams must also carry out a number of processes such as learning, planning, reasoning, decision making, problem solving, remembering, designing, and assessing situations in order to solve these problems and be effective at doing so (Bolstad et al., 2007; Cooke et al., 2013; Letsky et al., 2008; Mishra et al., 2009; Parker and DeCottis, 2013; Salas et al., 2000). These processes are what make up

cognition in individuals and therefore, must also make up the cognition of the team (Cooke et al., 2013). It is important to note however, that team cognition is not the sum of individual team members, instead it emerges through the interactions of individuals within the team in the pursuit of a common goal (Cooke et al., 2008; Letsky et al., 2008; Parker and DeCottis, 2013; Salas and Fiore, 2004; Turner et al., 2014). Aggregation-based metrics of team cognition do not capture the adaptive interactions of individuals, which is its underlying feature, and therefore metrics which focus on processes would be more applicable (Cooke et al., 2008). A common problem with measuring and analysing individual cognition, this that this resides in the individuals mind and defies direct observation (Cooke et al., 2008) however, team cognition *is* directly observable via the coordination and communication behaviour of teams and rather than team communication being a window to team cognition, it is team cognition itself (Cooke et al., 2008). It is the team interactions which serve cognitive functions that integrate the thoughts of the system (Cooke et al., 2008).

There are several methods which have been employed to measure and/or analyse teams (see Chapter 2), including; communication analysis, simulation, cognitive task analysis and cognitive work analysis. What is clear from both the theory and measurement is that knowledge is central to team cognition (Cooke et al., 2000) and that communication is key to analysis.

One emergent property of team cognition during problem solving tasks is situation awareness, a topic that has received much attention within the literature both in terms of its definition and measurement (see Chapter 2). There is a heated debate within the literature about whether situation awareness can be associated with anything other than the individual (Endsley, 1995a; Stanton et al., 2014, 2010), and that it would be impossible to have team or system situation awareness due to cognition occurring only in the mind (Endsley, 1995a; Resnick,

2004), a concept also debated within the team cognition literature (Cooke et al., 2008). According to Endsley (1995a), the idea of team situation awareness occurs as an aggregate of individual situation awareness, however has previously stated within the team cognition literature, this aggregation style approach does not capture the adaptive interactions of individuals or show the complexity of situation awareness in teams. This follows the premise that team situation awareness is a product which occurs after a number of cognitive processes take place. By viewing team situation awareness as a process however, it is possible to capture this complexity by analysing interactions between individuals via communications (Gorman et al., 2006; Salas et al., 1992). Team process which facilitate communication and therefore help build team situation awareness (Salas et al., 1995), is made available through the communications of team members (Endsley, 1995b).

## **1.2 RESEARCH QUESTIONS**

### **1.2.1 Question 1: How can the use of agent-based modelling help explore humanlike behaviours and the distribution of knowledge throughout a system?**

The debate about whether team situation awareness is possible or whether situation awareness can only be within the human mind is interesting. In the 1990's there was an emphasis on using task simulations in order to study team cognition (Cooke et al., 2008) although modelling humans themselves has been a more difficult task, with researchers again arguing that humans are far too complex to model. Team situation awareness has also fallen into this conflict. However, if one were to take the team cognition approach to team situation awareness where knowledge is central (Cooke et al., 2000) and that communication is key to analysis, one should be able to model and simulate teams at work. The motivation for the first research question in this thesis is to explore whether it is possible to model human-like

behaviour in such a way that team situation awareness can be explored during problem solving tasks using agent based modelling and if it is necessary to model complex cognitive processes.

In their study, Moiser & Chidester (1991) reasoned that information solicitation and transfer among crew members during emergency situations could be captured and used as an indicator of situation awareness and that a level of situation awareness could be estimated based on the relevant information that the individuals possessed (Shrestha et al., 1995). Similarly, Smith & Hancock (1995) argue that “situation awareness specifies what must be known to solve a class of problems posed when interacting with a dynamic system”, that consciousness is part of an individual’s knowledge generating behaviour and that the product of situation awareness is the knowledge about and the directed actions within the environment. This notion is analogous with distributed situation awareness which is defined as “activated knowledge for a specific task within a system” and assumes that “‘knowledge’ is externalized through communication” (Stanton et al., 2006).

The work in Chapter 3 aims to provide a proof of concept where agents within a collaborative problem solving team (Wenger, 1998) can be modelled using agent-based modelling and that knowledge can be presented visually for analysis. This chapter introduces the concepts of agent-based modelling and concept maps; a definition of these terms will now be outlined.

“Agent-based modelling (ABM) is the computational study of social agents as evolving systems of autonomous interacting agents” (Janssen, 2005). It is used to study social systems from the perspective that dynamic systems are complex and adaptive and is used to explore the emergent phenomena which arises from micro level behaviour among a mixed group interacting agents (Holland, 1992). Many modelling packages are available, however due to its ease of use and fast learning curve it was NetLogo which was used to create the agent-

based models in this thesis. Refer to Chapter 2 for a review of modelling packages and applications of agent-based modelling.

Concept maps have been used as a common method for visually depicting knowledge (Novak and Cañas, 2006) and have been described to “facilitate the externalisation of knowledge” (Coffey et al., 2006). Concept maps are graphical tools which include concepts represented by text enclosed by circles or boxes and relationships between concepts indicated by a connecting line, with a linking word or phrase (Novak and Cañas, 2008). A concept is defined as “a perceived regularity in events or objects, or records of events or objects, designated by a label” (Novak and Cañas, 2008). Concept maps represent propositions, “statements about some object or event in the universe, either naturally occurring or constructed. Propositions contain two or more concepts connected using linking words or phrases to form a meaningful statement” (Novak and Cañas, 2008). Variations of concept maps, termed propositional networks, have also been used externalise the knowledge required for situation awareness in teams (Baber et al., 2006; Stanton et al., 2006).

Outputs of the model reveal that communication, be it via a model of team interactions and behaviour, can give insight into team and system situation awareness, using concept maps to visualise activated knowledge within the team/system. Therefore, the next stage of research involved a laboratory experiment which captured team communications with the intention of analysing their situation awareness using concept maps and agent-based modelling.

The reliability of individuals within a team during a detection task, where decision making is integral to that task, affects the performance of the team as a whole. When the reliability of those individuals is similar, the combined performance tends to be better if they were to work independently, as long as they are free to communicate the confidence in their own decisions (Bahrami et al., 2010). If either person within that team has lower reliability compared to the

rest of the team, the overall performance is much worse than if the individuals worked independently. One could argue that in this case the team is spending more time bringing the level of reliability up to a common standard and evidence has also shown that teams focussing on this type of teamwork can become dysfunctional (Janis, 1982). Mesmer-Magnus and Dechurch (Mesmer-Magnus and DeChurch, 2009) suggest that when team members already have all the information they need to complete a task within the group, they are more likely to become involved in the sharing process. This could therefore have a detrimental effect on teams with highly capable individuals when sharing is encouraged as time could be spent “wasted” sharing when there is no need to. Therefore, one could suggest that in some situations sharing may not be optimal and working independently would achieve better results than focusing on sharing throughout the task, that is working in a Distributed without Sharing network, opposed to a Distributed with Sharing network as outlined by Dekker (2002).

How these teams work together and decide what and when to share information influenced the work in Chapter 4, which aims to explore the effects of sharing information on situation awareness via the analysis of team communication. Concept maps are used to visually represent the knowledge of individuals extracted from communication transcripts and agent-based models are used to explore the idea further.

The outcomes of the work in Chapter 5 provides evidence for the notion of distributed situation awareness and encourages the idea that visually representing situation awareness, through the use of communications, can be of great benefit to analysts who want to avoid task intrusion or research bias. The next stage of the research was to develop a way of analysing communications in terms of (but not limited to) agent interactions and coherence, which could then ultimately be used to inform key decision makers of the system situation awareness as a visual aid.

### **1.2.2 Question 2: How can the analysis of communication give insight into team situation awareness and team behaviour?**

It is this focus on cognitive processes which can be directly observed via the communications of team members which is the motivation for the second research question within this thesis. Using communication as the raw data for team situation awareness has received interest in the literature, however how team processes can be extracted and presented from this communication data is limited. Currently, there are no team situation awareness measurement techniques (see Chapter 2) which are non-intrusive on the task and which show the dynamic nature of teams and team situation awareness.

Through the utilisation of externalized communication between team members, one can see that the commonly observed problem of intrusion on individuals within a team task (see Chapter 3) can be eliminated. The work in Chapter 6 uses the methodology employed by Wiltshire et al. (2017) to generate a metric for analysing team situation awareness. As previously discussed, taking communication as a proxy for externalised knowledge (Hutchins, 1995, Stanton et al., 2006) and distributed situation awareness is considered activated knowledge for a task (Stanton et al., 2006, Stanton et al., 2010) which is achieved through the interactions of agents within the system or team (Stanton et al., 2017), it is argued that the order and disorder (i.e. entropy) of communications and team processes could be used to analyse team and system situation awareness.

This chapter introduces the term entropy, which is a quantification of the amount of order or disorder within a system as a function of the number of units of information needed to describe that system (Shannon and Weaver, 1959).

The work within this chapter aims to develop a visual display of team and/or system interactions through the use of communications in order to: a) explore the emergent properties of distributed situation awareness and b) provide a visual aid for key decision makers within a system to better understand team behaviour and processes and, c) detect trends in system performance, operation and team behaviour.

## **1.3 THESIS STRUCTURE**

### **1.3.1 Chapter 2 – Situation awareness in teams**

The work in Chapter 2 outlines the current theories which surround the subject of situation awareness in teams and systems and techniques which measure team cognition and situation awareness in teams and systems are critiqued. This chapter also introduces the use of agent based modelling and outlines the process for choosing an agent-based modelling package and provides a critique of current packages available.

### **1.3.2 Chapter 3 – Modelling the HMS Dryad Operations Room**

The work in Chapter 3 describes the design and development of the model of the operations room of HMS Dryad in terms of agent layout, roles and responsibilities on using the chosen package is then designed and developed. This model is then used to simulate the operations room on HMS Dryad during a target detection exercise. The results of the simulations are presented, analysed and discussed. The chapter introduces the use of concept maps to display system knowledge.

### **1.3.3 Chapter 4 – Communication as Knowledge: A Study of Team Working**

The work in Chapter 4 outlines the design, execution and analysis of a target detection experiment using teams of three participants. The experiment captures communications

between the team members through written transcripts, the content of these transcripts are used to extract participant knowledge. Concept maps are again used to display the organisation of knowledge throughout the team structure.

#### **1.3.4 Chapter 5 – Communication as Knowledge: Modelling Teams**

Using the experiment design and results from Chapter 4, a model was created to simulate the actions of the teams involved in the experiment in Chapter 5. The development and design of the model is outlined, and simulations are carried out to explore the information flow and knowledge acquisition of the agents within the system. Results are presented, and concept maps are used to display the temporal nature of the organisation of knowledge throughout the team structure.

#### **1.3.5 Chapter 6 – Communication as Action: A Study of Team Processes**

The work in Chapter 6 utilises the communication transcripts obtained from the experiment in Chapter 4. The content of these transcripts is used to extract participant actions, described as team processes, and the level of order and disorder of these processes is calculated. Several displays of the team processes are presented, analysed and discussed in terms of taskwork and teamwork.

#### **1.3.6 Chapter 7 – Discussion**

The implications of the findings from Chapters 3 to 6 and their relation of the theories of situation awareness are discussed in Chapter 7. The benefits and limitations of using agent-based modelling and analysing the order and disorder of team processes is also discussed. Finally, examples of how the measurement of team processes and the resulting outputs can be integrated into a user interface are presented.

## CHAPTER 2 LITERATURE REVIEW

*Parts of this chapter have been published in:*

[1] *“A comparison of shared and distributed situation awareness in teams through the use of agent-based modelling” in the Journal of Theoretical Issues in Ergonomics Science, 2016, 17(1), p 8-41*

[2] *“The Dynamics of Distributed Situation Awareness” in the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2017, 61(1), p 277-281.*

*The sections: Distributed Situation Awareness on Page 10 of [1] and Introduction on Page 277 of [2] have been used to prepare this chapter.*

### **2.1 LITERATURE REVIEW METHOD**

#### **2.1.1 Reasons for Conducting a Literature Review**

Based on Hart’s (2018) 11 reasons for conducting a literature review, it was felt that 3 were most appropriate to the aims of this thesis:

1. Distinguish what has been done from what needs to be done;
2. Enhance and acquire the subject vocabulary;
3. Identify the main methodologies and research techniques that have been used.

#### **2.1.2 Choosing a Literature Review Method**

Generally when conducting a search of the literature, one starts with a scoping review with the aim to provide an initial indication of the potential size and nature of the available literature on a particular topic (Grant and Booth, 2009; Paré et al., 2015). Such a review may

also be conducted to examine the extent and range of research activities, determine whether a full systematic review needs to be conducted, or to identify research gaps in the literature (Arksey and O'Malley, 2005; Kitchenham et al., 2011; Rumrill et al., 2010). Scoping reviews also tend to focus on the breadth of the literature rather than the depth (Arksey and O'Malley, 2005; Rumrill et al., 2010) and unlike narrative and descriptive reviews, the goal of a scoping review is to be as comprehensive as possible (Paré et al., 2015). For this thesis, it was felt that a scoping review would be sufficient to cover identify areas in the literature to which the methods and approach of this work could contribute. Although there is no exact set of procedures for conducting a scoping literature review (Peterson et al., 2016), there is a framework published by Arksey and O'Malley (2005) that researchers can follow in order to guide the process, and this is followed in this thesis.

#### ***2.1.2.1 Identifying the research question(s)***

#### ***2.1.2.2 Identifying the relevant studies***

Sources consulted included: Google scholar, Science Direct, Web of Science, the University of Birmingham Libraries (FindIt@Bham) and the Bodleian Libraries at the University of Oxford (FindIt@Oxford). The search was conducted in two phases, first a broad review of how teams are analysed was conducted which provided the terms used in phase two. Phase 1 search terms included:

- Measurement, measurement techniques, analysis, teams, teamworking

Phase 1 identified many ways in which teams are analysed and in order to structure and analyse the results in a coherent manner, 6 main topics were identified. These include: Agent Based Modelling, Communication Analysis and Situation Awareness. Phase 2 of the search used these 3 main topics along with the following terms:

### **Topic 1 – Communication Analysis**

[*Communication Analysis*] AND [transcripts OR text OR speech] AND [measurement OR measurement techniques OR analysis] AND [teams OR teamworking]

### **Topic 2 – Agent Based Modelling**

[*Agent Based Modelling* OR simulations] AND [measurement OR measurement techniques OR analysis] AND [teams OR teamworking]

### **Topic 3 – Situation Awareness**

[*Situation Awareness* OR Situational Awareness OR Team Situation Awareness OR System Situation Awareness OR Distributed Situation Awareness] AND [measurement OR measurement techniques OR analysis] AND [teams OR teamworking]

The list of terms above provided the means for the initial scoping search, however many articles reviewed were found from the reference lists of the searched articles. Literature relating to any of the 6 main topics and team measurement and/or analysis was included.

#### ***2.1.2.3 Study selection***

Instead of collating all the literature and then reviewing it in one go, the literature search and selection was continuous throughout the course of the project. Literature selection was based on its relevance to team analysis or measurement, that is process driven rather than outcome driven.

#### ***2.1.2.4 Collating, summarizing, and reporting the data***

All literature was stored online using the reference management software Mendeley (<https://www.mendeley.com>). As the literature was reviewed throughout the PhD, the summarising and reporting of the literature were constantly updated, the results of which can be found in the next sections of this chapter.

## **2.2 TEAM COGNITION**

The literature has highlighted three theories of team cognition: the information processing perspective, the team holistic ecology and dynamic activity (THEDA) perspective and the neurodynamics perspective.

### **2.2.1 Information processing**

The information processing perspective is influenced by process-oriented theories from psychology of small groups and industrial-organisations (Cooke et al., 2008). Hackman (1987) suggested that interaction processes could be studied in order to explore the effects of individual, team and environmental factors on team outputs. This approach is termed the input-process output (I-P-O) framework for work team productivity (Cooke et al., 2008). Viewing team cognition in terms of the I-P-O framework, knowledge is distributed over team members and is operated on by team process behaviours (Cooke et al., 2008). The I-P-O framework has been linked to team cognition by a number of researchers, either as an input (Mohammed and Dumville, 2001), a process (Brannick et al., 1995) or an output (Mathieu et al., 2000).

### **2.2.2 Team holistic ecology and dynamic activity**

The THEDA perspective provides a view of team cognition, which is motivated by alternative views of psychology, including; distributed cognition (Hutchins, 1995a), ecological psychology (Reed, 1996) and dynamical systems theory (Alligood et al., 1997). Team cognition from this perspective is considered emergent and is focused on the interplay of team members. The observation is that cognition is likely to be distributed throughout a system of individuals (human or non-human). Hutchins (1995b) explores the notion that, in an aircraft cockpit, it would be unlikely that a single agent within a system would hold all the knowledge

required to know the speed of the aircraft, and that it must be the cockpit system which holds this knowledge and that the knowledge occurs through the interactions of the pilots within that cockpit (Hutchins, 1995b). In other words, “no one member has the overall SA, rather it is distributed around the system” (Salmon et al., 2007). This means that it is important to study team structures and interactions beyond the summation of team knowledge. Cooke et al (2008) describe this focus on team interactions as having much in common with the small group work on decision making (Festinger, 1954), social decision schemes (Davis, 1973; Hinsz, 1995; 1999), and transactive memory (Hollingshead and Brandon, 2003). Team cognition within the THEDA perspective is considered a single organism which adapts itself to the ever changing environment via the coordination of team processes and perceptual systems (Stanton et al., 2014). The coordination and communication behaviour of teams allows for team cognition to be directly observed and rather than team communication being a window to team cognition, it is team cognition itself. In other words, the team interactions are cognitive functions that integrate the thinking and decision making of the team (Cooke et al., 2008).

### **2.2.3 Neurodynamics**

The neurodynamics approach is a more recent perspective on team cognition and has been explored primarily by Stevens & colleagues (e.g. Stevens *et al.*, 2010, 2012, 2017; Stevens, 2013; Stevens, Galloway and Lamb, 2014; Stevens and Galloway, 2016; Stevens, Galloway and Willemsen-Dunlap, 2017, 2018; Stevens, Galloway and Willemson-Dunlap, 2017; Stevens, Willemsen-Dunlap, *et al.*, 2018; Stevens, Galloway, *et al.*, 2018). This perspective views teams as complex systems which operate at a level which self-organises between random and highly organised states (Stevens, 2013). Teamwork in this sense was first described as “the continuous effort involved in stabilization of an inherently unstable system”

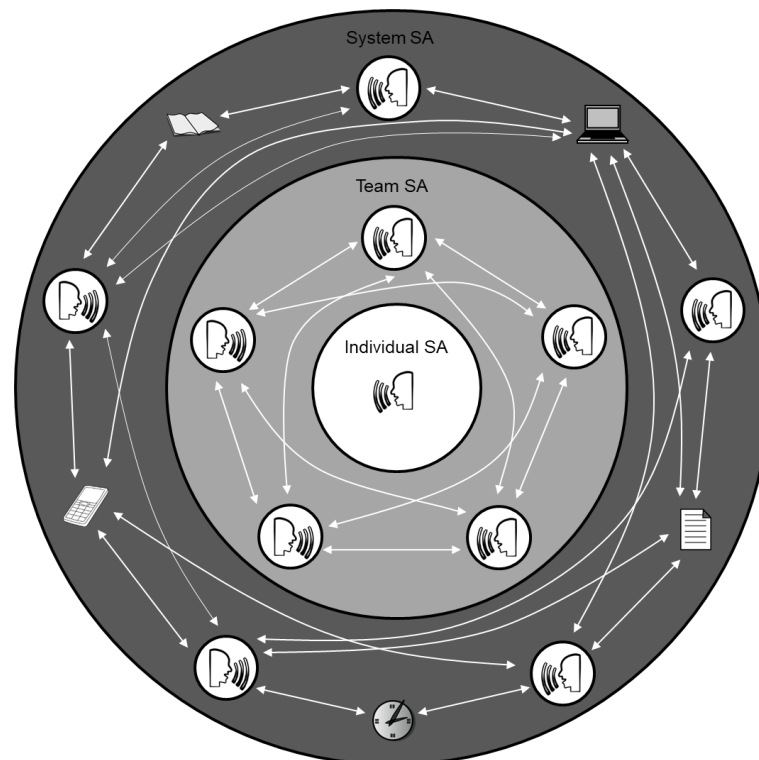
(Gorman et al., 2010; Stevens, 2013; Treffner and Kelso, 1999) and more recently the “evolving dynamics across temporal scales that are continually punctuated by small and large fluctuations as disturbances to the team’s normal rhythms are encountered and resolved” (Stevens and Galloway, 2017). In this sense, the dynamics of teams not only includes the communication and behaviours of teams seen in the THEDA perspective, it also considers neurophysiological changes. Stevens and colleagues have been exploring these neurophysiological changes through the use of EEG-derived levels of engagement (Stevens et al., 2011; Stevens and Gorman, 2011) which they term Neurophysiologic Synchronies (Stevens, 2013). Their aim is to detect pattern dynamics within the Neurophysiologic Synchronies in the context of changing team tasks across different timescales and quantifying the degree of organisation through the use of entropy, where low entropy indicates a greater degree of organisation in the team neurophysiological state (Stevens, 2013). The fluctuations of entropy in the Neurophysiologic Synchronies data has been linked with team experience, communication and variations in the task environment (Stevens, 2013). While the neurodynamic approach requires the collection of EEG data from team members, this could be intrusive and so it is a moot point as to whether the approach could be applied from other sources of data (for this thesis, the focus will be on the content of messages that team members exchange).

### **2.3 TEAM SITUATION AWARENESS**

Endsley’s (1995a) definition of SA is generally accepted and is as follows:

“Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.”

SA can be split into; Individual SA, Team SA and System SA (see Figure 1). While Endsley is resolute in the idea SA itself can only occur at an individual cognitive level (Endsley, 2015, 1995b), indicating her roots in the process-oriented view outlined above. However, SA can also be seen from a THETA or system level where compatible information is distributed throughout the systems agents (humans and artefacts) (Salmon et al., 2008; Stanton et al., 2005, 2014, 2006). The arrows, in Figure 1 show the knowledge or information transfer. Although there several theories of individual SA (Endsley’s Three Level Model (1995a), Smith and Hancock’s Perceptual Cycle Model (1995) and Bedny & Meister’s Activity Theory Model (1999)), this review will be focussing on Team and System SA only. These Team and System SA models include the Wellens (1993) Model of Distributed Decision Making, Salas et al.’s Framework of Team SA (1995), Endsley’s Team SA Model (1995a) and Chiappe et al. (2012b) Situated SA Theory, as well as Stanton et al.’s (2006) Distributed Situation Awareness Model which describes System SA.



**Figure 1 – Hierarchy of the types of situation awareness**

### **2.3.1 Distributed Decision Making (Wellens, 1993)**

The model of distributed decision making describes SA during a collaborative team activity and suggests the arrangement of teams is the key to team SA, so that there is sufficient overlap between the individuals SA enabling the team members to work together, but still leaving enough distance to allow for individual SA to develop (Salmon et al., 2008).

### **2.3.2 Framework of Team SA (Salas et al., 1995)**

The perception of SA elements (i.e. Level 1 SA (Endsley, 1995a)) is influenced by factors such as communication of mission objectives, individual tasks, team capacity etc. (Salmon et al., 2008), where the comprehension of this (i.e. Level 2 SA (Endsley, 1995a)) can be affected by interpretations by other individuals within the team (Salmon et al., 2008). This suggests a cycle of SA, where the development of individual SA leads to and modifies SA both the individuals SA, but also the other team members SA. They conclude that team SA: "...occurs as a consequence of an interaction of an individual's pre-existing relevant knowledge and expectations; the information available from the environment; and cognitive processing skills that include attention allocation, perception, data extraction, comprehension and projection" (Salas et al., 1995). The Salas et al. (1995) framework comprises of individual SA and team processes, where the team SA depends on communication at various levels (Salmon et al., 2008), using the Endsley (1995a) three level model of individual SA in its approach.

### **2.3.3 Team SA (Endsley, 1995a)**

According to Endsley (1995a) each member of the team has their own specific set of SA elements (to be perceived i.e. Level 1 SA) which is determined by each of the team member's responsibilities or requirements, with an overlap of some of those requirements between team members (Endsley, 1995a). This subset of overlapped information is described by Endsley

(1995a) as what constitutes much of team coordination and is termed “shared SA”. Endsley (1995a) also states that every team member must have SA of their own requirements for team SA to be complete. Endsley (1995a) describes team SA as: “...the degree to which every team member possesses the SA required for his or her responsibilities. This is independent of any overlaps in SA requirements that may be present” (1995a). Team situation awareness is the overlap of the individuals situation awareness within the team and this overlapping occurs when team members share knowledge and communicate. Another important aspect of this theory is that situation awareness is still a cognitive activity occurring in the individuals mind and it is the sharing of this or common ground which represents team situation awareness. However, according to (Stanton et al., 2006), sharing awareness does not necessarily require communication. If all team members attempted to share their interpretation of their own individual awareness via communication it may be confusing or misleading (Stanton et al., 2006).

#### **2.3.4 Situated Situation Awareness**

The situated SA theory states that individuals will off-load cognitive computation and information storage to the environment as often or as much as possible (Chiappe et al., 2012a), based on the notion that at times to achieve SA knowing where the information is in the environment is all that is required, rather than having to remember exactly what that is (Durso et al., 1999). This reduces the amount of information held in working memory, making better use of the individuals working memory capacity. Chiappe, Strybel & Vu (2012a) emphasises that off-loading will only be useful if the individuals incorporate artefacts into their environment in which they can off load to and the offloading occurs in such a way that it benefits performance. However, there are cognitive overheads which occur when the act of communication takes place, for example communication may interrupt ongoing tasks or

the information communicated may need to be processed. Therefore, it could be of benefit to the individual and team to have a central repository where information and knowledge is pooled, reducing the amount of direct communication required. The notion of Situated SA (Chiappe et al., 2012b, Chiappe et al., 2012a, Durso et al., 1999) suggests that individuals will utilize artefacts in the environment in order to off-load computation and information storage allowing for a reduction of cognitive processes such as internal memory expenditure. This process would reduce the amount of knowledge held by each individual, but the system including the utilized artefacts, would hold the knowledge required for the team to function.

### **2.3.5 Distributed Situation Awareness**

Distributed Situation Awareness (DSA) properties that are not part of individual cognition, with SA therefore being an emergent property of the system (Salmon et al., 2008). “No one member has the overall SA, rather it is distributed around the system” (Salmon et al., 2007). It is important for the agents within the system to interact with each other to maintain and develop the DSA of the system as well as the humans individual SA (Salmon et al., 2007). Stanton et al. (2006) defines SA as: “...activated knowledge for a specific task, at a specific time within a system.” (Stanton et al., 2006). This knowledge is distributed throughout the system and is held by the human agents, e.g. via working or long term memory, and captured by either the human or the hardware used, e.g. via digital sensory inputs (Stanton et al., 2006). The information for the system SA is held by the individual agents (both human and hardware) however no single agent has overall SA, this is only achieved at the system level. Each human has their own individual SA, but this will undoubtedly be limited to their own environment and elements, with the system SA being much more information rich. It is important to note that DSA does not replace the individual SA of the human or render it redundant; neither does it suggest that the hardware or artefacts used have its own individual

SA, more over it provides an approach to viewing and describing SA at a higher systems level (Stanton et al., 2014, 2006).

## 2.4 MEASURING SITUATION AWARENESS IN TEAMS

45 different situation awareness (SA) measurement techniques have been identified, the earliest noted method dating 1988 and the latest 2018. The quantity of measurement techniques reflects differences of opinion as to what the concept of ‘situation awareness’ indicates and how it ought to be measured. Figure 2 depicts when these measures were introduced into the academic domain as a cumulative sum (bars) and shows the prevalence of individual SA measures compared to team and system measures (lines). The majority of situation awareness measurement techniques were developed in the 90’s and 00’s and focused primarily on individual situation awareness, with team situation awareness methods gaining more interest in the 00’s. Out of all the techniques available, 32 assess individuals, 18 assess teams (although some of the techniques available have been developed to assess both

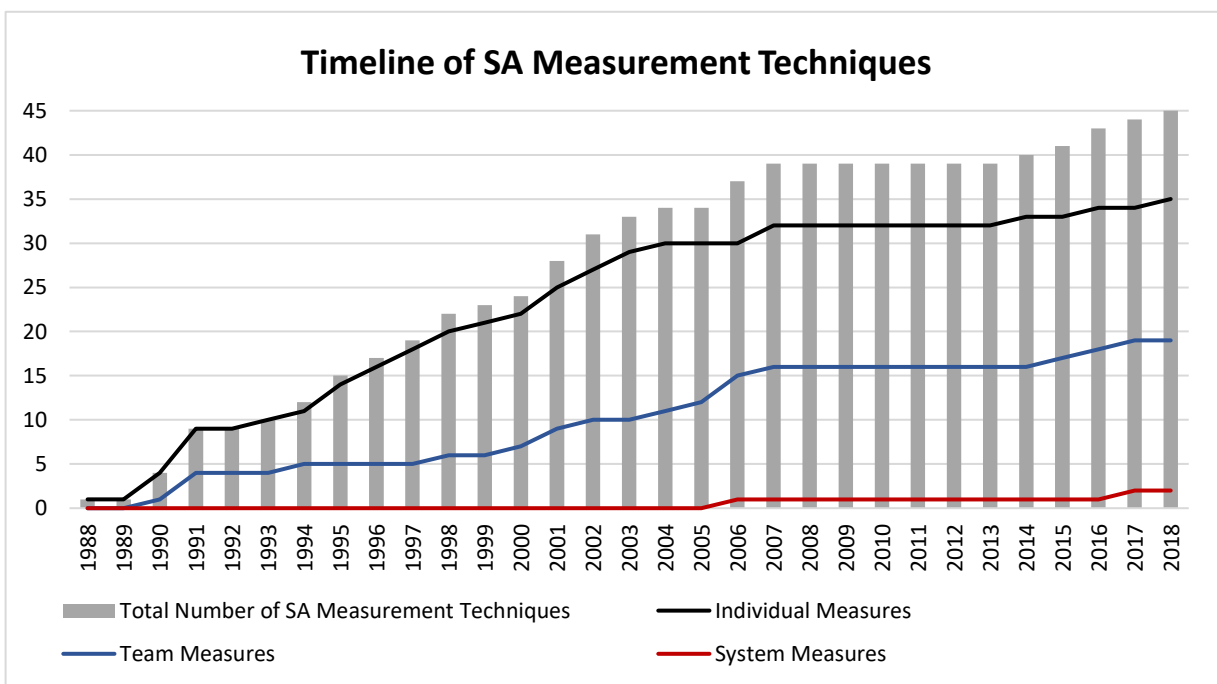


Figure 2 - Timeline of SA measurement techniques

individual and team situation awareness) and only 2 take into account the assessment of systems. Appendix A provides a table of these techniques categorised in terms of whether they focus on individual, team or system; when they are applied; which type of measurement technique is used; and their advantages / disadvantages.

Observer rating methods (e.g. CAST, SALIANT, TARGETS, CSA & SAM-TC) where a subject matter expert (SME) allows trained observers to rate a team, based on predefined SA criteria. However, SA is determined by changes in real-world situations, which makes the technique inflexible to change within the scenario under observation, unfortunately in the real-world it is not possible to know beforehand what SA should or will comprise of (Stanton et al., 2013). One could argue that the act of observing itself could have an impact on the individual's behaviour. Team members may revert to 'by the book' actions which would exhibit high SA while in reality they may have low, undetected, SA (Salmon, 2008). It may also be difficult to distinguish between different levels of SA perception / comprehension / prediction) using this method (Salmon, 2008), however there are plenty of individual SA measurement techniques available which can be utilised alongside the observer rating to achieve this, although these have their own implications on an individual's SA and so the technique would need to be chosen wisely.

Freeze-probe techniques have a number of benefits such as using queries based on SME expertise rather than using self-rating methods (Salmon et al., 2008), the ability to gather data concurrently negating the risk of limited information retrieval post-hoc (Salmon et al., 2006; Stanton et al., 2013) and, arguably, the capability to provide a direct measure of individual SA (Endsley, 1995b, 1995a, 1988; Salmon et al., 2006; Stanton et al., 2013). SAGAT (Endsley, 1988) can be used to measure team SA by summing each individual's SAGAT score, the higher the score the greater the team SA (Wright et al., 2004). The technique TSAGAT

(Crozier et al., 2015) aims to achieve this. By using this method, one can detect the levels of SA of each of the individuals, while also having an overall metric of the team SA. However, freeze-probe techniques have been heavily criticised for (but not limited to) their intrusiveness on task performance, inability to be applied to real-world scenarios, requirement for costly simulation and hardware equipment, predetermined definitions of SA which are inflexible to changing situations and the risk that the probes/queries used may direct individuals to particular states or elements of SA that they were previously unaware of.

Considering that communication is vital for collaborative team tasks, be it verbally or non-verbally, it stands to reason that communication itself can be key to understand the SA of teams. For example, SAMTC (Lampton et al., 2006) analyses team communication using the observer rating method and rates the comments made as either 'good' or 'bad', with an average of all ratings giving an overall team SA score. The score is based on a predetermined standard of what good or bad SA comments are and so as the team communicate what is said can be simply compared to that standard. Unfortunately, the technique does not give insight into how SA has been formed, although, it could be possible to conduct some sort of content analysis to provide more in-depth knowledge of how the team reached its own level of SA. One such technique has tried to do this (IPTE) (Banbury and Howes, 2001; cited in Breton, Valcartier and Tremblay, 2007) using decision-making analysis and real-time probes (similar to freeze-probes, however the task is not paused). The creators argue that the real-time probe results in a measure of team SA based on how much each individual knows about other team members goals and knowledge. However, the more interesting part of this technique is in how the process of team SA is analysed using individual decision making. By tracking critical information within the team by analysing decisions made by individuals, i.e. if an information 'seed' has been received then a particular decision will be made, a more in-depth analysis of

how team SA was acquired can take place. This process of information seeds propagating through the system and being transformed at different nodes within the system, supports the notion of distributed cognition.

The DSA approach follows the premise that 'knowledge' is externalised through communication and research has shown that there is a strong link between communication and team SA (Endsley and Jones, 2001; Fischer and Orasanu, 1999; Garbis and Artman, 2004; Gorman et al., 2005; Hazlehurst et al., 2007; Wright et al., 2004) The content of communication (whether spoken or typed) therefore could be used as a proxy for what individuals within a team may know and how that could be used to inform situation awareness. A typical way of showing knowledge in a team or system is through concept maps (Novak and Cañas, 2008) which are described to "encourage the externalization of information" (Coffey et al., 2006). It is plausible that due to the individuals own experience and perception of the environment that they would have different knowledge from one another, resulting in different SA (Salmon et al., 2008).

Using PropNets to show activated knowledge within the system is one of the only methods that view team/system SA as more than just the sum of its parts. Monitoring the knowledge in the team allows the analyst to see how, when and where that knowledge is being used, if at all. The emergence of DSA can be seen using this technique. It does not rely on individual measures of SA because it is not the individual that is being measured, it is the system.

However, using PropNets to analyse teams and systems is a time-consuming task, although the data can be collected during the task, the creation of the PropNets can only really be done post-hoc. There are also a lot of results to analyse, the networks tend to be large with many knowledge objects and propositions to keep track of as well as there being several networks representing different points within the task, or different sub-tasks being carried out. Other

limitations of using PropNets is that the data used to populate the networks is carried out using CDM, which unfortunately is prone to memory degradation as it is carried out post-task (Key, 2016), the method may have difficulties identifying knowledge that has been used but not openly expressed (Key, 2016). However, the technique is not intrusive on the task at hand, which allows for the team/system to run through the scenario unhindered. Unfortunately, however, the networks only show activated knowledge, they do not show who (or what) has activated that knowledge. This may sound like a contradiction to what has already been said about team/system SA not being about individual SA, however for practical reasons it may be of use to know where that knowledge is coming from or who/what is using it. In Human Factors it is important to ensure that individuals within any system are not put under unnecessary cognitive or physical load. If the PropNets could give insight into where the knowledge is generated and used (and by whom), then they may also give insight into the cognitive load of certain parts of that team/system or even specific nodes within the system. The question is: how can this be done without intrusion on the task and how can the extracted knowledge be analysed to show a measure of team SA?

One study (Foltz et al., 2017) used TeamPrints, a system that utilised computational linguistics and machine learning techniques coupled with Latent Semantic Analysis (LSA) to analyse and model team communications, with the aim of predicting team SA levels (as in Endsley's 3 Levels of SA) and performance. The study used post-hoc transcript data from a simulated collaborative team task which TeamPrints learned, once a model was created other transcript data was then analysed using the model to predict SA. The model results were not as accurate as expected (~50% agreement with transcripts), although the authors suggest this could be due to "having to infer SA based on post-hoc analysis of team communications". However, findings did show that the TeamPrints system was able to identify certain levels of

SA within the team, however the findings did not correlate with scores from SAGAT.

Considering that team SA in this case was based on Endsleys 3 level model, one would expect for there to be a better relationship between the results of TeamPrints and SAGAT. A reason for this could be, as previously mentioned, team SA could be a different construct to individual SA and therefore individual SA measurement techniques will not be comparable to team SA measurement techniques.

A number of other studies have also used communication transcripts as the unit of measurement for analysing team SA (Bowers et al., 1998; Cooke et al., 2004; Fischer and Orasanu, 1999; Garbis and Artman, 2004; Hazlehurst et al., 2007; Kiekel et al., 2001; Min et al., 2004; Parush et al., 2011; Wiltshire et al., 2017). A number of these approaches relies on coding communication transcripts based on a set of classifications suited for the task at hand and then looking for patterns which emerge from the resulting data. Some of these classifications are based on process behaviours and used distributed cognition as the theoretical framework (Cooke et al., 2004; Fischer and Orasanu, 1999; Hazlehurst et al., 2007) where others step away from the theoretical semantics and simply describe the approach as an analysis of task coordination and/or collaboration (Heath and Luff, 1991; Min et al., 2004; Wiltshire et al., 2017). What is clear is that the content of communication contains rich data which can give insight into the way a team is behaving and constructing their knowledge of situation (Parush et al., 2011) and there is a strong focus on team processes rather than individual knowledge.

## **2.5 ANALYSING TEAMS**

### **2.5.1 Social Network Analysis**

Social Network Analysis (SNA) has been used in many domains, e.g. construction (Zheng et al., 2016), healthcare (Bae et al., 2015; Chambers et al., 2012), education (Cela et al., 2015), project management (Mead, 2001), sports (Clemente et al., 2015) and command & control (Walker et al., 2008a). It is used to analyse and investigate interconnected networks of individuals and focusses on the relationships between individuals and the patterns that arise from the interactions between them (Wasserman and Faust, 1994).

Commonly, SNA is used to indicate the size of the network, via the number of nodes, and how busy a network is, via the number of links between nodes (Scott, 1988). The analysis can also identify distinct sub groups within the network, known as components (Scott, 1988).

Then density of a network, that is the number of total links within the network, can show the extent to which a network is interconnected (Scott, 1988). SNA can also show, on average, how often links pass through nodes (mean degree centrality) and the number of unique paths pass through nodes (mean betweenness) (Scott, 1988).

In the healthcare for example, SNA has been used to present complex interaction patterns between primary care providers (Scott et al., 2005), to show how social influence impacts personal and professional relationships (Zheng et al., 2007) and identify gaps in informal networks which have been shown to impede the dissemination of information and influence between directors of nursing and medical directors (West et al., 1999; West and Barron, 2005). SNA has also been used to explore teams within sports. In a study by Ribeiro et al. (2017), SNA was used to explore complex interactions between players by mapping actions (such as ball passing) onto a teammate network to evaluate individual and collective

performance data. In order to study how cooperation among organizations occur, Washe (2015) used SNA to investigate an informal sport tourism network in order to better understand the mechanisms of interorganizational cooperation.

Although SNA has been a method used in research since the 1950's (Freeman, 2004) it is still providing a way of analysing teams. Recently it enabled researchers to discover several interesting features of teams, for example, teams are more creative when the process of information flow is supported a large number of interactions between team members and that shared leadership promotes a positive effect on knowledge sharing (Wu and Cormican, 2016). In sports, Clemente et al (2015) was able to show that high performance was associated to a large volume of connectivity between teammates. SNA has also allowed researchers to delve into how emergency response teams behave when responding to an emergency at an oil and gas refinery. Mohammadfam and colleagues (2015) were able to show that in this particular emergency response teams, there was poor coordination between key members of the team network and that there low levels of coordination and cohesion. SNA has also been used to explore how teams gain awareness of their teammates and identify leaders within that team (Bourbousson et al., 2015). In the same study, it was found that there was often one team member which either hindered or was hindered by their team mates which was used to identify them at the leader within the team. Interestingly, experts within the team showed little awareness of their teammates implying they can work alone up until the point they are alerted to their teammates and need to respond.

Stanton and Roberts (2018) has shown that SNA not only can be used to explore the outcomes of team performance, but also the dynamic nature of teams in complex systems, in particular within submarine command and control. By analysing social, task and information networks they were able to clearly see that the types of social interactions, information transition and

focus of task is highly dependant on the operation taking place. Their approach has enabled the analysis of both human and non-human agent (hardware) and has allowed a more comprehensive analysis of the submarine command and control system.

Stanton and colleagues (2008, 2018) have incorporated SNA into a larger team analysis technique, Event Analysis of Systemic Teamwork (EAST), which uses a combination of team networks to explore team performance; including task networks, social networks and information networks. This method focuses on the team system, to explore patterns and behaviours which occur through interactions.

Social Network Analysis, as well Stanton et al's (2008, 2018) EAST method of including task and information network analysis has provided a way of both visually and quantitatively study teams statically and dynamically. There are however, several other ways in which communication interactions can be analysed and explored in order to give insight into teams and teamwork. The next section will develop this discussion further.

### **2.5.2 Communication**

Communication in this context is the exchange of information occurring both verbally and non-verbally between team members (Adams, 2007; Marlow et al., 2018; Mesmer-Magnus and DeChurch, 2009). This team communication is integral to many of both team processes and interdependent team behaviours which lead to performance (Marks et al., 2001) and researchers posit that communication assists with emergent team states, such as team cognition (Salas et al., 1997).

Communication has been used by many researchers to measure performance in teams and deficiencies in communication has been linked to catastrophic outcomes in routine and high-stakes environments (Bundy, 1994; Foushee, 1984; Lingard et al., 2004; Moorman, 2007;

Salas et al., 2004; Sasou and Reason, 1999; Singleton, 1989; Sutcliffe et al., 2004). Initially it was believed that more communication leads to more information processing and therefore better performance, although not all research has supported this premise (Rosen, 2010). There is evidence that larger volumes of communication acts are associated with higher performance (Foushee and Manos, 1981; Mosier and Chidester, 1991), however the findings have not been replicated elsewhere (Bowers et al., 1998). On the other hand, other researchers have provided evidence that increased communication was associated with poor performing teams (Choi and Levine, 2004) and that it is the quality of communication is more integral to team performance (Taylor and Faust, 1952; Barnlund, 1959; Campbell, 1968; Lamm and Trommsdorff, 1973; MCGrath, 1984; Marks, Zaccaro and Mathieu, 2000; Hassall, 2009; Sorensen and Stanton, 2013; Marlow *et al.*, 2018). This conflicting research has been discussed by Hassall (2009), and MacMillan et al. (2005) within the team cognition literature. It has been suggested that teams do require communication to coordinate actions but can be costly in terms of workload for the team members. Depending on the team, more actions may need to be discussed and therefore more communications occurring, regardless of the outcomes of the teams themselves. Additionally, Marlow et al. (2018) suggest that high frequency communication may contain distracting and irrelevant information which could interfere with teams setting priorities appropriately. This method of simply counting the number of comments therefore, like other aggregated based measures, does not capture the dynamic nature of the processes taking place.

Other methods have tried to capture this dynamism via analysing the content of the communication of teams. Research has shown communication is related to higher performance when the content of that communication is consistent with the task requirements (Hackman, 1978; MCGrath, 1984; Salazar *et al.*, 1994; Harris and Sherblom, 2005). Rosen

(2010) identified two general methods for analysing the content of communications: manual content analysis done by hand (Krippendorff, 2006) and automated content analysis via Latent Semantic Analysis (Landauer et al., 1998).

Latent Semantic Analysis uses machine learning algorithms to statistically infer predicted relations between contextual uses of words in communication (Foltz, 2007). The method has been shown to predict team performance outcomes which were reasonably accurate compared to actual team performance scores (Gorman et al., 2012; Martin and Foltz, 2010). The method does have the benefit of discriminating between high and low performing teams, however has been criticised for having a low level bottom up approach to understanding team communication (Rosen, 2010).

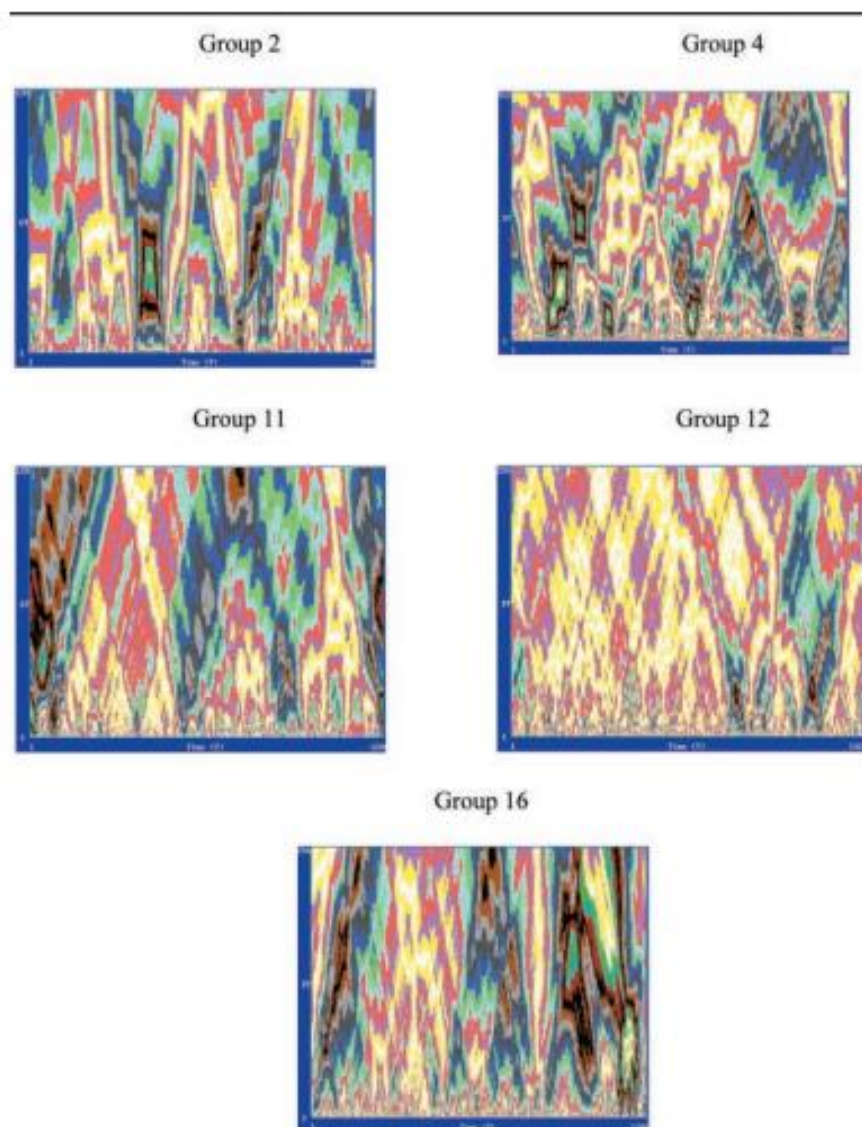
Manual content analysis involves coding of transcripts in order to categorise the type of communication occurring. A number of coding schemes have been developed to explore team effectiveness (Bales, 1950; Bowers et al., 1998; Fisher, 1970; Rosen, 2010; Tschann, 1995). Depending on the number of categories used, the richness and complexity of the content may become lost, however it is argued that this abstraction is necessary part of generating measures of team processes (Rosen, 2010). Despite this, there has been substantial research looking at the type of communication or interactions in relation to team performance (Hackman and Morris, 1975; Hirokawa, 1990, 1980; Mabry and Attridge, 1990; Sorenson, 2006; Sundstrom et al., 1997). For example, research has shown that there is a positive relationship between communication activity and performance quality (Sorenson, 2006). In this example, communication activity was based on Bales's (1950) Interaction Process Analysis (IPA) approach, where team members structure, elaborate and evaluate shared tasks. Mabry and Attridge (1990) also used Bales's (1950) IPA approach to compare production (structured) and problem solving (unstructured) tasks. In their study, they found no

relationship between communication activity and performance in the structured task, however in the unstructured problem-solving task there were significant findings between communication activity and performance. Following the common theme of research in this area, not all findings within the literature have discovered relationships between communication activity and performance. For example, the findings of a study conducted by Sundstrom et al. (1997), where teams performed a desert survival problem solving task, found no relationship between communication activity measures and team decision quality.

Although the research exploring the content of communication discussed above endeavours to move away from aggregate-based measures and provide insight into the dynamics of teams, they are still in a way, aggregate-based measures. The number of times a particular communication activity, process or behaviour occurs over the course of a task is summed and compared to a predetermined standard of performance. This could explain the reoccurring conflict between findings within this area of research. There are some researchers however who have been exploring at patterns of communication activities occurring over the course of a task (Angus et al., 2012; Dale et al., 2014; Fusaroli et al., 2014; Hassall, 2009; Kiekel et al., 2001; Roberts et al., 2004; Wheelan and Williams, 2003; Wiltshire et al., 2017) as well as methods which look more specifically at team dynamics (Demir et al., 2018a; Gorman et al., 2017; Reed and Vallacher, 2019). For example, Wheelan and Williams (Wheelan and Williams, 2003) were able to identify three types of communication patterns within their sample of teams using Wheelan et al's (1994) 8 communication categories and plotting this data as a wavelet transform image. Wiltshire et al. (2017) were also able to identify patterns of communication over time based on Rosen's (2010) 16 communication categories.

Both of these studies have attempted to show the dynamics of team processes visually and have accepted that teams are inherently non-linear and complex. Wheelan and Williams

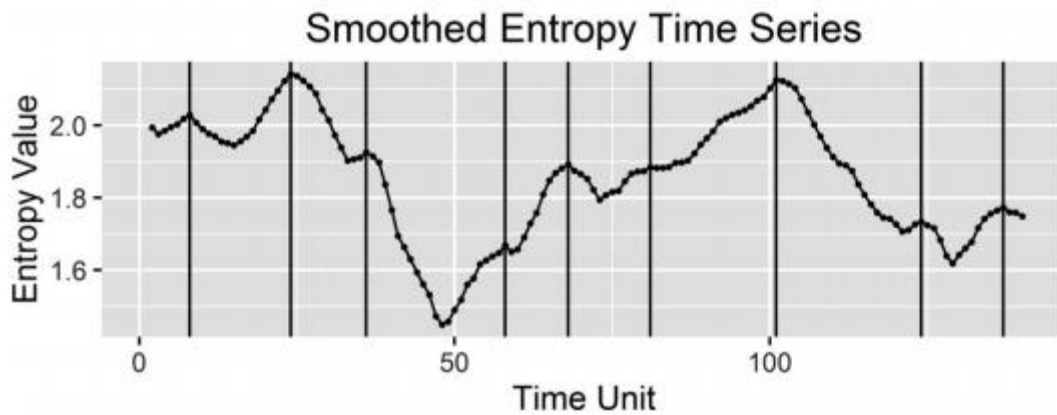
(Wheelan and Williams, 2003) based their work on Dyke's (1990) chaos/complexity theory (i.e. the study of patterns) and looks at the change in frequency or amplitude of the extreme and/or subtle differences in coded communications from one statement to the next and in relationship to the other statements. This was done by inputting the resultant codes into the an accepted complexity software, Chaos Data Analyzer, (Alligood et al., 1997; Casti, 1996). The end product of the analysis is a colour image of the verbal interaction sequence that occurred during team interaction, with colours representing patterns of comments and shifts in those patterns across time (Wheelan and Williams, 2003). An example of these outputs can be seen in Figure 3, with the X-axis representing time.



**Figure 3 - An excerpt from Wheelan & Williams (2003) showing patterns of the verbal interaction sequence**

Wiltshire et al. (2017) chose to display the complex nature team processes through the use of entropy, where entropy is a way of displaying the order and disorder with a system. They also coded transcripts and provided a time series of data based on the entropy results of those codes over a sliding window, using Shannon's (1959) entropy equation. They were able to plot these entropy results on a graph, which allowed for a visual representation of the complexity of presented team processes, which in turn allowed for the detection of patterns

which were associated with transitions between specific team processes. An example of these outputs can be seen in Figure 4.



**Figure 4 - Excerpt from Wiltshire et al. (2017) showing entropy time series for a team with vertical black lines representing transition points between team processes**

Researchers working within the neurodynamics domain have also examined entropy in the context of team performance. Work by Stevens and colleagues (Likens et al., 2014; Stevens, 2012; Stevens et al., 2012) have attempted to understand how entropy, using EEG data rather than communications, relates to peoples expertise and performance. Entropy in this context corresponds to the degree of cognitive flexibility exhibited by the team and Stevens (Stevens, 2012) found that teams who performed better on team tasks exhibited higher entropy than poor performing teams.

This shift towards analysis of communication and the visual representation of team processes shows promising results, both in terms of understanding how teams conduct themselves over the course of a task and also in terms of detecting patterns in team behaviours. However, due to the necessary abstraction from the micro to the macro, as seen in the above two examples, the exact processes taking place are lost. Therefore, there is clearly a trade off between

exploring the macro team processes over time and understanding the micro processes taking place all within the same visual output.

## **2.6 AGENT BASED MODELLING**

As systems become comprised of more autonomous sensing artefacts, those artefacts could potentially be considered as members of the team. This raises the question about the situation awareness of individuals and the situation awareness held by the system in which those individuals are interacting (Woods and Sarter, 2010). A way in which this can be explored is by using Agent-Based Models, which can be configured to create a range of team and system structures. Agent Based Models allow for situations to be modified and manipulated to ensure the conditions applied to each agent within that model is the same each time. The models also allow for many “participants” to be recruited and many trials to be run.

A justified argument against using agent based modelling is that internal cognitive processes are complex and cannot be reduced to a simple set of calculations or algorithms. It is recognized that a reduction of cognitive process is a potential limitation of the approach one could argue any form of simulation of cognitive activity (from Artificial Intelligence to Cognitive Architectures) have the same limitation. Therefore, accepting the limitations while utilizing the benefits of agent based modelling makes it possible to explore aspects of teams and systems which would be difficult in the real world, such as the link between the micro-level behaviour of individuals and the emergent properties arising from the interactions of those individuals.

With this in mind, using agent based modelling to simulate tasks in order to study situation awareness has not received widespread attention in the literature, although some researchers have acknowledged its potential (Baber et al., 2013; Bolstad et al., 2005; Bosse et al., 2013b,

2013a; Bosse and Mogles, 2014; Connelly et al., 2007). The study by Bolstad et al. (2005) aimed to develop a computational model of shared situation awareness by employing cognitive modelling and Social Network Analysis (SNA). Baber et al. (2013) on the other hand used the program NetLogo to explore the impact of a Common Operating Pictures (COP) on the transfer of information within a Search and Rescue system. The model was used to explore the transfer of information and how that information could be lost during the task. The model allowed for a visual representation of the situation awareness of the network. Baber et al. (2013) highlighted a number of benefits for using NetLogo as an agent based modelling package, including the large amount of models and code available online through the NetLogo community, the high-level programming language being easy to learn and use and that the graphic representation of the model makes it easier to understand how the model is working

### **2.6.1 Choosing an Agent Based Modelling Package**

There is a vast array of ABM packages available, 85 packages were identified in a review by Abar *et al.* (2017) and compared using a range of categories including coding language, availability/accessibility, type of agent based on interaction behaviour and application domain. The purpose of this chapter is not to replicate this research, but to explain and justify the use of the chosen ABM package, NetLogo, in this thesis. A review of two other ABM packages, Behaviour Composer and Scratch, can be found in Appendix B.

Six criteria from the categories in Abar *et al.* (2017) were identified as important for deciding on an ABM package to use in this project, a summary of which can be seen in Table 1. The first relates to the level of programming experience and skill required to create the agent based models, represented by “Easy to code/develop” in Table 1. Many of the packages do not require any coding experience and have been developed in such a way that the coder is

writing a story or giving instructions in plain English, and the platform interprets that into code which the computer can understand (Abar et al., 2017). These packages enable the user to generate ABM quickly with little training, however due to the high-level programming they can restrict both the complexity and scale of the agent based model. For more flexibility competent programmers with knowledge of languages like C, C++ or C#, can use (Abar et al., 2017). Clearly for someone with limited coding experience, at least to start with, the effort for both learning and developing agent based models would need to be kept low to achieve results in a timely manner. This was the first and deemed the most important criteria for deciding which ABM package to use.

Similar to keeping the learning based on the ABM itself, rather than a new programming language, it was important to have an ABM package that is standalone i.e. does not require any advanced setup or additional processes to execute the models/simulations. A number of packages come with their own modelling environments, which allow for a more plug and play type (Abar et al., 2017). This, plug and play type feature was added to the list of criteria for choosing the ABM package, represented by “Inbuilt coding/development” in Table 1.

Scripting the behaviour of individual agents in ABM can be approached in a variety of ways, e.g. complex formulas, BDI, reactive-behavioural / ‘if-then’. To maintain simplicity in the code and due to the nature of the models to be produced, a reactive ‘if-then’ approach was chosen, using a package which enables goals, actions and attributes to be assigned to active agents using a class like structure. Therefore, only packages which focussed on the agents/objects which are implemented as class structures were considered and therefore all of the packages in Table 1 have this feature. The package must also be free and easy to access, this again was to ensure that research could be carried out swiftly without any unnecessary time delays. Considering the large variety of free ABM packages available, this was deemed a

reasonable criterion, represented by “Free/Open Source” in Table 1. Ensuring that there were also no time delays in obtaining specialist hardware or software, the second criterion was that the ABM must be able to be run on a Windows or Mac PC, both readily available at the start of the research project, this was deemed a reasonable criterion, represented by “Used on Windows/Mac” in Table 1.

**Table 1 - Summary of Agent Based Models**

	Easy to code/develop	Use on Windows/Mac	Free/Open source	Models & Librarys Available	Used in social sciences	Inbuilt coding/development	Score
<i>AgentScript</i>	✓	✓	✓	✓	✓	x	5/6
AgentSheets	✓	✓	x	x	✓	✓	4/6
Altreva Adaptive Modeler	✓	✓	x	x	x	✓	3/6
Behaviour Composer	✓	✓	✓	✓	✓	✓	6/6
FlexSim	✓	✓	x	✓	x	✓	4/6
Framsticks	✓	✓	x	x	x	✓	3/6
JAMEL	✓	✓	✓	✓	x	x	4/6
JAS	✓	✓	✓	✓	✓	x	5/6
JCASim	✓	✓	✓	x	x	✓	4/6
jES	✓	✓	✓	x	x	✓	4/6
MOBIDYC	✓	✓	✓	x	x	✓	4/6
NetLogo	✓	✓	✓	✓	✓	✓	6/6
PedSim	✓	✓	✓	✓	x	✓	5/6
<i>PS-I</i>	✓	✓	✓	✓	x	✓	5/6
<i>Scratch</i>	✓	✓	✓	✓	✓	✓	6/6
<i>SeSAm</i>	✓	✓	✓	x	✓	✓	5/6
SimJr	✓	✓	✓	x	x	x	3/6
SimSketch	✓	✓	✓	x	x	x	3/6
SOARS	✓	✓	✓	x	x	✓	4/6
<i>StarLogo</i>	✓	✓	✓	x	✓	✓	5/6
<i>StarLogo TNG</i>	✓	✓	✓	✓	x	✓	5/6
<i>Sugarscape</i>	✓	✓	✓	✓	x	✓	5/6
<i>VisualBots</i>	✓	✓	✓	✓	x	✓	5/6
<i>VSEit</i>	✓	✓	✓	✓	x	✓	5/6

The final criterion was based on the intended application domain of the ABM package and the availability of example solutions in the literature. Considering that the research domain of the project is under the social sciences umbrella, it was important to choose an ABM package that had already proven its worth within that domain. As the ABM package needed to allow for low effort development only packages that fulfilled this criterion were considered, this was deemed a reasonable criterion, represented by “Used in social sciences” in Table 1. Out of the 24 identified, only 3 packages fulfilled all 6 criteria: Behaviour Composer, NetLogo and Scratch. The following section will explain why NetLogo was chosen for this project.

### **2.6.2 NetLogo**

NetLogo has already been mentioned in the above description of Behaviour Composer, essentially the only difference between NetLogo and Behaviour Composer is that in NetLogo you do the ‘coding’ where in Behaviour Composer the coding has been done for you. The NetLogo version shown here is the downloadable executable from the <https://ccl.northwestern.edu/netlogo/> website, however a web version is also available and this is the one that Behaviour Composer is built upon, however there is no difference in how models are created or run in either of the two versions. The Netlogo website also has a large amount of support, including a primitive dictionary which explains with examples what the different primitives within the language can do and where they can do it as well as user manuals in several different languages. There is also a vast array of sample models, both online and in the downloaded package.

**Figure 5 – Netlogo: Code View**

The example in Figure 5 (the code) & Figure 6 (the output/interface) is similar to the fish swarm in Behaviour Composer and it is clear how similar they are visually in the output/interface view.

In NetLogo (and Behaviour Composer) there are 4 main components:

- Turtles: agents that move around in the world (the output view)
- Patches: square pieces of ‘ground’ over which turtles moves and can interact with
- Links: agents that connect two or more turtles, represented by a line

- The observer: the overseer of the world of turtles and patches

The code allows for turtles to be created and attributes assigned to them, for example under “to setup” in Figure 5, several turtles are created based on the selected population variable in the interface view (Figure 6) and a number of attributes are assigned to those turtles, such as colour, size & position within the view window. The turtles are then asked to carry out the “flock” procedure, which involves a number of actions and procedures which have been coded and are called during the “go” command.

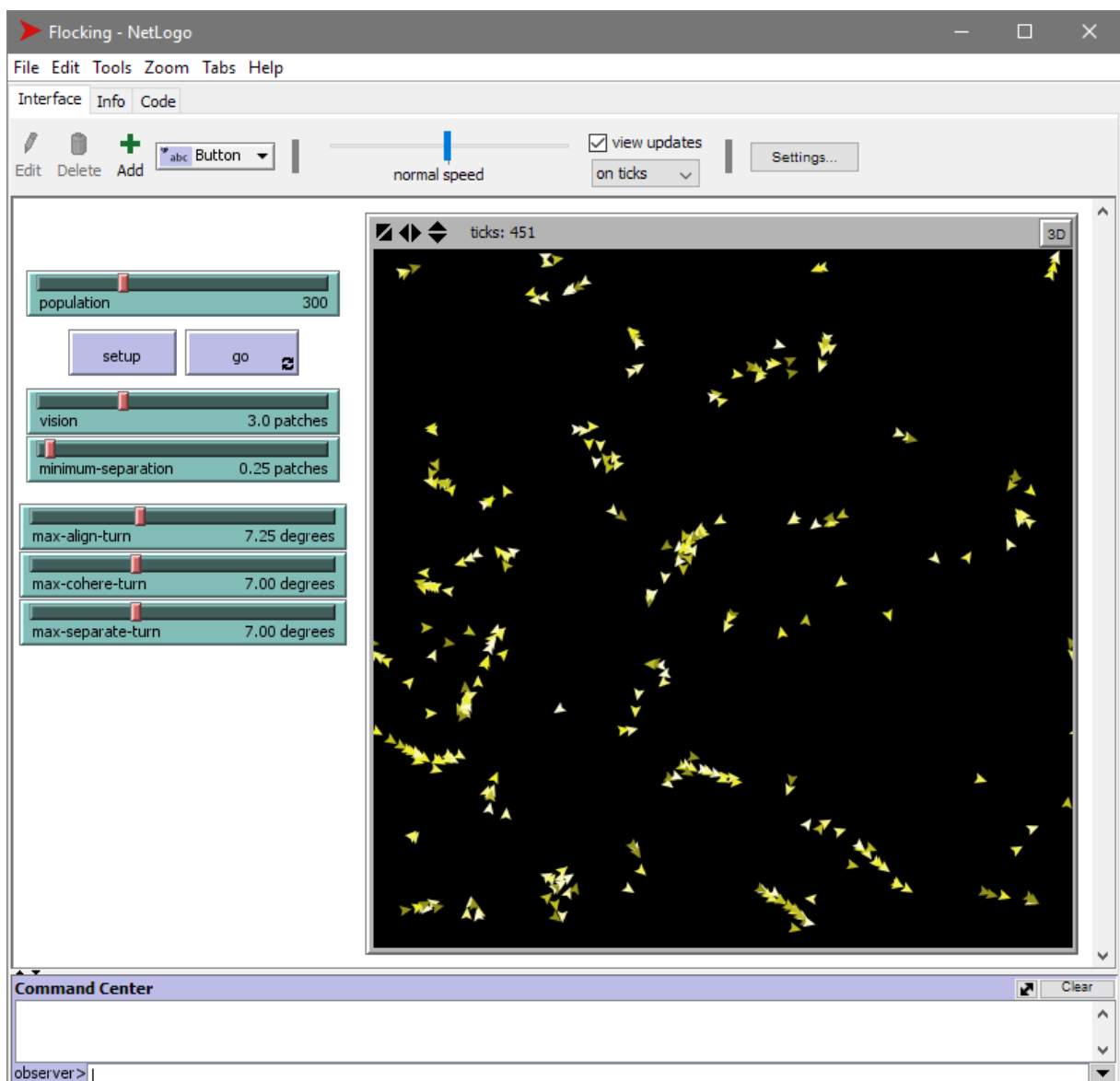


Figure 6 – NetLogo: Interface View

## 2.7 SUMMARY

The work in this chapter has outlined the current theories which surround the subject of situation awareness in teams and systems and provided a critique of the current techniques and methods which measure situation awareness.

Some theories suggest that SA is a cognitive process which must be held in the head of the human agents in the system (Endsley, 1995b; Nofi, 2000). In contrast, Distributed Situation Awareness recognise that it is the collective knowledge of each agent, human and non-human, within the system which builds the situation awareness. Situation awareness from this perspective is developed via the interactions between agents in the system and is described as an emergent property of the whole system. Therefore, one could argue that situation awareness can be defined by the ‘external’ presentation of information, potentially from the content of messages or displayed information in the system and that system SA is an accumulation of relevant information for a particular function, process or task. Various theories of SA agree that SA is in fact task specific (Endsley, 1995, Bedny & Meister, 1999) and involves “...activated knowledge for a specific task, at a specific time within a system” (Stanton et al., 2006). In order to take this perspective, one needs methods which enable the collection and analysis of activated knowledge.

The work in next chapter introduces the use of agent-based modelling using NetLogo. The process for designing and developing a model in terms of agent layout, roles and responsibilities in the operations room on HMS Dryad using the chosen package is then presented.

# **CHAPTER 3 SIMULATING THE HMS DRYAD OPERATIONS ROOM**

*Parts of this chapter have been published in:*

[1] “A comparison of shared and distributed situation awareness in teams through the use of agent-based modelling” in the *Journal of Theoretical Issues in Ergonomics Science*, 2016, 17(1), p 8-41

[2] “Towards Agent-Based Modelling for Situation Awareness: modeling a ships Operations Room” in the *Proceedings of Contemporary Ergonomics and Human Factors*, 2016, p 284-289.

*The sections: Why use concept maps to describe SA? on Page 14 of [1], Concept Maps on Page 287 of [2], Models Description on Page 286 of [2], and Discussion on Page 288 of [2] have been used to prepare this chapter.*

*The chapter is based on the work in [1] & [2].*

## **3.1 CASE STUDY: AN AGENT BASED MODEL OF THE HMS DRYAD OPERATIONS ROOM**

### **3.1.1 HMS Dryad**

A model was designed and developed using NetLogo with the aim to simulate the operations room on a Type 23 Frigate naval vessel. The layout of the agents in the model represented the layout of the operators during a training session at Her Majesty’s Ship (HMS) Dryad in the study by (Stanton et al., 2006). The agents were both human and non-human entities within the operations room, a radar screen in which airplanes move randomly was also presented

along with arrows which transferred information from one agent to another. The human agents in the model represented the following personnel in the operations room: Air Picture Supervisor (APS), Missile Director (MD), Principle Warfare Officer (PWO), Anti-Air Warfare Officer (AAWO), Captain and Electronic Warfare Officer (EWD). the rules in which they work within the operations room can be found in Table 2 and these were the rules in the model were based on these.

**Table 2 - Roles and responsibilities of agents in Model 1 and Model 2**

<b>Agent Title</b>	<b>Roles and Responsibilities</b>
Anti-Air Warfare Officer (AAWO)	Responsible for the plan of defence in response to an air attack Works with the PWO to assess and prioritise the targets
Principle Warfare Officer (PWO)	Responsible for the tactical handling of the ship and use of its weapons systems Works with the AAWO to assess and prioritise the targets
Air Picture Supervisor (APS)	Monitors the Radar picture compiler
Captain	Oversees the operations room and makes final decisions
Electronic Warfare Officer (EWD)	Monitors the electronic systems in the operations room and on the ship
Missile Director (MD)	Monitors the weapons systems on the ship

### **3.1.1.1 Model Description**

The task modelled is an airstrike determination task, where the system of human and non-human agents work together to decide on a particular course of action; either eliminate a target or declare the target as safe/a non-threat. This task is similar to the SCUDHunt game that Dekker (2002) uses in his study on C4ISR Architectures and Military Organisational Structures. SCUDHunt used a 4x4 grid with four randomly-located missile launch sites, where four squadrons were each allocated to one of the 16 squares with the aim of detecting the launch site. The squadrons used two sensors, one provided intelligence about a column of the grid and the other provided intelligence about the whole grid. Before a squadron is allocated, they used this intelligence to plan where they to be placed; this planning added a

time delay to the action of squadron allocation. During this time, there was a chance, determined by probability of 0.01 to 0.5, that the missile launch locations moved to a new location, resulting in an unsuccessful airstrike. The higher the probability, the more critical for the planning stage to be quick to ensure a successful strike. The sensors used had a quality metric, which may result in “false alarms” where a target was reported although one is not present.

The HMS Dryad model in this chapter is similar to the ~SCUDHunt game in a number of ways. First, the system of human and non-human agents share and use intelligence from a sensors and computers (i.e. the Radar, Jam Status, Stock and Threat) in order to decide on a particular outcome; either eliminate a target or declare the target as safe/a non-threat.

However, the sensors in this model do not have a quality metric and therefore are always accurate at the time of sharing, e.g. if the Radar shares a red aircraft with the APS, the aircraft is indeed red. Secondly, the agents in the model must plan, creating time delay, before a decision is made. Intelligence must be passed through the system to get to the PWO which in itself takes time, but also each act of sharing takes an amount of time to complete. Thirdly, during this planning stage the airplanes are moving on the radar at a set speed, when the speed is low the time to plan is not critical however the faster the airplanes, the more crucial it is that a decision is made quickly. If the decision is delayed for too long, then the result may be a “false alarm” or even to the detriment of agents as the aircraft has reached the ship. In this case the airplanes are the equivalent of the missile launch sites and therefore the speed of the airplanes is this models version of battlefield tempo. Each of these parameters relate to the settings that the model deploys, and it is possible for future versions of the model to be run with, for example, different levels of sensor reliability or different settings for decision delay.

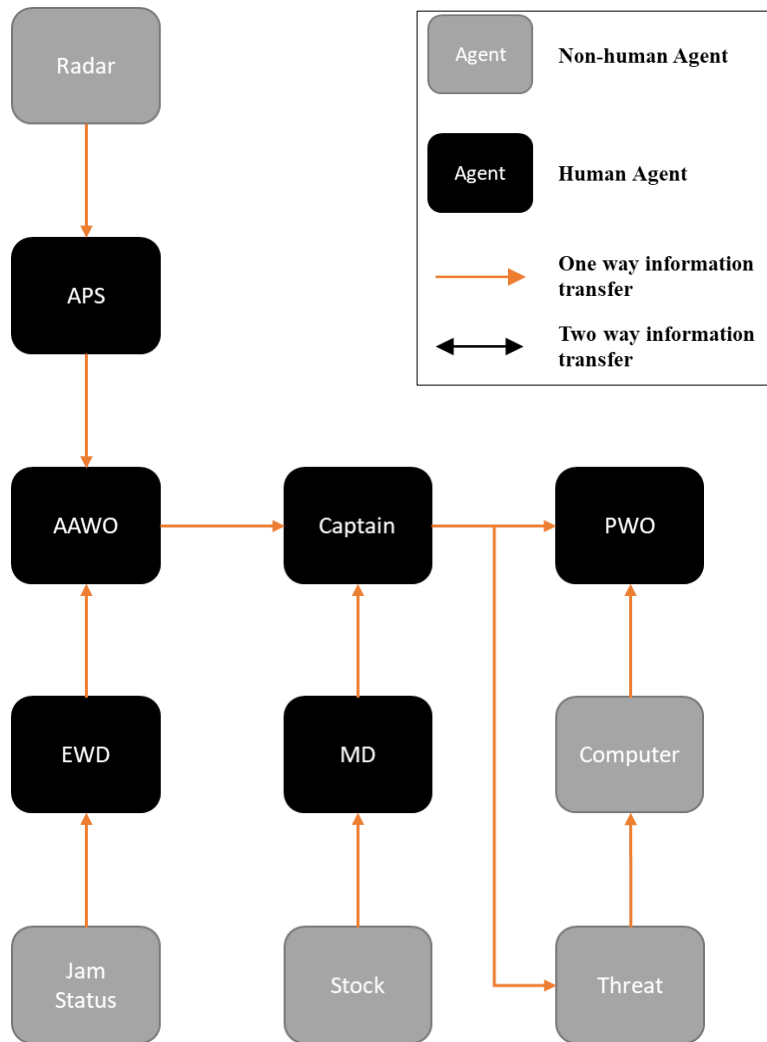
As the aim of the model here is to explore communication activity, it was not felt necessary to manipulate these parameters.

The model has two settings, one where knowledge is distributed throughout the model within the agents and the other where knowledge is shared with all human agents within the system. The agent communication networks of the model are analogous to the Distributed without Sharing and Distributed with Sharing network structures outlined by Dekker (2002). The Distributed without Sharing networks focus on nodes working towards their own goals and communicating when those goals are complete, this could be described as a task-work directed approach to completing the macro level system goal. The Distributed with Sharing network has the same structure Distributed without Sharing network. However, more connections are made between the nodes within the Distributed with Sharing network, with its emphasis on sharing information. The proposed benefit of a Distributed with Sharing network is that a pool of intelligence is created with an increase in the accuracy of that intelligence (Houghton et al., 2006), however there is the caveat that more sharing leads to more delays in intelligence reaching the right node in time to complete the system goal (Dekker, 2002). As part of each node's individual task is to share information, this approach can be described as a teamwork directed approach to completing the macro level system goal.

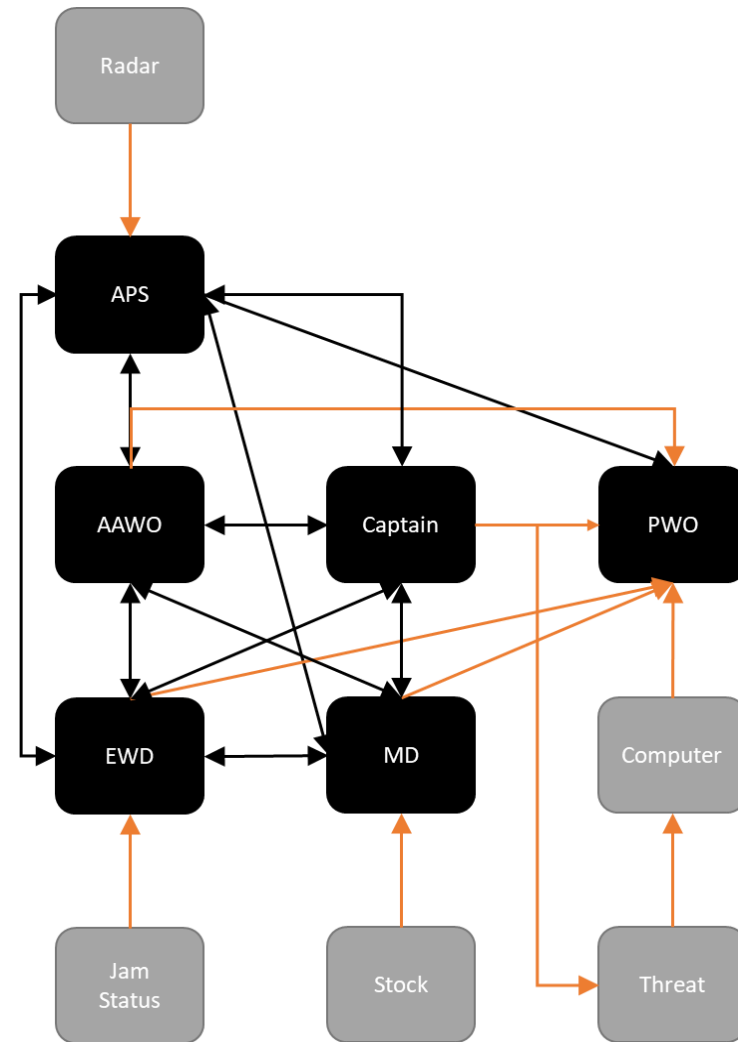
As shared SA requires nodes to share information about of each individuals task knowledge and environment (and therefore focussing on teamwork), it can be argued that the Distributed with Sharing network can be used as a framework for exploring shared SA within an agent based model. On the other hand, as distributed SA does not require agents to share or even know about of each individuals task knowledge and environment (and therefore focussing on task work), the Distributed without Sharing network can be used as a framework to explore how distributed SA affects the outcome of system goals. System performance in this manner

is achieved by reducing distractions caused by over-interacting / sharing of knowledge and limiting cognitive load to only that in which is necessary for the agents to complete their own individual task. It is also argued that due to effective training and experience, it is not necessary to have a high level of information sharing as agents are already aware what is required for the system to achieve its goal.

Figure 7 and Figure 8 show a Distributed without Sharing network and a Distributed with Sharing network. The rules of the agents described above ensure that these networks are achieved during the model simulations. There is a deviation from the shared SA theory in this approach, which can be seen in Figure 7, where non-human agents are considered within the system. The shared SA theory is based on Endsley's (1995b) individual SA theory, in which SA can only be held within the individuals mind and therefore not within non-human agents. The interpretation of shared SA in the context of this chapter allows for non-human agents to be a part of the team, making up a system of human and not human agents. Therefore, the approach here is to explore the notion that sharing information within a system (team work) benefits system performance, and whether a larger pool of knowledge is a help or a hindrance.



**Figure 7 - Agent interactions and information flow directions in the distributed without sharing version of the model**



**Figure 8 - Agent interactions and information flow directions in the distributed with sharing version of the model**

### ***3.1.1.2 Model of HMS Dryad Operations Room***

As previously mentioned, the agent based model is based on the agent networks within the As previously mentioned, the agent based model is based on the agent networks within the operations room on HMS Dryad. In the Distributed without Sharing version of the model when information is received via an arrow, the agent will store that information, generate a new arrow and send that information on to one other agent. Figure 9 shows a snapshot of the model in action during using this version of the model. The overall goal of the system is to make correct decisions about potential air threats, ultimately it is the PWO who makes the decision about what to do with the airplane being tracked. Once the PWO has relieved all the information needed to make that decision it will do so. In the Distributed with Sharing version of the model, when information is received via an arrow, the agent will store that information, generate a new arrow and send that information on to all other agents. The PWO will decide what action to take once it has relieved all the information needed to make that decision and when all of the other agents in the team have stored the ID of the airplane being tracked. This is to simulate the teamwork aspect of the network, that all agents must “agree” on which airplane must be acted upon. Figure 10 shows a snapshot of the Distributed with Sharing version of the model in action during the simulation. For both versions of the model, to simulate the act of an individual completing a task, the act of storing information takes time and has priority over other tasks. This could result in information being ignored or missed while the task of storing information is complete.

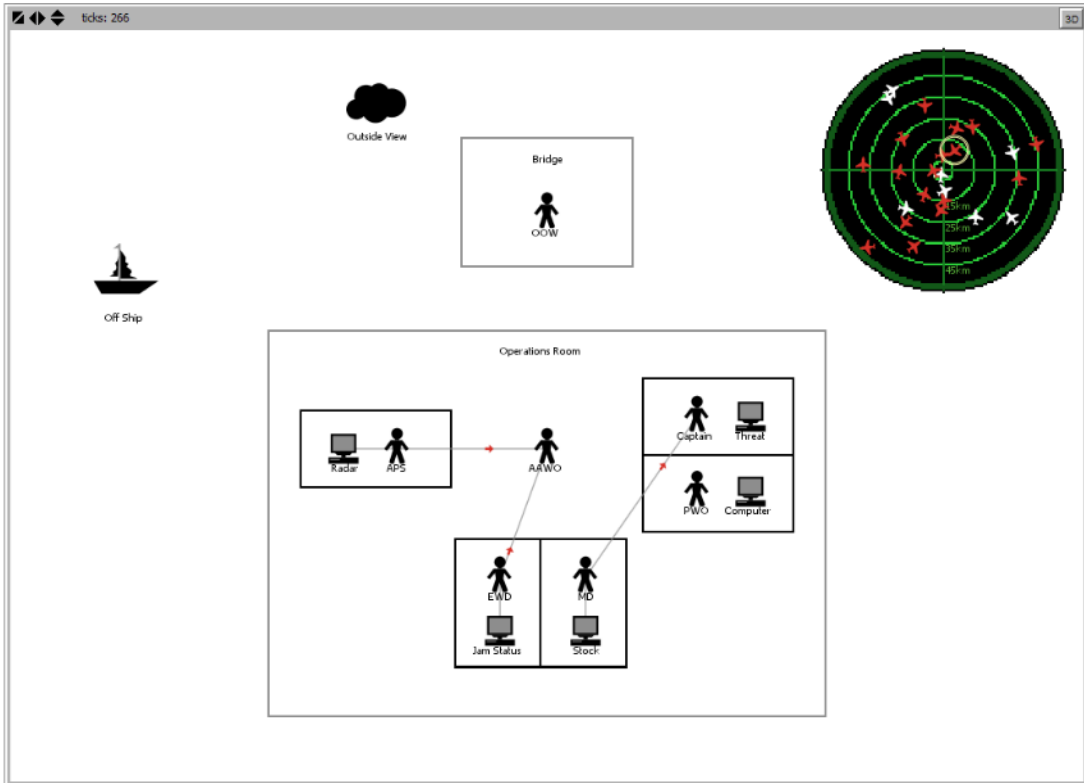


Figure 9 - Screenshot of the distributed without sharing version of the model

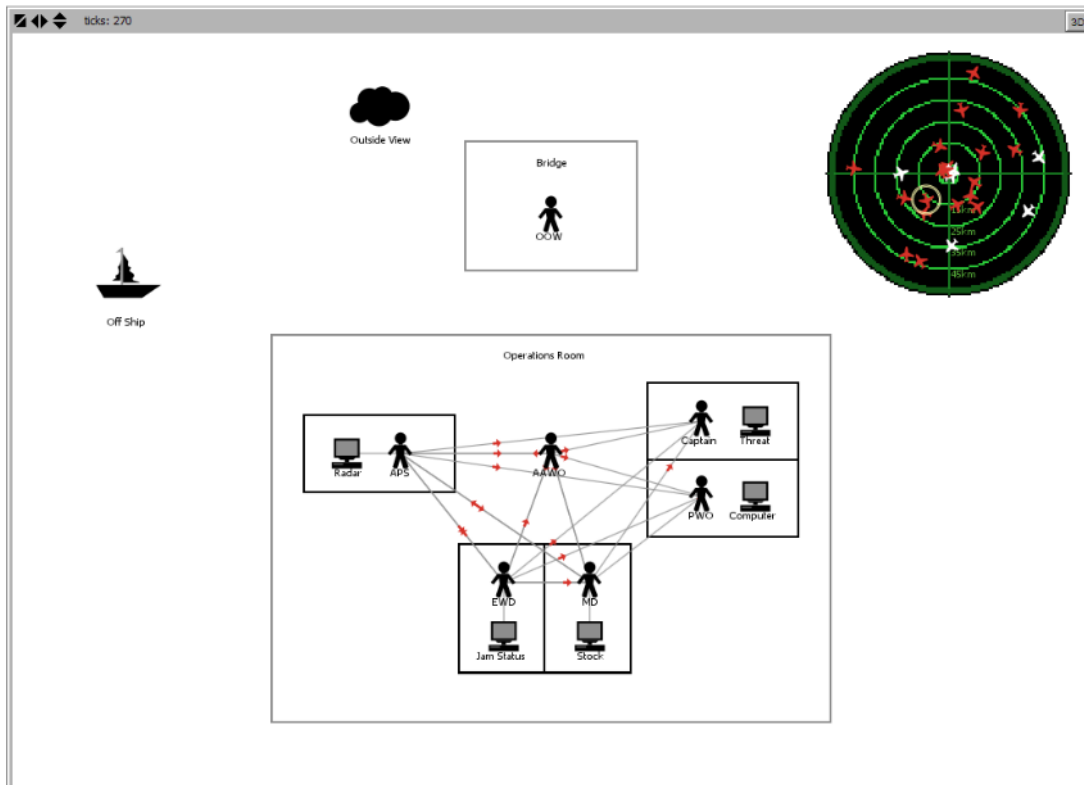


Figure 10 - Screenshot of the distributed with sharing version of the model

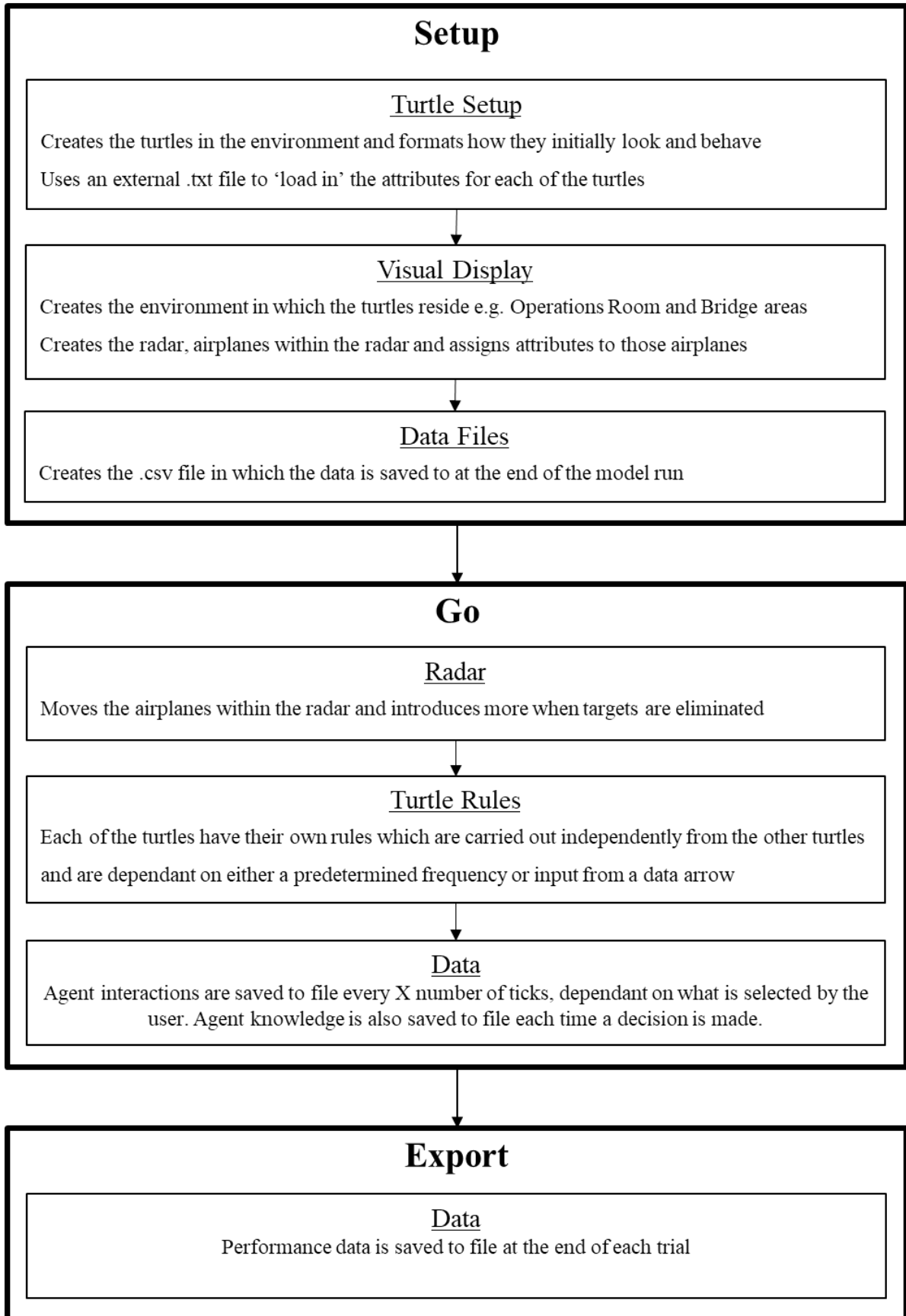
### 3.1.2 Model Design

#### 3.1.2.1 The Model

Figure 11 shows a simplified flowchart and description of the model design; which involves the model setup, the main 'go' function and the export of the recorded data. The setup function is called once by the user via a button on the main interface. The go function is started via a button on the main interface and is called every tick resulting in 40,000 cycles of the go code. This makes up one trial, the model allows for any number of trials to be carried out however, for this study 100 trials were chosen. The model environment and turtles are reset at the beginning of each trial. The parameters used in the study are as follows:

- Task time – 200 ticks
- Model duration – 40,000 ticks
- Airplane speed – 0.1 patches
- Information introduction frequency – 200 ticks plus a random number of ticks between 0 and 100
- Number of trials -100

Where the task time is the time it takes for an agent to carry out the 'store information' task, the model duration is the total number of cycles of the 'go' code, the airplane speed is the distance travelled over the radar by each airplane per tick and the information introduction frequency determines when the Radar, Stock and Jam Status agents share information, each calculated separately. The models were run with the number of trials selected eight times, with the airplane speed increasing by 0.2 each time, simulating a workload increase for the agents. The statistical analysis of performance results shown in this chapter are from the original 0.1 airplane speed data, where the performance results of each of the eight airplane speeds are analysed qualitatively.



**Figure 11 – Flowchart of the model code**

### 3.1.2.2 *The Agents*

Each of the agents has attributes which are used throughout the model. Knowledge attributes are what is stored during the data transfer action, from a data arrow to an agent.

#### **Knowledge Attributes**

- selected-airplane-colour – the colour of the selected airplane in the radar
- selected-airplane-proximity – the proximity to the ship at the time of data transfer.
- selected-airplane-id – the id of the airplane
- selected-airplane-threat – the threat level of the airplane
- operator-stock-level – the missile stock level
- operator-signal-strength – the electronic signal strength for potential incoming/outgoing messages

Functional attributes are used during the actions, and determine when tasks are performed, or when counters record processes within the model.

#### **Functional Attributes**

- knowledge – the amount of knowledge the agent holds, to a maximum of 6
- info-count – the agents' internal stopwatch for a task being carried out, i.e. receiving information.
- task-go – is set depending on the info-count of the agent. If the info-count is greater than the task time, it is set to 0 and if it is less than the task time, it is set to 1; with 0 meaning run next task and 1 meaning wait until the task time is over.
- ignored-info – the amount of data arrows ignored while the agent is busy dealing with a data arrow.
- info-used - the amount data arrows the agent accepts
- new-info – the amount of new data arrows created by the agent. The Radar, Stock and Jam Status arrows create new sources of data in the model

Each of the agents has role-specific rules which they follow during each of the trials. The following outlines what those rules are for each agent.

#### 3.1.2.2.1 Agent Actions

In this model the agents communicate directly from one another, that is they request and share information from each other. The actions that take place can be described as active and reactive. These active and reactive actions within the model can be described as analogous to the push/pull actions described by Demir et al. (2018b). The pushing and pulling of information described by Demir et al. (2018b) explains how information is requested and provided by agents via particular individual behaviours. In this model the agents do not replicate these specific behaviours, however the pushing and pulling of information is still carried out, that is between both human and non-human agents within the system, e.g. the radar agent. Depending on the agent, they will either push and/or pull information to agents with in the system.

An explanation of the rules of each of the agents are to follow, but first ow these rules and the actions are activated and carried out will be discussed. Referring back to Figures 8 and 9, the arrows show either a one-way action (push) or two-way action (push pull) of information between the agents. Figure 12 and Figure 13 show examples of how these actions propagate around the distributed and shared tasks models, respectively.

Figure 12 shows the distributed tasks model. Here the agents push information onto the other agents within the system. Each of these actions have two parts; sending the information and receiving the information. This is demonstrated with the first two steps in Figure 12. Once this is complete, the receiver agent is triggered to push information to other agents in the model. We can see this propagation of actions via the numbers in Figure 12. The different coloured arrows show whether this information is being passed between human agents, non-human agents or a combination of the two. In the figure, we can see that the path of information either starts with the Radar and Jam Status agent or the Stock agent. The first

path is represented by numbers, 1 to 12 and the second is represented by letters, A to J.

Information flows through the system from one agent to another following these paths until it reaches the PWO, at which point the PWO, if they have enough information about the airplane to do so, will decide about whether to remove the airplane or dismiss it. During this time information is continually passing along this path and the agents are updating their knowledge.

Figure 13 shows the other hand shows the shared tasks model. This model is much more complex and there are many more potential paths of information transfer compared to the previous model. Only two of these paths have been represented in the figure, as to provide more would make the figure unreadable. The first path, represented by numbers 1 to 12 and a thick red line, follows the same route as the one in the previous model. The second route, represented by letters A to M and a dashed red line, shows a more complex route of information transfer, where information is both received and sent from multiple, and sometimes the same, agents. In this second route, information starts with the Jam Status Agent and is transferred to the EDW agent which in turn shares information with the MD Agent. The MD agent sends information back to the EWD agent, who then sends information to the APS agent. The information is then transferred to the AAWO agent before reaching the PWO, at which point they will make their decision about the airplane as usual. As the information is passed through the system, agents knowledge is updated and modified along the route based on the information they currently hold and information that may be missing. The next section describes in more detail the rules for each of agents in the system which govern when and what information is to be sent.

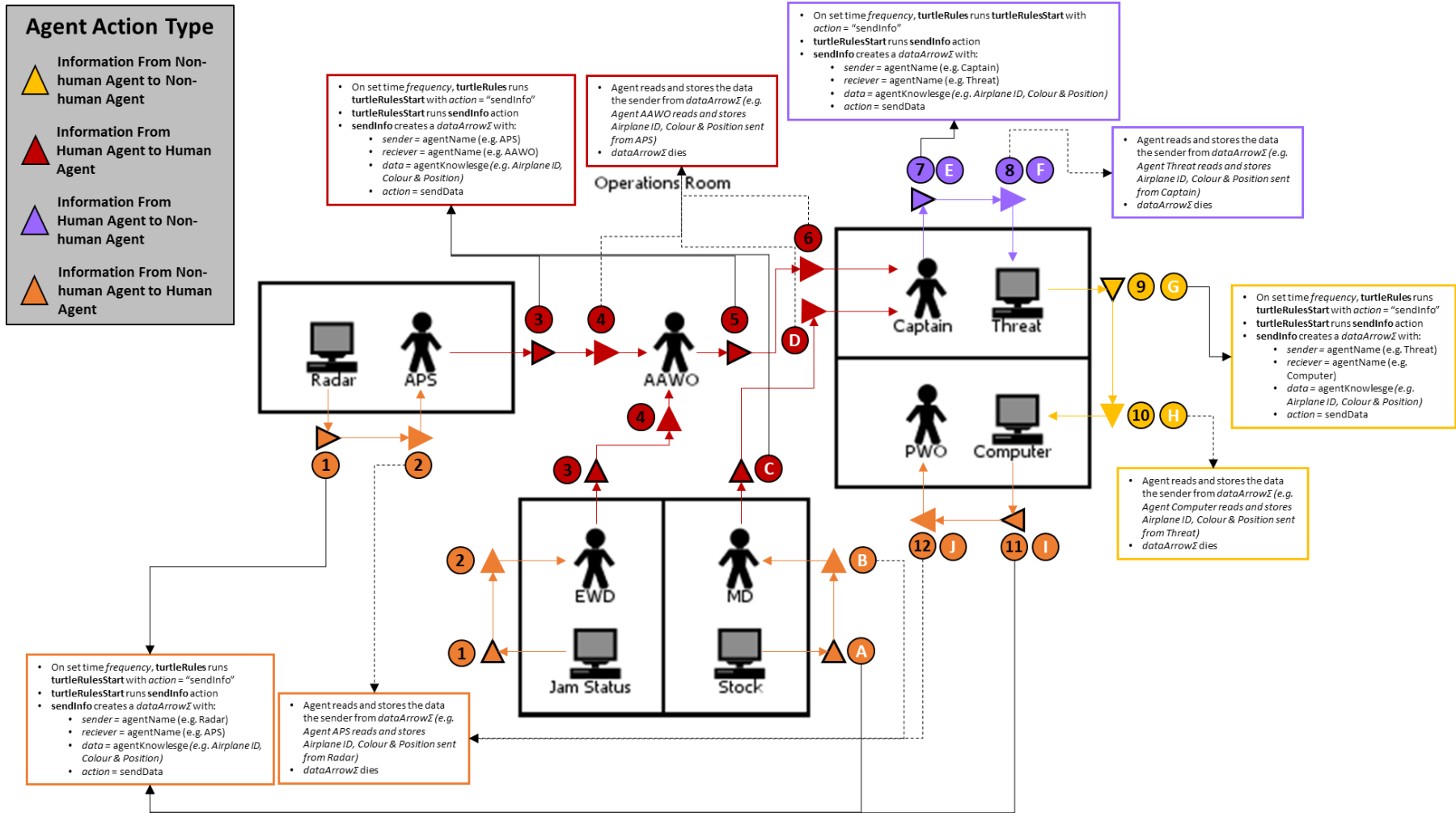


Figure 12 - Summary of agent rules, how they are activated and carried out in the distributed tasks model

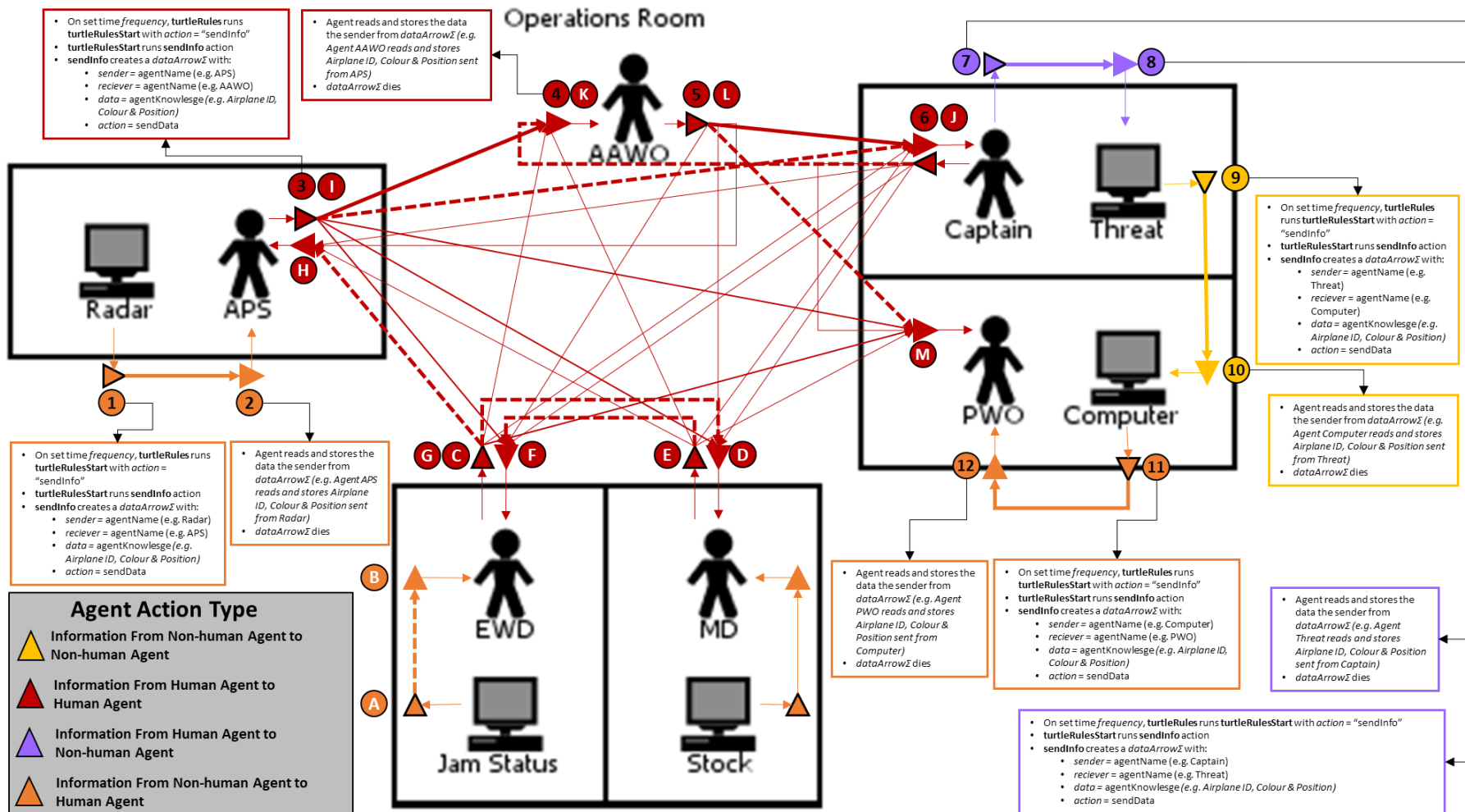


Figure 13 - Summary of agent rules, how they are activated and carried out in the shared tasks model

#### 3.1.2.2.2 Rules of Non-human agents

##### 3.1.2.2.2.1 Radar Agent

If no airplane has been selected, the Radar Agent selects one of the airplanes within the radar and saves the airplane ID, colour and proximity to 'memory' as knowledge. This happens at the start of the model and when a target has been eliminated or disregarded.

After a set amount of time based on the frequency variable, set by the user, the Radar Agent creates a link to the APS Agent. A data arrow is created containing the knowledge of the Radar Agent, and has its heading set towards the APS Agent.

##### 3.1.2.2.2.2 Stock Agent

After a set amount of time based on the frequency variable, set by the user, the Stock Agent saves the stock level to 'memory'. It then creates a link to the MD Agent as well as creating a data arrow containing the knowledge of the Stock Agent, and has its heading set towards the MD Agent.

##### 3.1.2.2.2.3 Jam Status Agent

After a set amount of time based on the frequency variable, set by the user, the Jam Status Agent saves the signal strength to 'memory'. It then creates a link to the EWD Agent as well as creating a data arrow containing the knowledge of the Jam Status Agent, and has its heading set towards the EWD Agent.

##### 3.1.2.2.2.4 Threat Status

For both the distributed without sharing and distributed with sharing versions of the model, when an arrow arrives at the Threat Status it creates 1 data arrow containing the knowledge of the Threat Status with its heading set towards the Computer, a link to the Computer is also

created. The Threat Status uses the “colour” and “proximity” knowledge items to determine the “threat” of the tracked airplane.

#### 3.1.2.2.2.5 *Computer*

For both the distributed without sharing and distributed with sharing versions of the model, when an arrow arrives at the Computer it creates 1 data arrow containing the knowledge of the Computer with its heading set towards the PWO, a link to the PWO is also created.

#### 3.1.2.2.3 *Rules of Human Agents*

##### 3.1.2.2.3.1 *APS Agent*

For the distributed without sharing version of the model, when an arrow arrives at the APS it creates 1 data arrow containing the knowledge of the APS with its heading set towards the AAWO, a link to the AAWO is also created.

For the distributed with sharing version, the APS it creates 5 data arrows containing the knowledge of the APS with each having its heading set towards either the AAWO, Captain, EWD, MD or PWO. Links are also created between the APS and the AAWO, Captain, EWD, MD or PWO.

##### 3.1.2.2.3.2 *EWD Agent*

For the distributed without sharing version of the model, when an arrow arrives at the EWD it creates 1 data arrow containing the knowledge of the EWD with its heading set towards the AAWO, a link to the AAWO is also created.

For the distributed with sharing version, the EWD it creates 5 data arrows containing the knowledge of the EWD with each having its heading set towards either the APS, AAWO,

Captain, MD or PWO. Links are also created between the EWD and the APS, AAWO, Captain, MD or PWO.

#### *3.1.2.2.3.3 MD Agent*

For the distributed without sharing version of the model, when an arrow arrives at the MD it creates 1 data arrow containing the knowledge of the MD with its heading set towards the Captain, a link to the Captain is also created.

For the distributed with sharing version, the MD it creates 5 data arrows containing the knowledge of the MD with each having its heading set towards either the APS, AAWO, Captain, EWD or PWO. Links are also created between the MD and the APS, AAWO, Captain, EWD or PWO.

#### *3.1.2.2.3.4 AAWO Agent*

For the distributed without sharing version of the model, when an arrow arrives at the AAWO it creates 1 data arrow containing the knowledge of the AAWO with its heading set towards the Captain, a link to the Captain is also created.

For the distributed with sharing version, the AAWO it creates 5 data arrows containing the knowledge of the AAWO with each having its heading set towards either the APS, MD, Captain, EWD or PWO. Links are also created between the MD and the APS, MD, Captain, EWD or PWO.

#### *3.1.2.2.3.5 Captain Agent*

For the distributed without sharing version of the model, when an arrow arrives at the Captain it creates 1 data arrow containing the knowledge of the Captain with its heading set towards the PWO, a link to the PWO is also created.

For the distributed with sharing version, the Captain it creates 6 data arrows containing the knowledge of the Captain with each having its heading set towards either the APS, MD, AAWO, EWD, PWO and Threat Status. Links are also created between the MD and the APS, MD, AAWO, EWD, PWO and Threat Status.

#### *3.1.2.2.3.6 PWO Agent*

The PWO is the decision maker in both models, the PWO does not send information to any other agent and action depends on the information gathered from all other agents in the system.

First the PWO checks the airplane colour and proximity to determine the threat level of the airplane under examination and assigns this to the selected-airplane-threat attribute. The PWO then carries out the kill-target action: in the distributed without sharing version of the model the action will be executed when the PWO has an airplane-ID attribute stored, in the distributed with sharing version of the model all human agents (APS, AAWO, MD, EWD, Captain) must have the same airplane-ID as the PWO stored. The PWO then checks its own selected-airplane-threat and selected-airplane-proximity attributes. If the threat is high the selected airplane is eliminated and removed from the radar. If the threat is low, the selected airplane is dismissed and another airplane is selected. All of the PWO knowledge attributes are set to 'unknown' as it now has to wait for new information to be received from other agents in the system. The decisions-made counter is increased by 1 and if the airplane was eliminated, the operator-stock-level attribute of the Stock Level agent is reduced by 1. The model then records the decision made by the PWO was correct based on the colour and proximity values of the actual airplane in the radar. There are four potential outcomes of the PWO decision:

- Potential threats hit = correct decision
- None threats passed = correct decision
- None threats hit = incorrect decision
- Potential threats missed = incorrect decision

By adding the potential threats hit and none threats passed the total number of correct decisions is calculated, similarly adding the none threats hit and potential threats missed provides a total of incorrect decisions. Additionally, if the airplane being monitored by the system reaches the centre of the radar, i.e. has a proximity of <10km to the boat, before a decision has been made an additional potential threat missed is added to the total incorrect decisions.

### ***3.1.2.3 Agent Interactions***

The interactions between agents depend on the version of the model being used. Figure 7 show the predetermined or allowed interactions between agents in the distributed without sharing version of the model, for example the Radar can interact with the APS, but the APS does not interact with the Radar, that is the information flow is from the Radar to the APS, but no information is passed from the APS to the Radar. In this sense, an interaction is the sharing of information from one agent to another. In the same model, the APS and EWD shares information with the AAWO, but the AAWO does not share information with either of the APS or EWD. In this version of the model, information flow is in one direction throughout the system. This is one of two main differences between the distributed without sharing and distributed with sharing version of the model. As well as there being a two-directional flow of information within the distributed with sharing version of the model between the human agents, the agents can also share information with more agents compared to the distributed without sharing version (Figure 8). For example, in the distributed with sharing version of the

model the AAWO can share knowledge with and receive knowledge from all other human agents.

#### ***3.1.2.4 Summary of data recorded by the model***

A number of variables are recorded during each trial, some of which have already been mentioned above. Below is a summary of all variables recorded and output at the end of each trial in a .csv file. The data can be grouped into three categories: performance data used for quantitative statistical analysis, knowledge data for concept map plotting and agent interactions for social network analysis.

##### 3.1.2.4.1 Performance Data

- Number of Correct Decisions Made
- Number of Incorrect Decisions Made
- Total Number of Decisions Made
- Total Number of Ignored Information
- Total Used/Stored Information
- Number of Times Info is Shared

An example of the output .csv data file can be seen in Figure 14.

	A	B	C	D	E	F	G	H	I	J
1		Sharing airplane ID	Sharing all information via links	Number of Correct Decisions Made	Number of Incorrect Decisions Made	Total Number of Decisions Made	Total Number of Ignored Information	Total Used/Stored Information	Total Info Shared	Total New Information Introduced to System
2	Trial 1	TRUE	TRUE	5	27	32	3904	5069	4641	499
3	Trial 2	TRUE	TRUE	8	6	14	3899	5058	4634	499
4	Trial 3	TRUE	TRUE	6	28	34	3890	5051	4623	499
5	Trial 4	TRUE	TRUE	5	2	7	3889	5052	4625	499
6	Trial 5	TRUE	TRUE	6	27	33	3891	5051	4623	499
7	Trial 6	TRUE	TRUE	7	22	29	3893	5053	4624	499
8	Trial 7	TRUE	TRUE	6	1	7	3891	5051	4623	499
9	Trial 8	TRUE	TRUE	5	4	9	3889	5052	4625	499
10	Trial 9	TRUE	TRUE	6	23	29	3891	5051	4623	499
11	Trial 10	TRUE	TRUE	5	10	15	3893	5053	4624	499
12	Trial 11	TRUE	TRUE	6	22	28	3891	5051	4623	499
13	Trial 12	TRUE	TRUE	6	21	27	3889	5052	4625	499
14	Trial 13	TRUE	TRUE	6	7	13	3891	5051	4623	499
15	Trial 14	TRUE	TRUE	7	12	19	3893	5053	4624	499
16	Trial 15	TRUE	TRUE	6	28	34	3891	5051	4623	499
17	Trial 16	TRUE	TRUE	8	6	14	3889	5052	4625	499
18	Trial 17	TRUE	TRUE	7	8	15	3891	5051	4623	499
19	Trial 18	TRUE	TRUE	5	33	38	3893	5053	4624	499
20	Trial 19	TRUE	TRUE	6	1	7	3891	5051	4623	499
21	Trial 20	TRUE	TRUE	6	8	14	3889	5052	4625	499
22	Trial 21	TRUE	TRUE	6	23	29	3891	5051	4623	499
23	Trial 22	TRUE	TRUE	5	9	14	3893	5053	4624	499
24	Trial 23	TRUE	TRUE	6	24	30	3891	5051	4623	499
25	Trial 24	TRUE	TRUE	6	3	9	3889	5052	4625	499
26	Trial 25	TRUE	TRUE	5	2	7	3891	5051	4623	499
27	Trial 26	TRUE	TRUE	6	4	10	3893	5053	4624	499
28	Trial 27	TRUE	TRUE	4	6	10	3891	5051	4623	499
29	Trial 28	TRUE	TRUE	6	30	36	3889	5052	4625	499
30	Trial 29	TRUE	TRUE	6	9	15	3891	5051	4623	499
31	Trial 30	TRUE	TRUE	6	0	6	3893	5053	4624	499
32	Trial 31	TRUE	TRUE	6	1	7	3891	5051	4623	499
33	Trial 32	TRUE	TRUE	6	2	8	3889	5052	4625	499

Figure 14 – Performance data output, example .csv file

### 3.1.2.4.2 Agent Interactions

- Interval matrices of agent interactions
- Final matrix of agent interactions
- An example of the output .csv data file can be seen in Figure 15.

	A	B	C	D	E	F	G	H	I	J
1	Radar	0	0	0	0	0	0	0	0	0
2	APS	0	0	0	1	0	0	0	0	0
3	EWD	0	0	0	1	0	0	0	0	0
4	AAWO	0	0	0	0	0	0	0	0	0
5	MD	0	0	0	0	0	1	0	0	0
6	captain	0	0	0	0	0	0	0	0	0
7	Stock	0	0	0	0	1	0	0	0	0
8	PWO	0	0	0	0	0	0	0	0	0
9	Jam Statu:	0	0	0	0	0	0	0	0	0
10	Radar	0	0	0	0	0	0	0	0	0
11	APS	0	0	0	1	0	0	0	0	0
12	EWD	0	0	0	0	0	0	0	0	0
13	AAWO	0	0	0	0	0	0	0	0	0
14	MD	0	0	0	0	0	1	0	0	0
15	captain	0	0	0	0	0	0	0	0	0
16	Stock	0	0	0	0	1	0	0	0	0
17	PWO	0	0	0	0	0	0	0	0	0
18	Jam Statu:	0	0	0	0	0	0	0	0	0
19	Radar	0	1	0	0	0	0	0	0	0
20	APS	0	0	0	0	0	0	0	0	0
21	EWD	0	0	0	0	0	0	0	0	0
22	AAWO	0	0	0	0	0	0	0	0	0
23	MD	0	0	0	0	0	1	0	0	0
24	captain	0	0	0	0	0	0	0	0	0
25	Stock	0	0	0	0	1	0	0	0	0
26	PWO	0	0	0	0	0	0	0	0	0
27	Jam Statu:	0	0	1	0	0	0	0	0	0
28	Radar	0	0	0	0	0	0	0	0	0
29	APS	0	0	0	0	0	0	0	0	0
30	EWD	0	0	0	1	0	0	0	0	0
31	AAWO	0	0	0	0	0	0	0	0	0
32	MD	0	0	0	0	0	1	0	0	0

Figure 15 – Agent Interaction data output, example .csv file

### 3.1.2.4.3 Agent Knowledge Data

- selected-airplane-colour
- selected-airplane-proximity
- selected-airplane-id
- selected-airplane-threat
- operator-stock-level
- operator-signal-strength

This is the knowledge attribute data previously outlined and an example of the output .csv data file can be seen in Figure 16.

	A	B	C	D	E	F	G	H
1	Decision	Operator	Targeted airplane colour	Targeted airplane proximity to boat	Targeted airplane id	Missile stock level	Current electronic signal strength	Current threat status
2	0	radar	15		21 (airplane 24)	unknown	unknown	unknown
3	0	APS	15		25 (airplane 24)	100	high	unknown
4	0	stock	unknown	unknown	unknown	100	unknown	unknown
5	0	MD	15		25 (airplane 24)	100	high	unknown
6	0	jam-status	unknown	unknown	unknown	unknown	high	unknown
7	0	EWD	15		25 (airplane 24)	100	high	unknown
8	0	captain	15		25 (airplane 24)	100	high	unknown
9	0	AAWO	15		25 (airplane 24)	100	high	unknown
10	0	PWO	15		25 (airplane 24)	100	high	low
11	0	computer	unknown	unknown	unknown	100	unknown	unknown
12	0	threat-status	unknown	unknown	unknown	100	unknown	unknown
13	1	radar	15		9 nobody	unknown	unknown	unknown
14	1	APS	15		6 nobody	100	low	unknown
15	1	stock	unknown	unknown	unknown	100	unknown	unknown
16	1	MD	15		6 nobody	100	low	unknown
17	1	jam-status	unknown	unknown	unknown	unknown	low	unknown
18	1	EWD	15		6 nobody	100	low	unknown
19	1	captain	15		6 nobody	100	low	unknown
20	1	AAWO	15		6 nobody	100	low	unknown
21	1	PWO	15		6 nobody	100	low	high
22	1	computer	15		6 nobody	100	low	unknown
23	1	threat-status	15		6 nobody	100	low	unknown
24	2	radar	15		41 (airplane 21)	unknown	unknown	unknown
25	2	APS	15		41 (airplane 21)	100	high	unknown
26	2	stock	unknown	unknown	unknown	99	unknown	unknown
27	2	MD	15		34 (airplane 21)	99	high	unknown
28	2	jam-status	unknown	unknown	unknown	unknown	low	unknown
29	2	EWD	15		34 (airplane 21)	100	low	unknown
30	2	captain	15		34 (airplane 21)	100	high	unknown
31	2	AAWO	15		34 (airplane 21)	100	high	unknown
32	2	PWO	15		34 (airplane 21)	100	high	low
33	2	computer	15		6 nobody	100	high	unknown
34	2	threat-status	15		34 (airplane 21)	100	high	unknown

Figure 16 – Agent Knowledge Data output, example .csv file

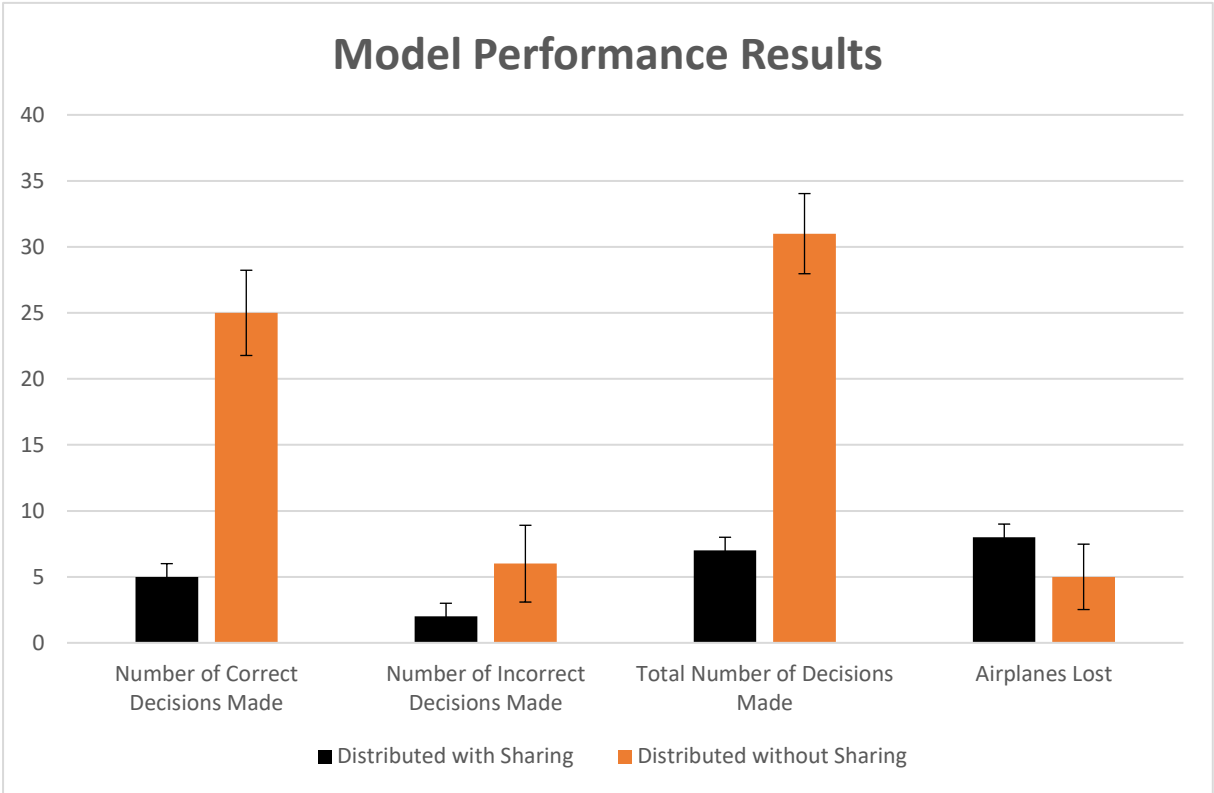
## 3.2 SIMULATION RESULTS

### 3.2.1 Analysis of Performance Data

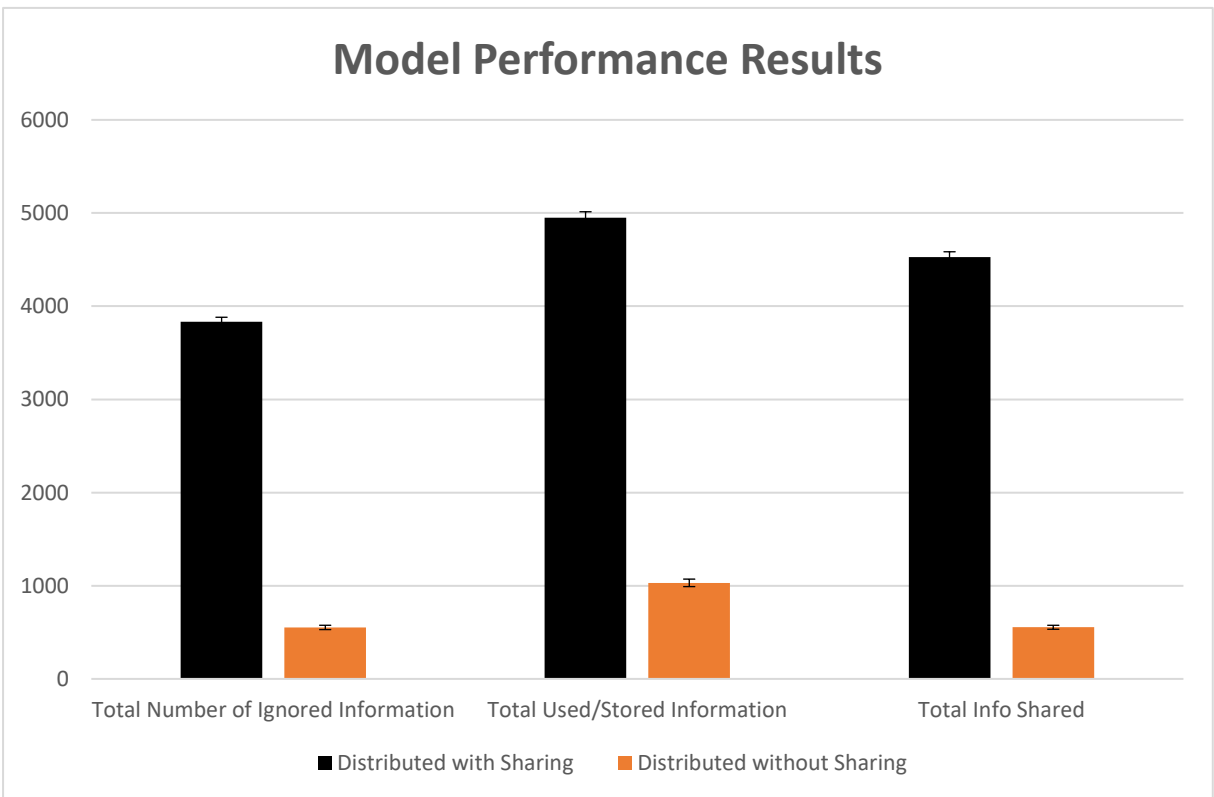
Figure 17 shows the results of variables 1-3 and Figure 18 shows the results of variables 4-6 (see Table 3 for a recap of the data variables recorded by the model). Referring to Figure 17, in the distributed with sharing version of the model there were fewer decisions made compared to the distributed without sharing version of the model (for correct and incorrect decisions, and total decisions). Figure 18 shows that more information was ignored, used/stored and shared in the distributed with sharing version of the model compared to the distributed without sharing version of the model.

**Table 3 - Summary of data variables from the model**

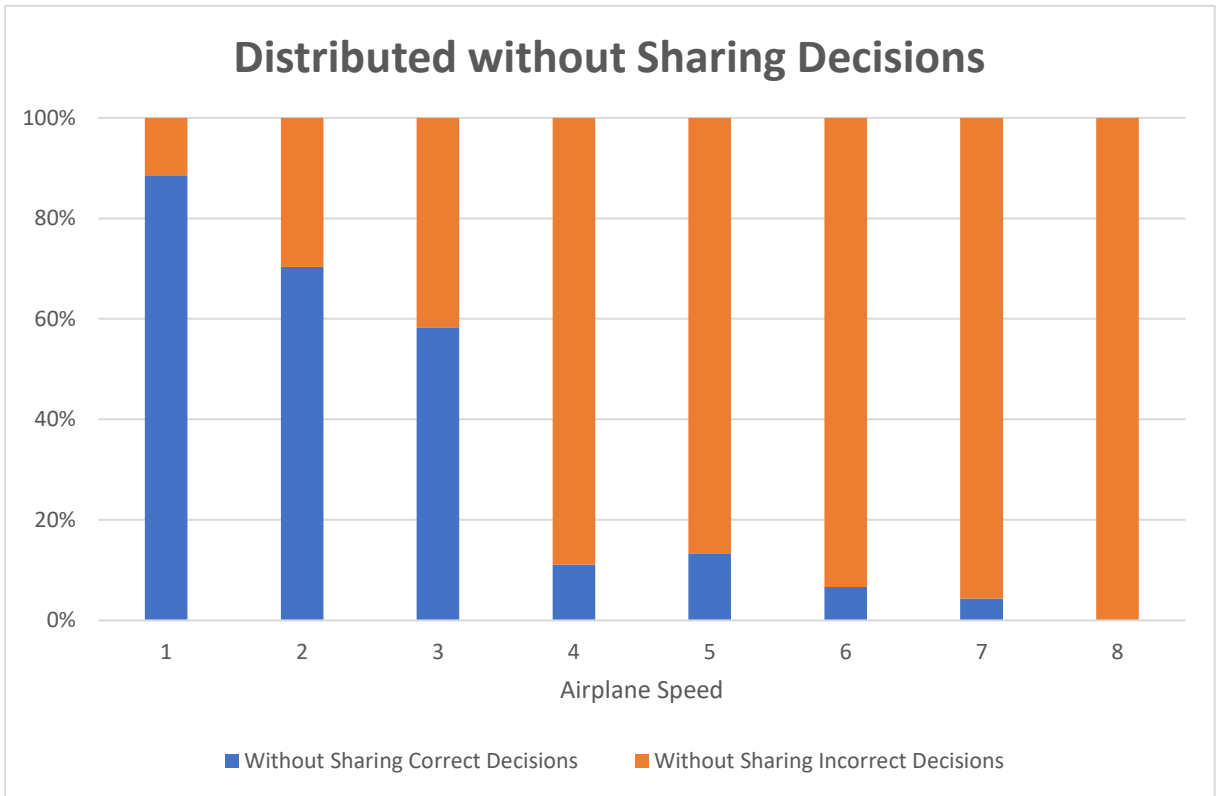
<b>Performance Data</b>	
Variable 1	Number of Correct Decisions Made
Variable 2	Number of Incorrect Decisions Made
Variable 3	Total Number of Decisions Made
Variable 4	Total Number of Ignored Information
Variable 5	Total Used/Stored Information
Variable 6	Number of Times Info is Shared
<b>Agent Interaction Data</b>	
Variable 7	Interval matrices of agent interactions
Variable 8	Final matrix of agent interactions
<b>Agent Knowledge Data</b>	
Variable 9	selected-airplane-colour
Variable 10	selected-airplane-proximity
Variable 11	selected-airplane-id
Variable 12	selected-airplane-threat
Variable 13	operator-stock-level
Variable 14	operator-signal-strength



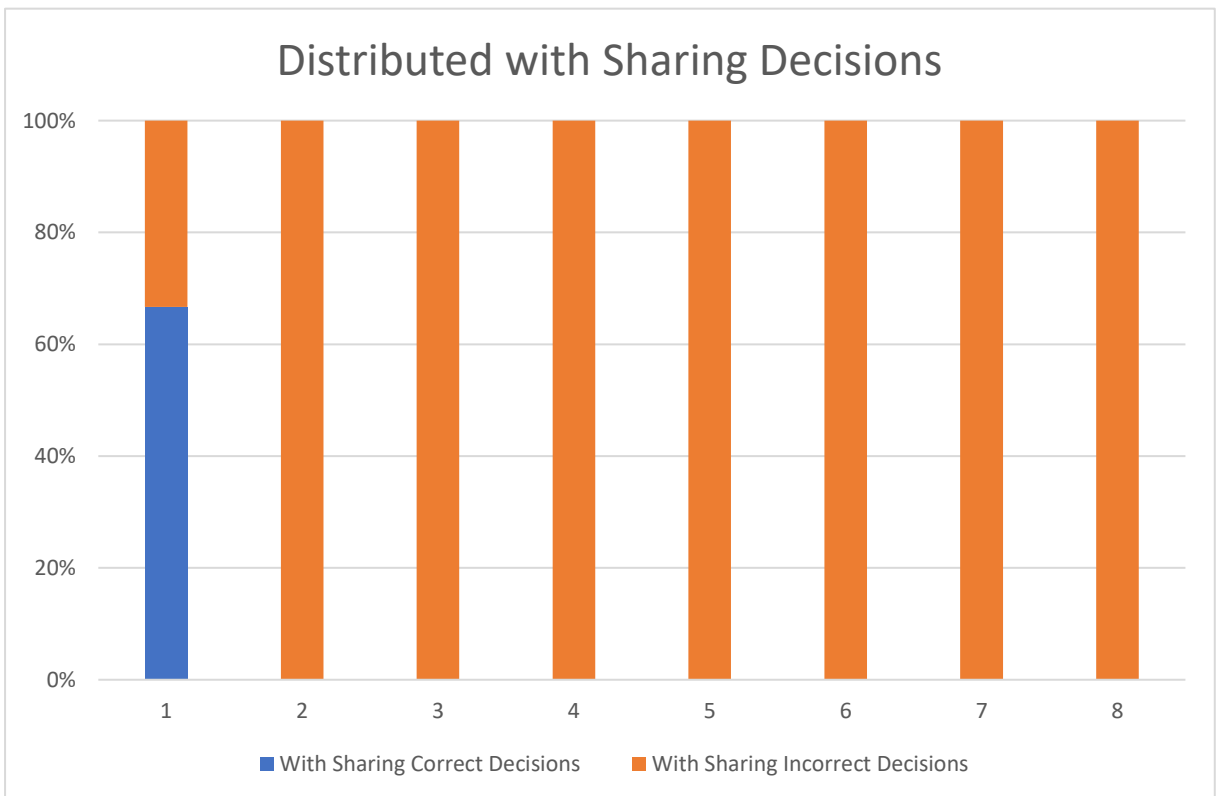
**Figure 17 – Performance results for both versions of the model**



**Figure 18 – Performance results for both versions of the model**



**Figure 19 – System workload results for the distributed without sharing version of the model**



**Figure 20 – System workload results for the distributed with sharing version of the model**

Figure 19 and Figure 20 show the performance for the two versions of the model for eight airplane speeds, with 1 being the slowest speed and 8 being the highest. Figure 19 shows the results for the distributed without sharing network and Figure 20 shows the results for the distributed with sharing network. At the slowest airplane speed, the performance of each version of the model is relatively high; above 60% correct decisions for the distributed with sharing network and above 80% correct decisions for the distributed with sharing network, however as airplane speed increases the amount of correct answers reduce for both networks. For the distributed without sharing network, the amount of correct decisions remains above 50% for the first three speeds and then drops off to under 20% for the remaining speeds with the final and fastest speed resulting in zero correct decisions. For the distributed with sharing network, only the slowest speed results in correct decisions, all other speeds result in zero correct decisions made.

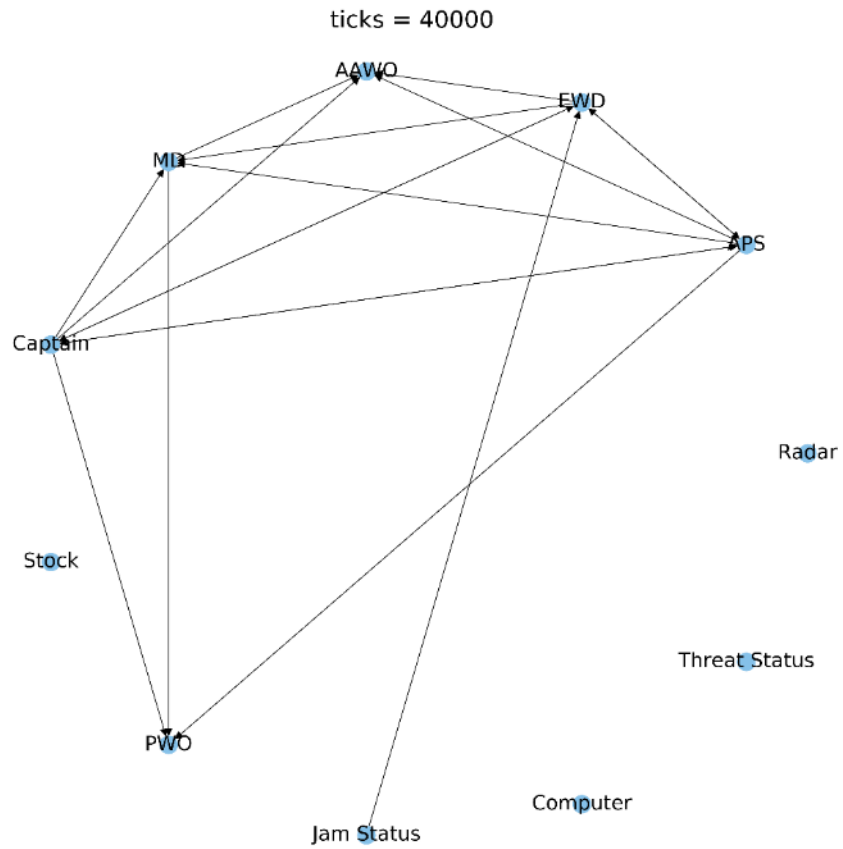
### **3.2.2 Social Network Analysis of Agent Interactions**

A Python script was written using the *networkx* and *matplotlib* libraries to calculate and present the interactions, degree centrality and density values for the agents using the agent interaction data. Figure 21 shows the agent interactions as a network of nodes and directed links at the end of a trial, after 40000 ticks, for the distributed with sharing and distributed without sharing version of the model. Figure 22 and Figure 23 show the degree centrality and the density values of the networks for each version of the model at the end of the trial, respectively.

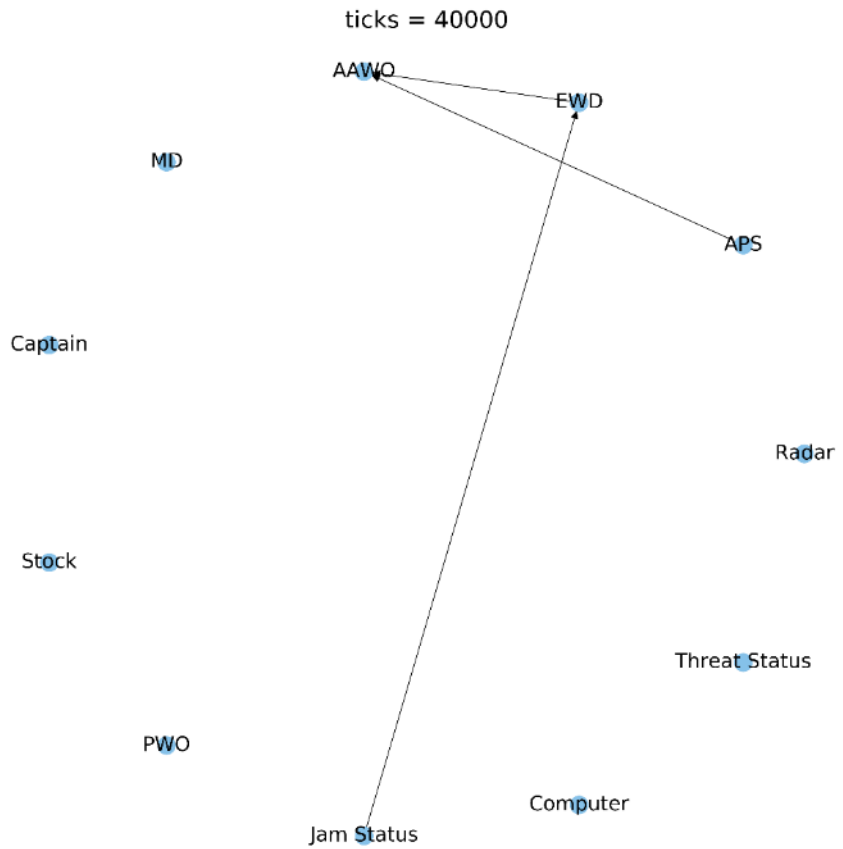
The networks in Figure 21 show that at the end of the trial, the agents within the distributed with sharing model have more connections throughout the network and that a number of those connections are in both directions. That is, agents are sharing and receiving information from each other. In comparison, the agents in the distributed without sharing model have much less

connectivity throughout the network and that connections made are in one direction, that is information is only shared in one direction.

**Interval Networks of Agents During the Shared  
HMS Dryad ABM Task for 40000 ticks**



**Interval Networks of Agents During the Distributed  
HMS Dryad ABM Task for 40000 ticks**



**Figure 21 – Directed agent networks at the end of the model trial for the distributed with sharing and distributed without sharing versions of the model**

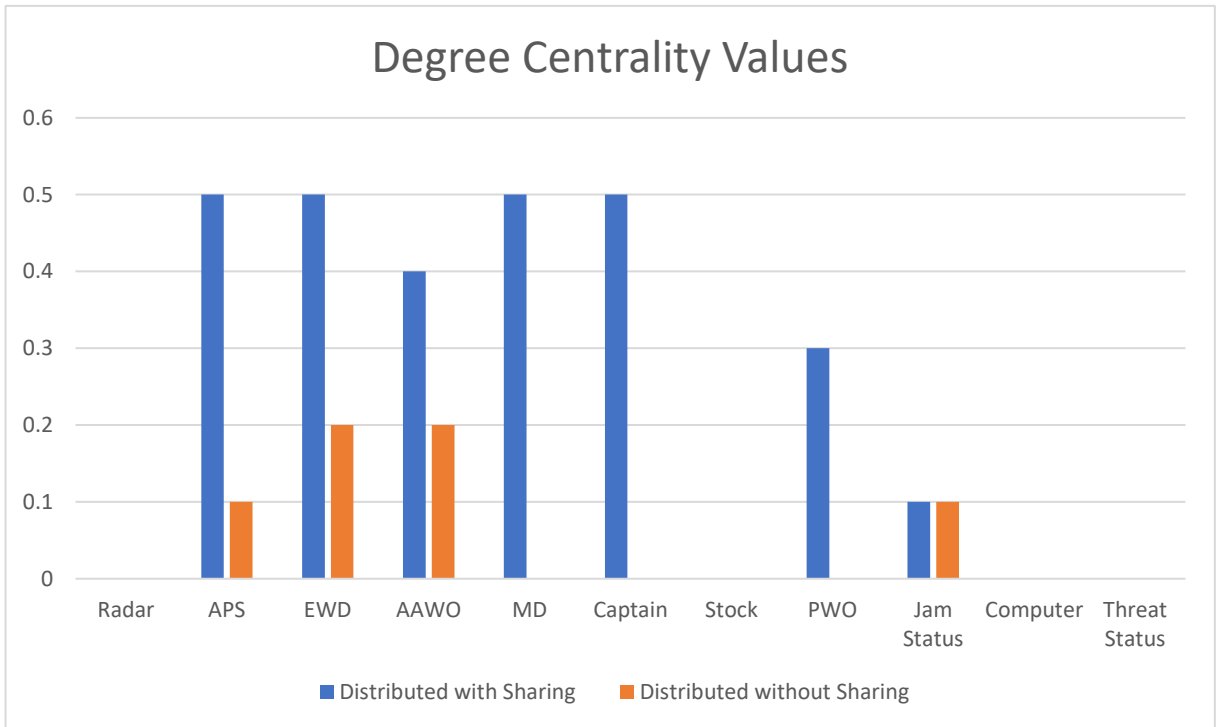
The degree centrality results (seen in Figure 22) support the network results, where agents have a higher degree centrality in the distributed with sharing model compared to the distributed without sharing model. The density value (seen in Figure 23) also shows that the agents in distributed with sharing model utilize more of the potential connections than that of the agents distributed without sharing model.

Although the SNA gives a snapshot of how the system was interacting at the end of the trial, it gives no insight into how the interactions changed during the trial. As situation awareness is dynamically changing throughout any task, the same SNA was applied to a moving window across the trial. A range of window sizes were used over the 40000 ticks, e.g., in intervals of 500, 1000, 2000 and 10000 ticks the SNA data was saved for further analysis.

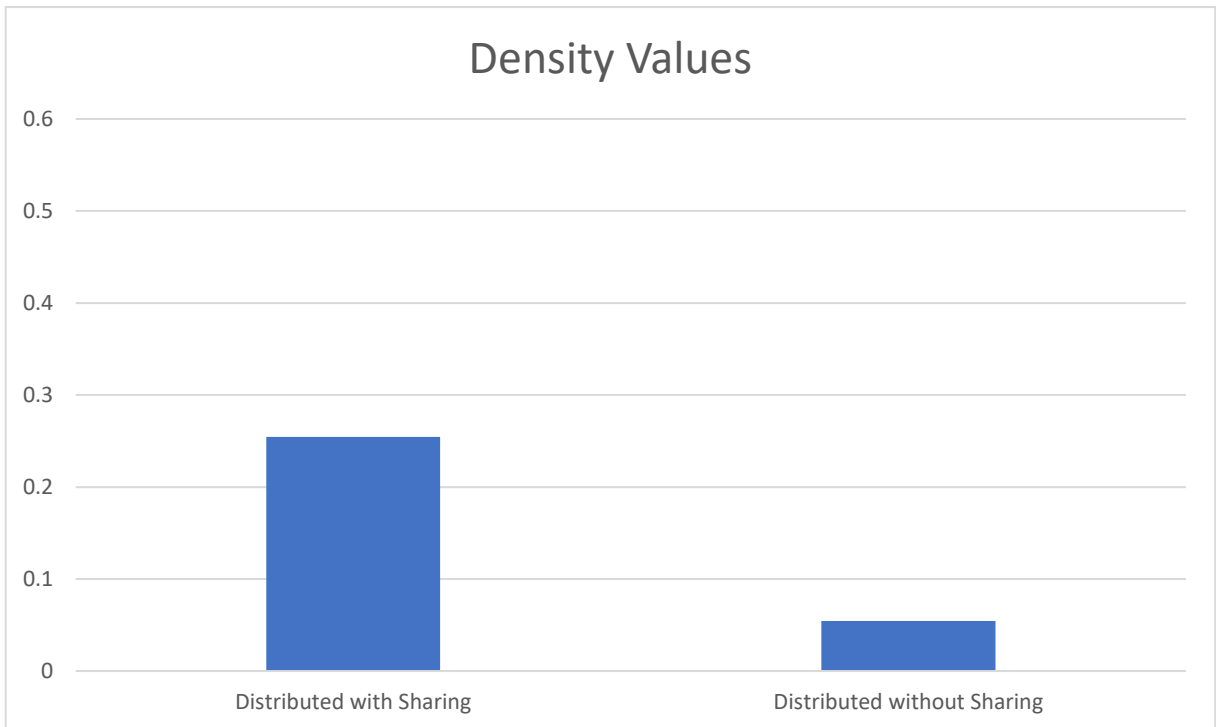
Figure 24, Figure 25, Figure 26 & Figure 27 show the interval networks for agents in the Shared Model, and Figure 28, Figure 29, Figure 30 & Figure 31 show the interval networks for agents in the Distributed Model.

Figure 32, Figure 33, Figure 34 & Figure 35 show the interval degree centrality for agents in the Shared Model, and Figure 36, Figure 37, Figure 38 & Figure 39 show the interval degree centrality for agents in the Distributed Model.

Figure 40, Figure 41, Figure 42 & Figure 43 show the interval density for agents in the Shared Model, and Figure 44, Figure 45, Figure 46 & Figure 47 show the interval density for agents in the Distributed Model.

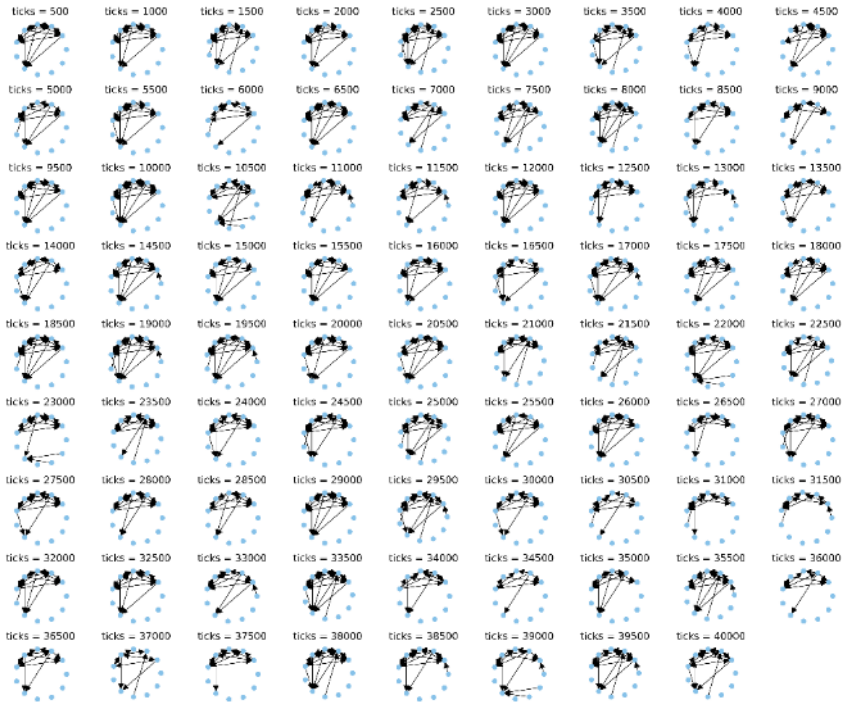


**Figure 22 - Degree centrality value results for both the distributed with sharing and distributed without sharing versions of the model**



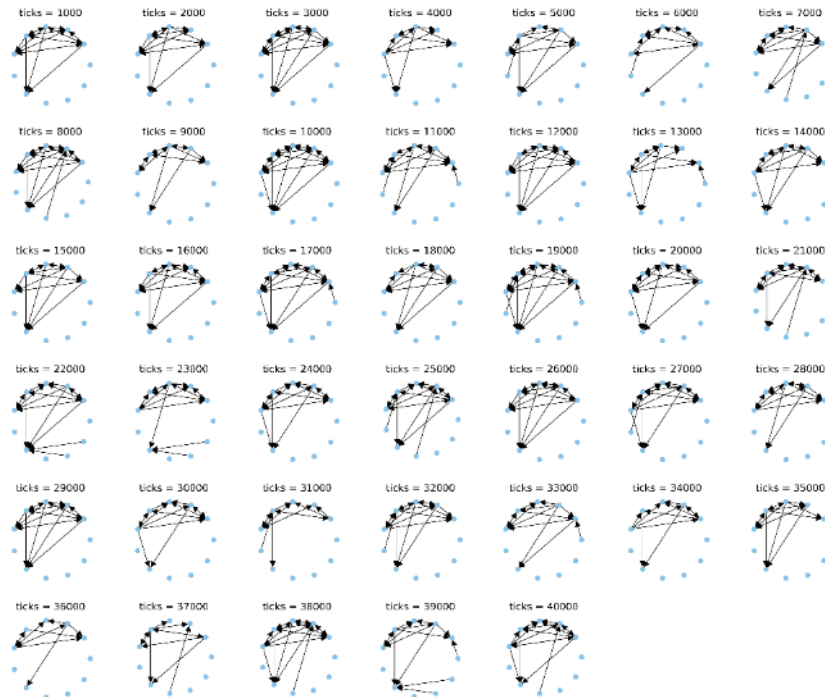
**Figure 23 - Density value results for both the distributed with sharing and distributed without sharing versions of the model**

**Interval Networks of Agents During the Shared  
HMS Dryad ABM Task for 40000 ticks**



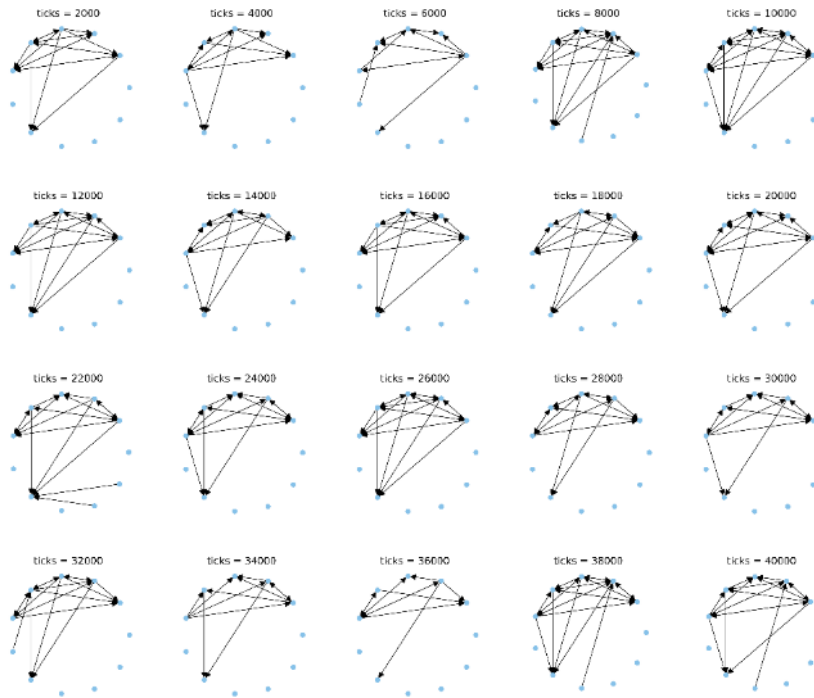
**Figure 24 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 500 tick intervals**

**Interval Networks of Agents During the Shared  
HMS Dryad ABM Task for 40000 ticks**



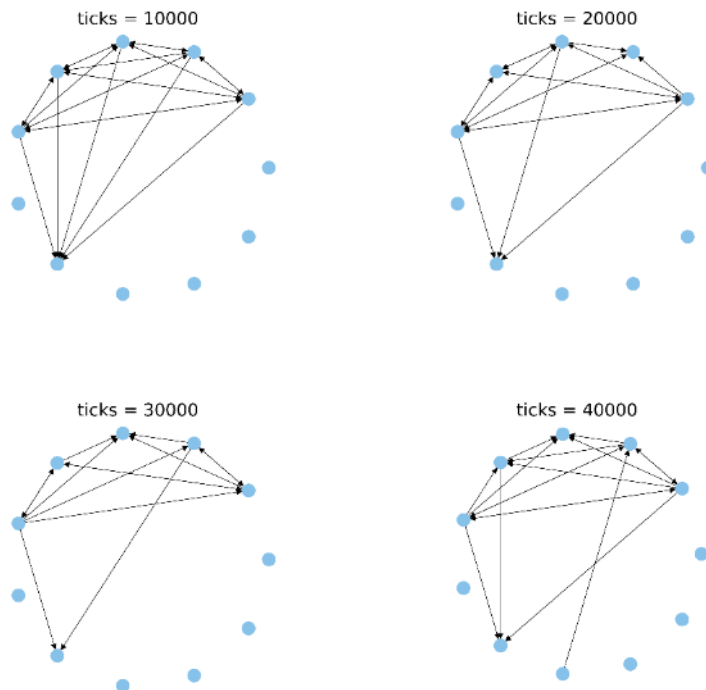
**Figure 25 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 1000 tick intervals**

**Interval Networks of Agents During the Shared HMS Dryad ABM Task for 40000 ticks**



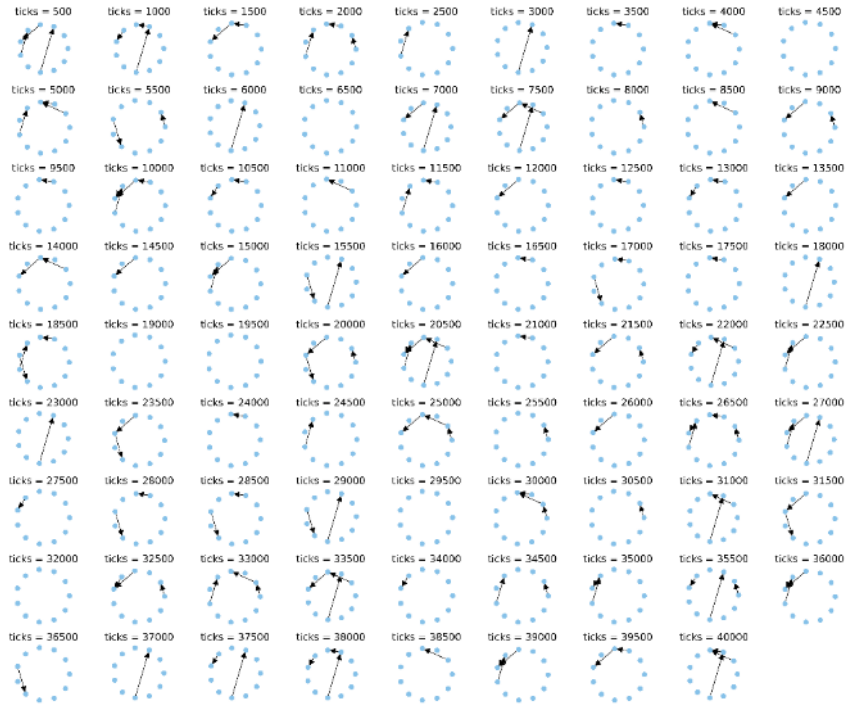
**Figure 26 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 2000 tick intervals**

**Interval Networks of Agents During the Shared HMS Dryad ABM Task for 40000 ticks**



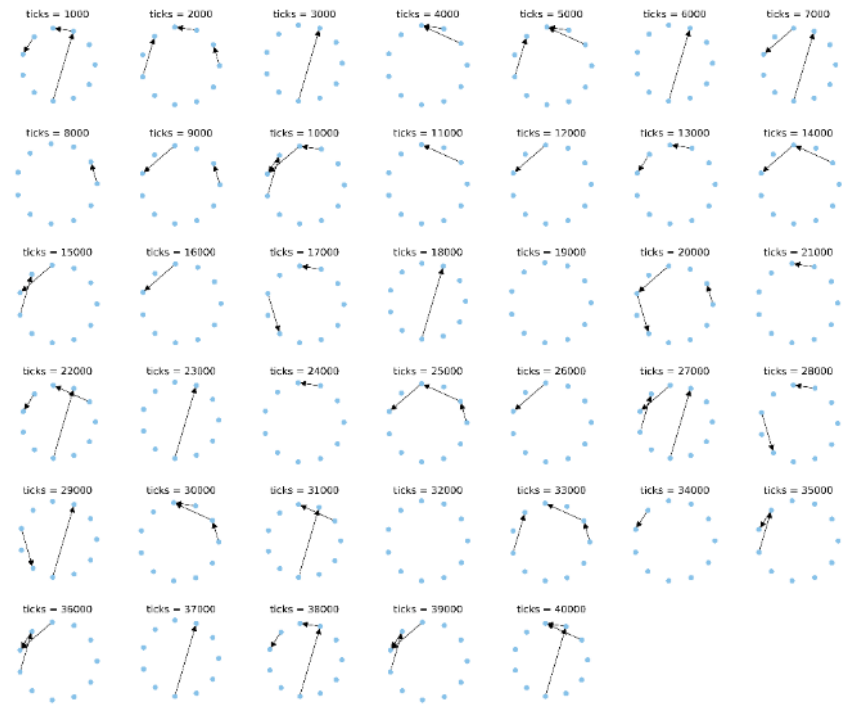
**Figure 27 - Interval Networks of Agents During the Shared HMS Dryad ABM Task: 10000 tick intervals**

**Interval Networks of Agents During the Distributed HMS Dryad ABM Task for 40000 ticks**



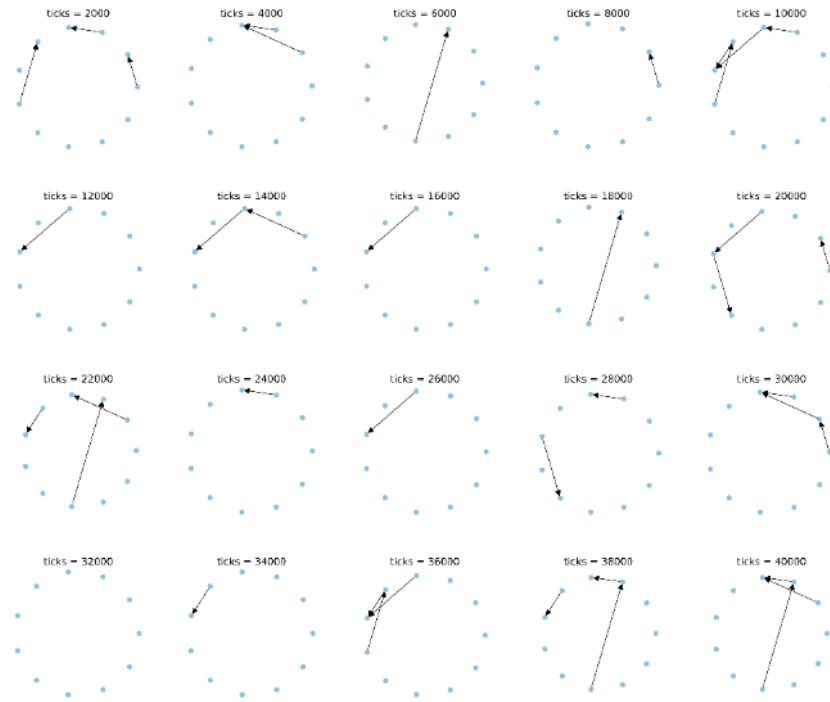
**Figure 28 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 500 tick intervals**

**Interval Networks of Agents During the Distributed HMS Dryad ABM Task for 40000 ticks**



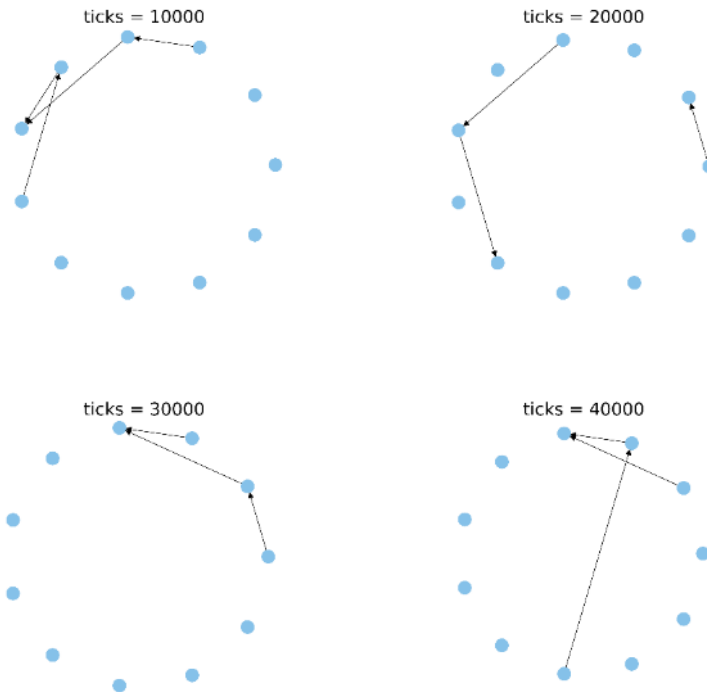
**Figure 29 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 1000 tick intervals**

**Interval Networks of Agents During the Distributed HMS Dryad ABM Task for 40000 ticks**

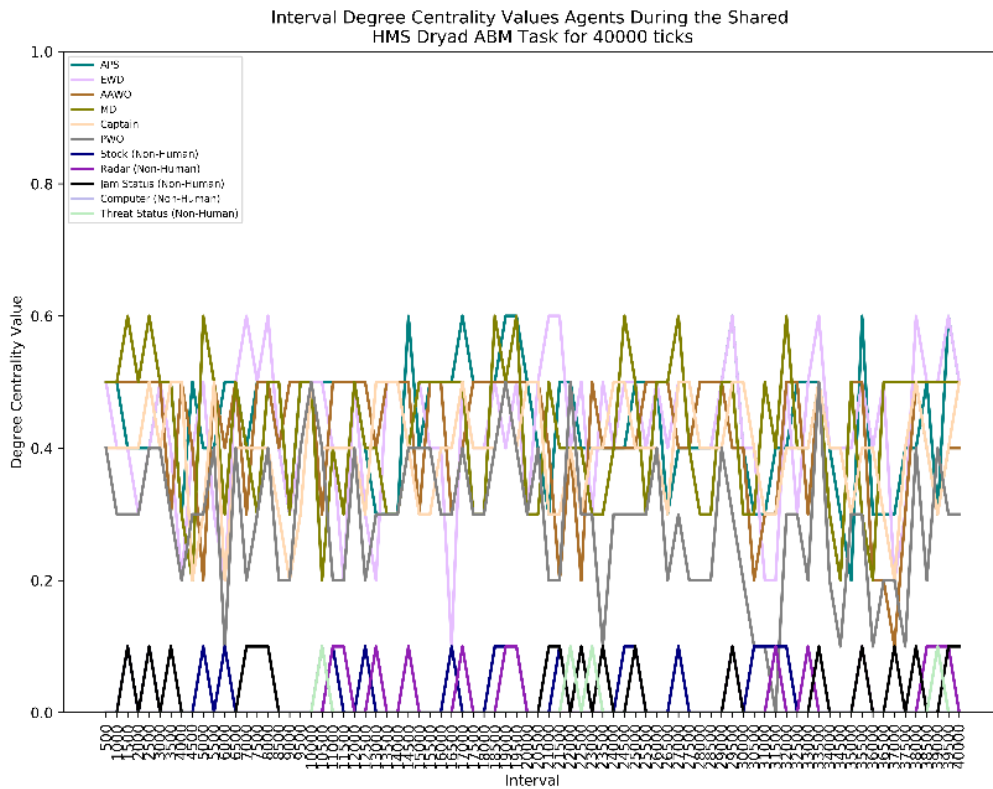


**Figure 30 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 2000 tick intervals**

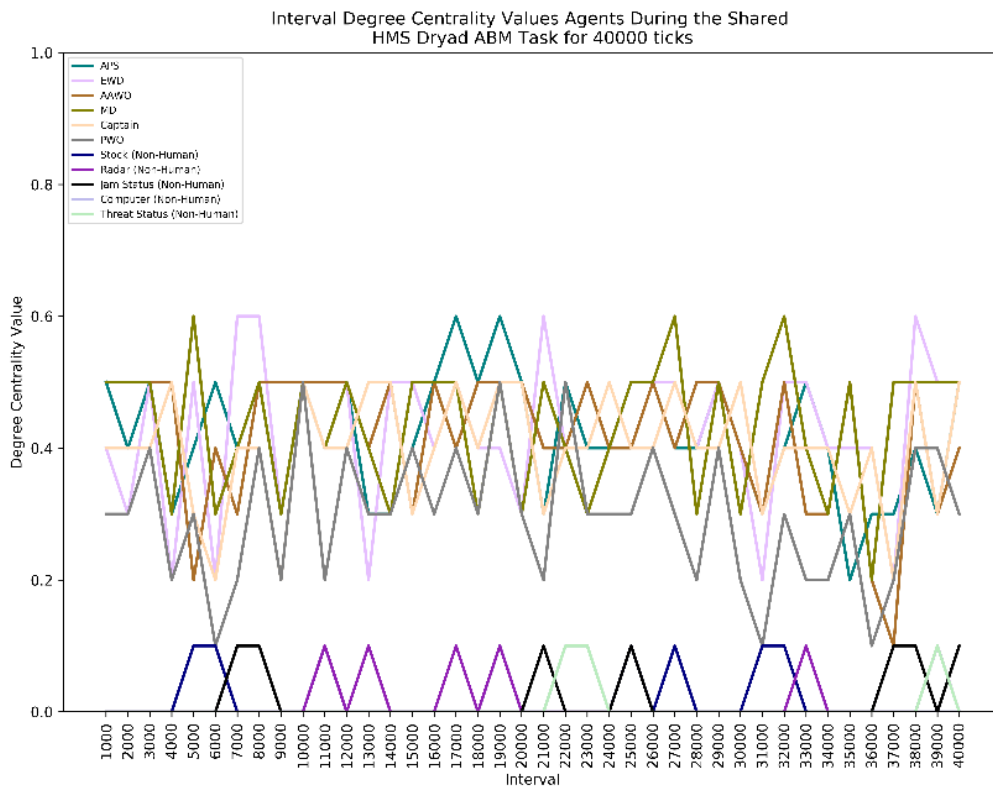
**Interval Networks of Agents During the Distributed HMS Dryad ABM Task for 40000 ticks**



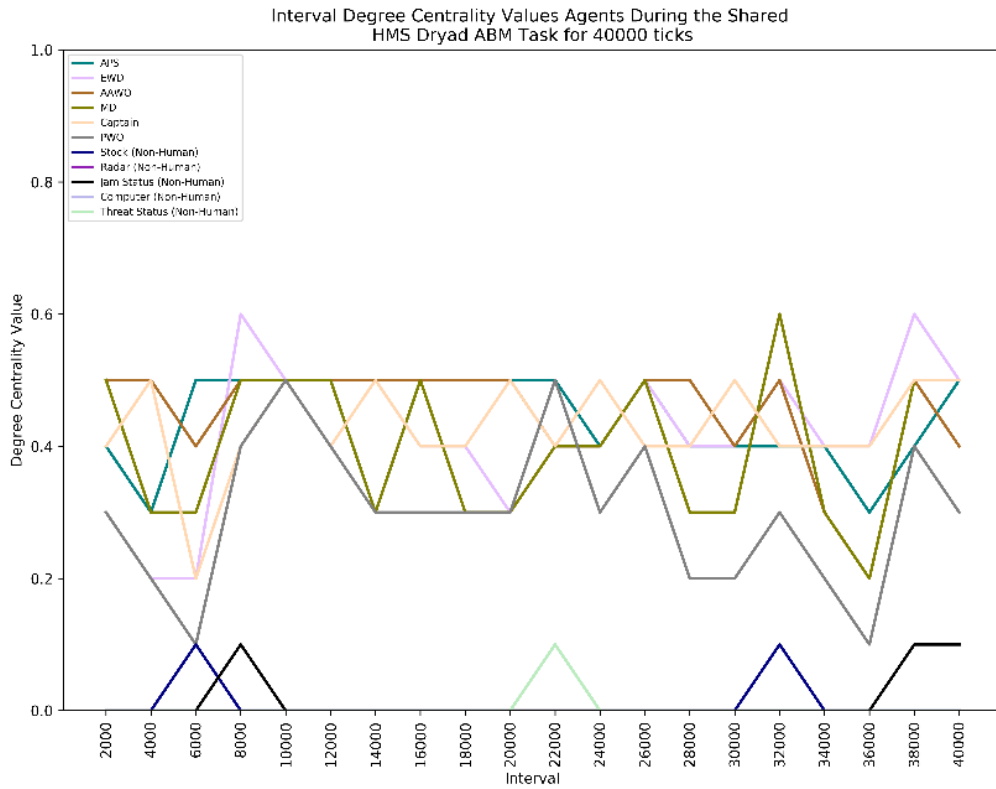
**Figure 31 - Interval Networks of Agents During the Distributed HMS Dryad ABM Task: 10000 tick intervals**



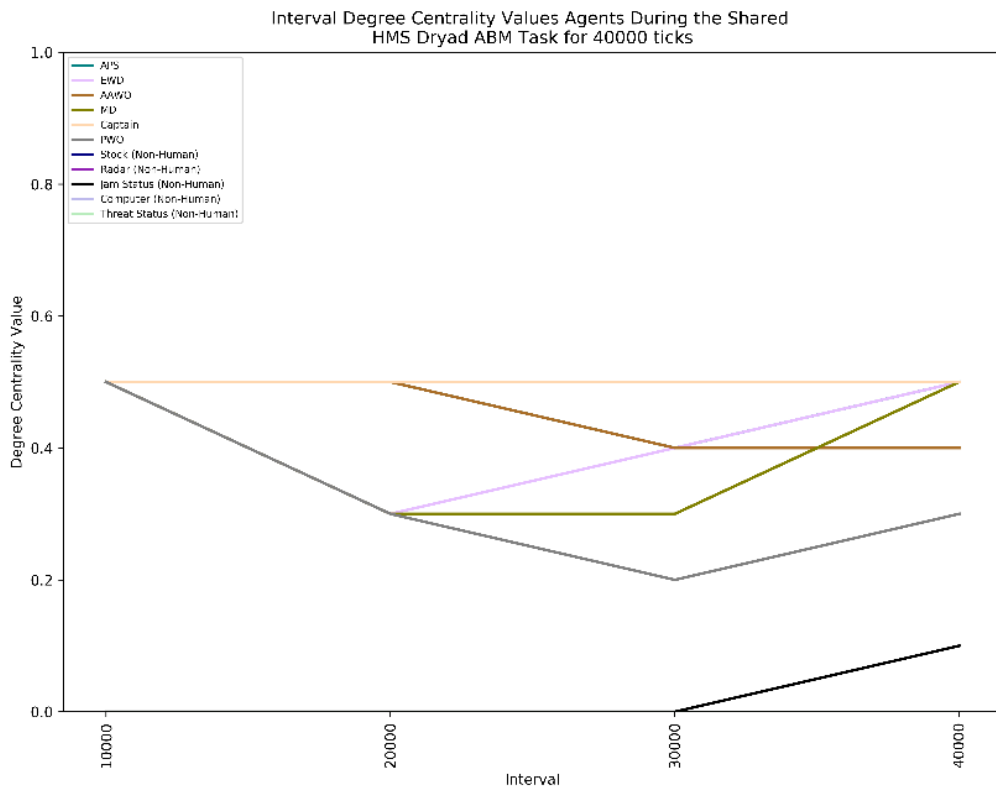
**Figure 32 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 500 tick intervals**



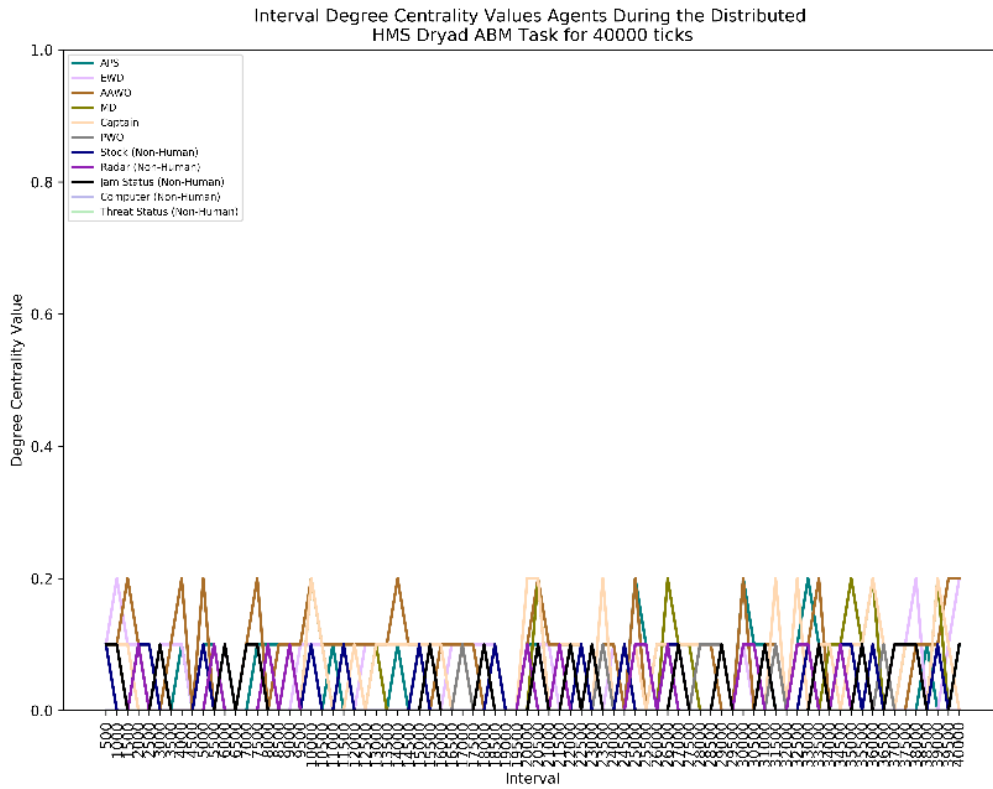
**Figure 33 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 1000 tick intervals**



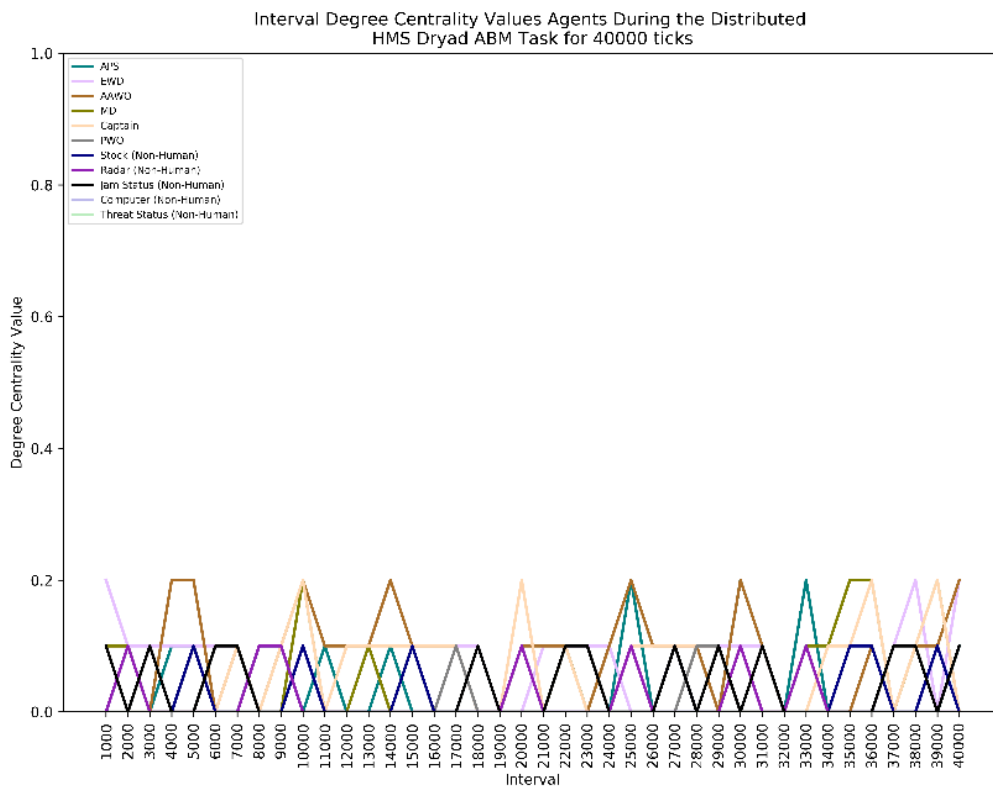
**Figure 34 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 2000 tick intervals**



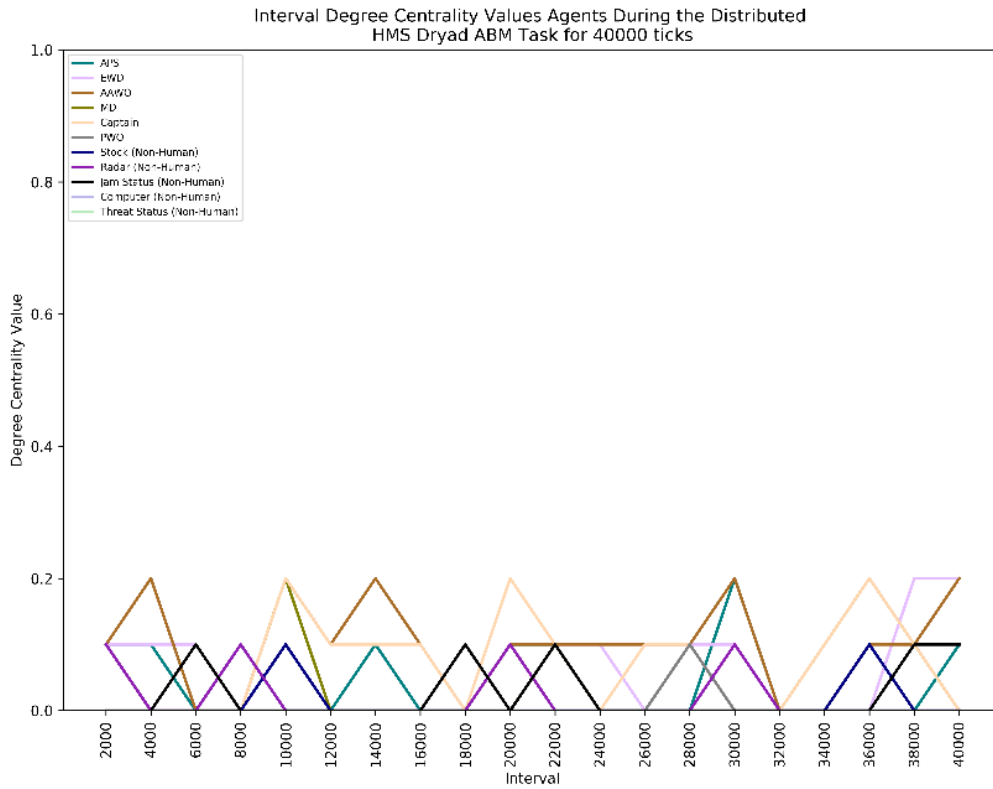
**Figure 35 - Interval Degree Centrality Values for Agents During the Shared HMS Dryad ABM Task: 10000 tick intervals**



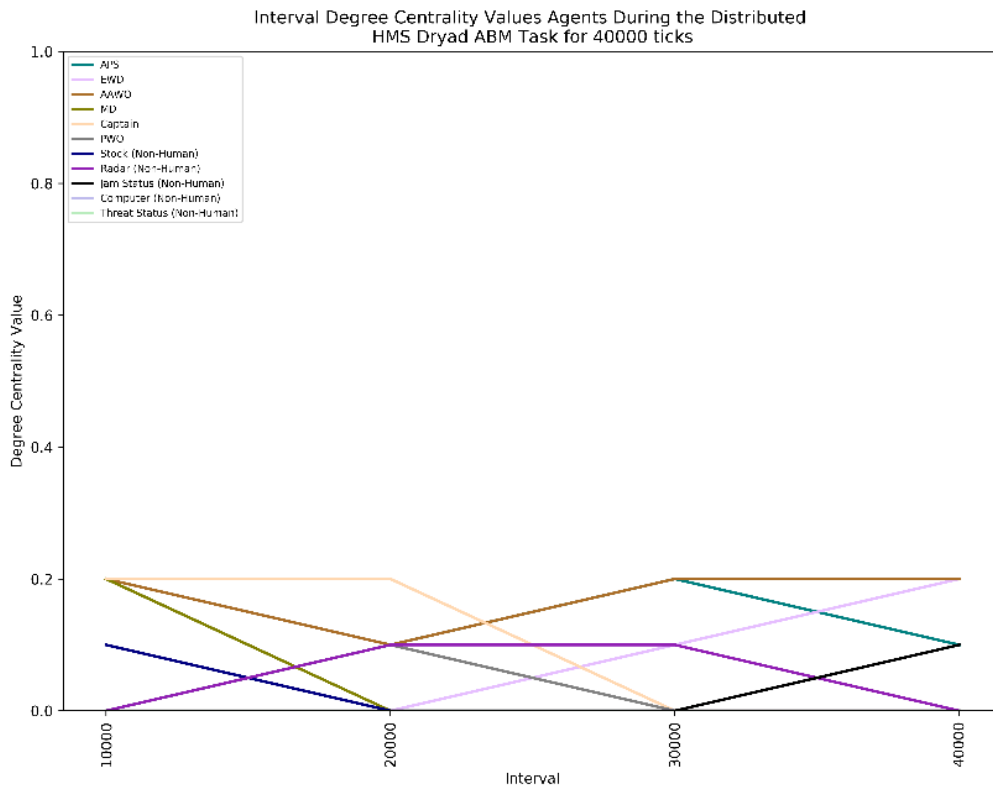
**Figure 36 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 500 tick intervals**



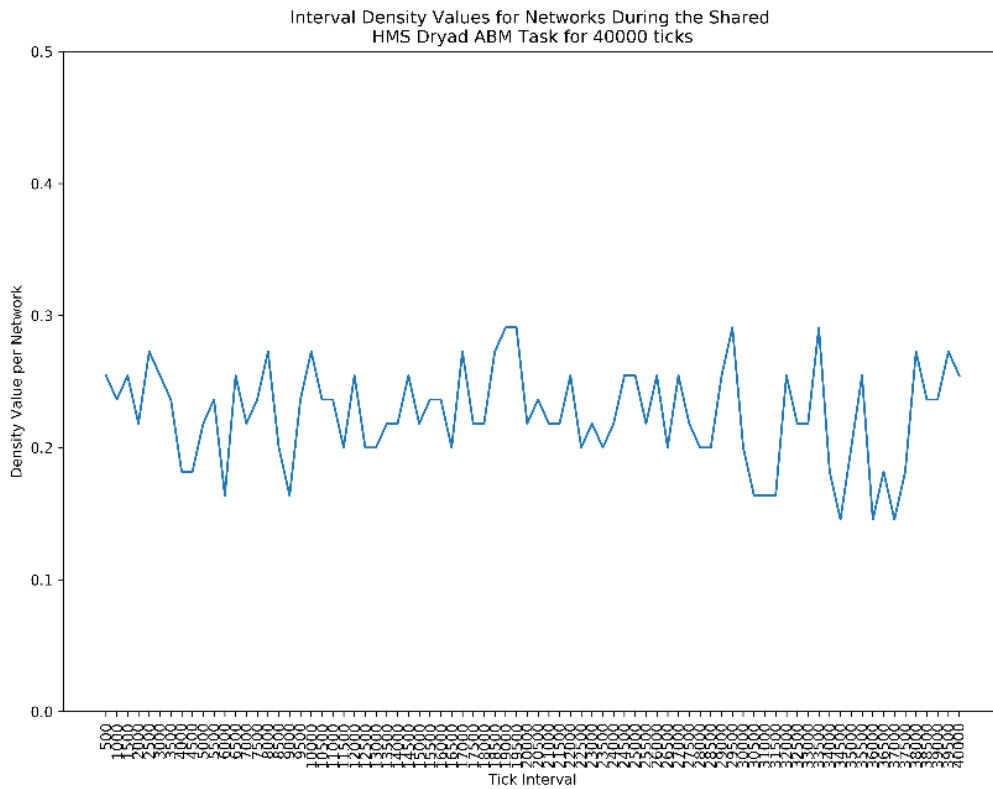
**Figure 37 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 1000 tick intervals**



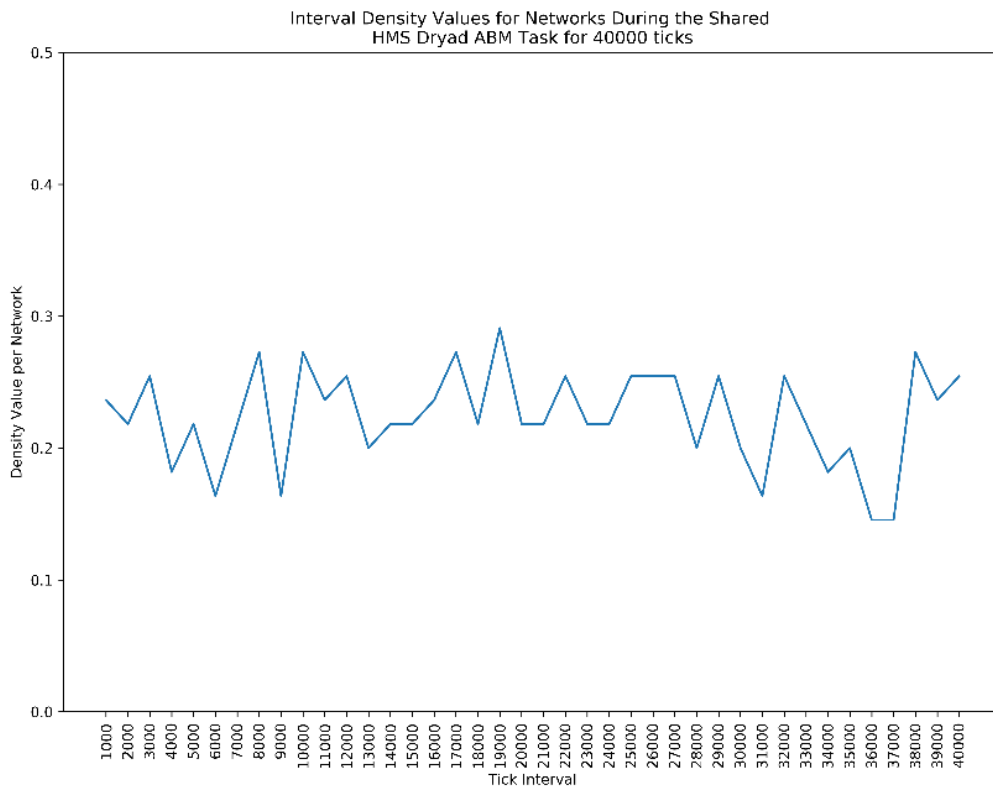
**Figure 38 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 2000 tick intervals**



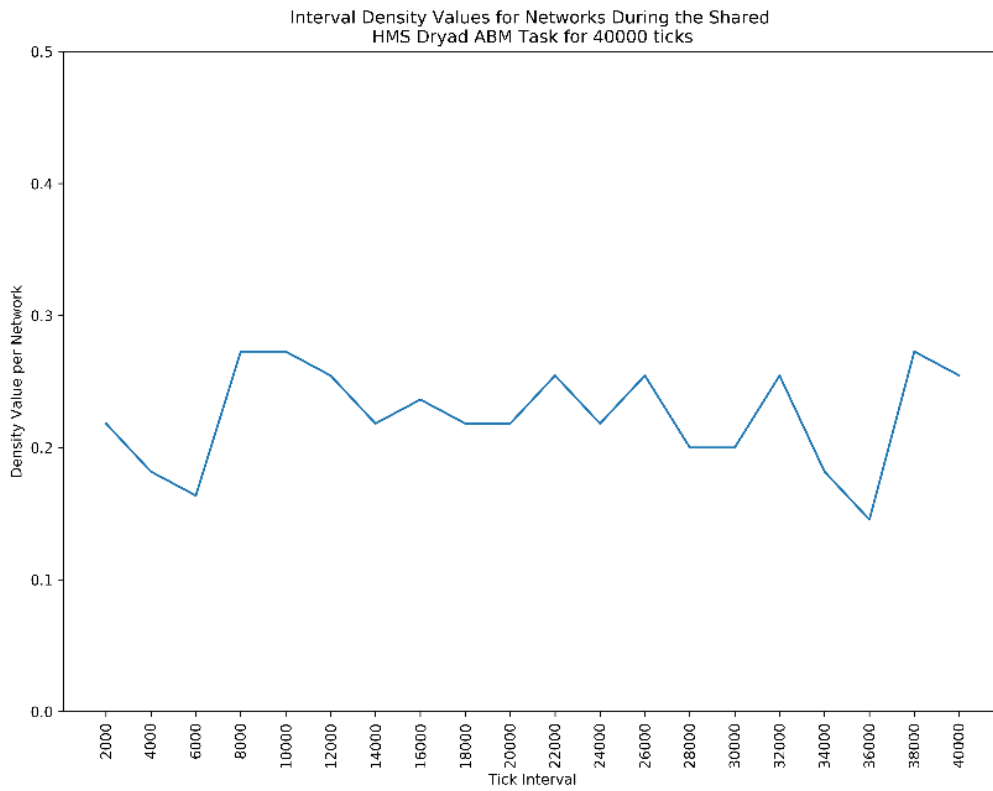
**Figure 39 - Interval Degree Centrality Values for Agents During the Distributed HMS Dryad ABM Task: 10000 tick intervals**



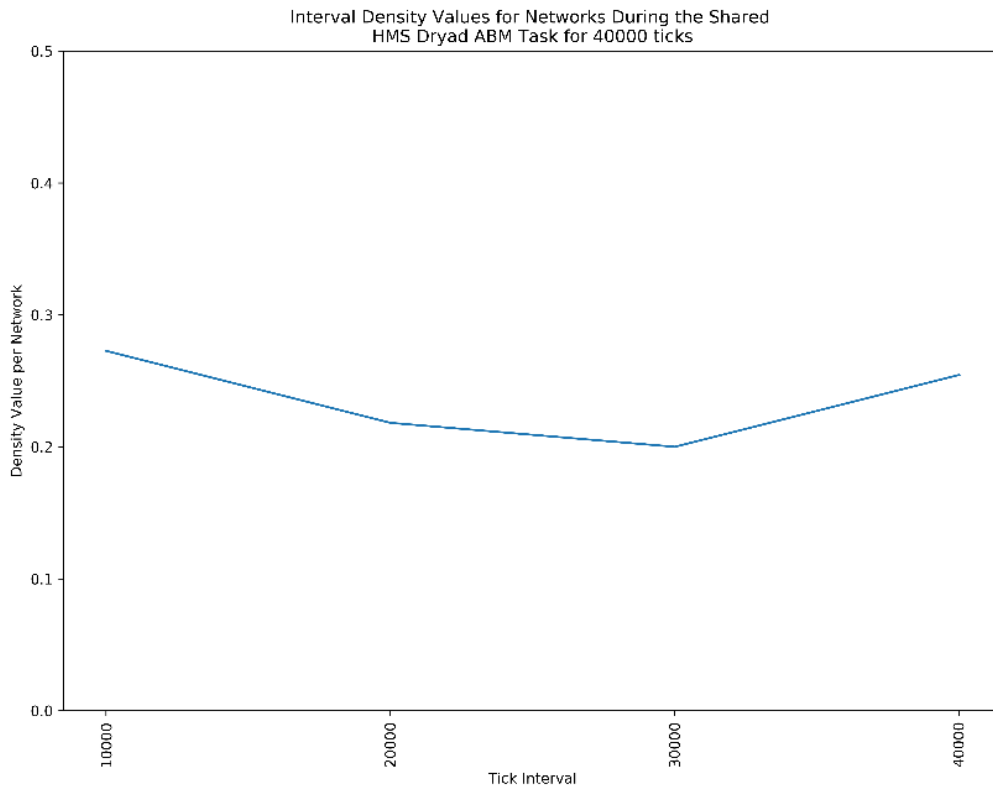
**Figure 40 - Interval Density Values During the Shared HMS Dryad ABM Task: 500 tick intervals**



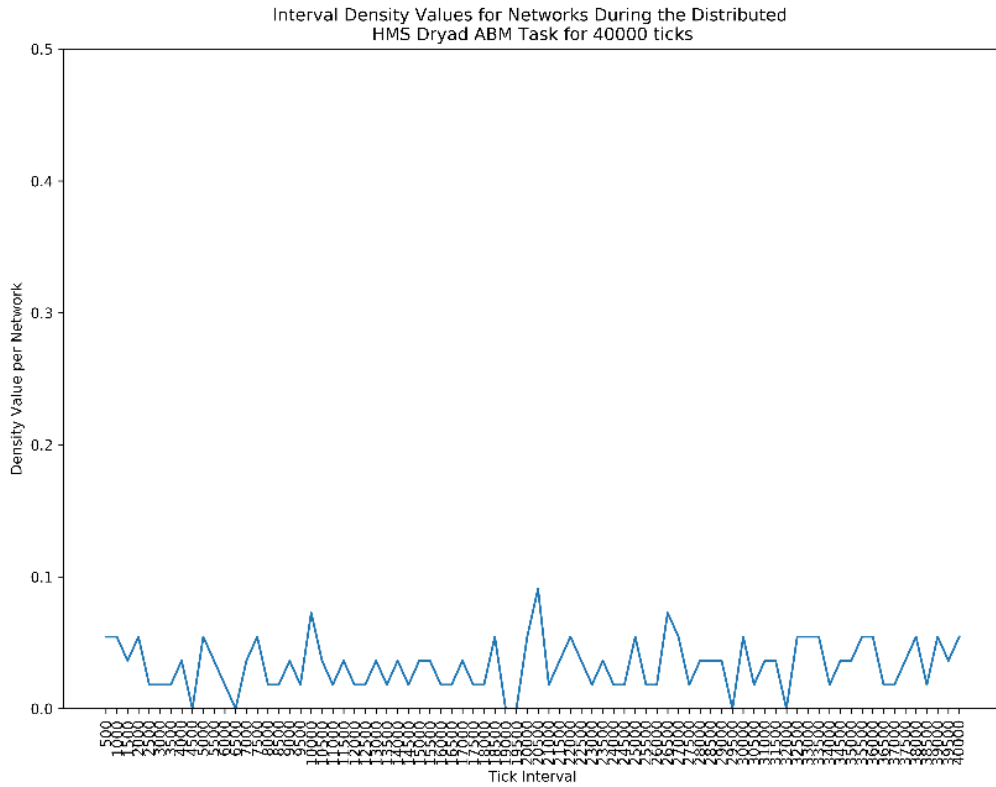
**Figure 41 - Interval Density Values During the Shared HMS Dryad ABM Task: 1000 tick intervals**



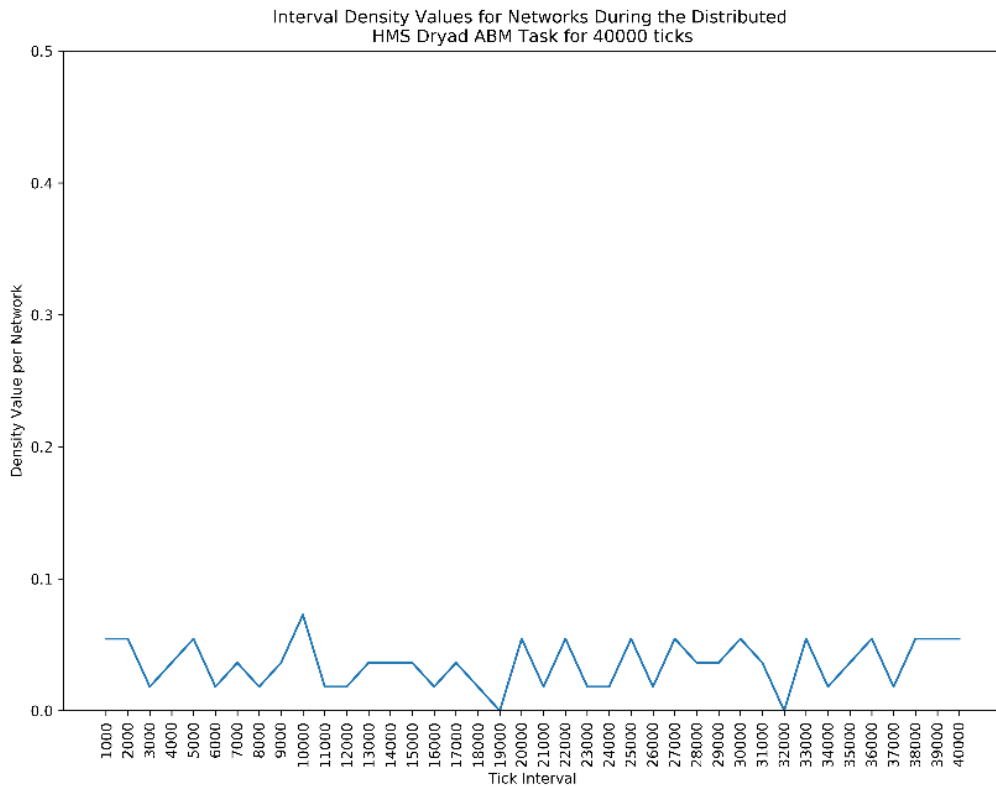
**Figure 42 - Interval Density Values During the Shared HMS Dryad ABM Task: 2000 tick intervals**



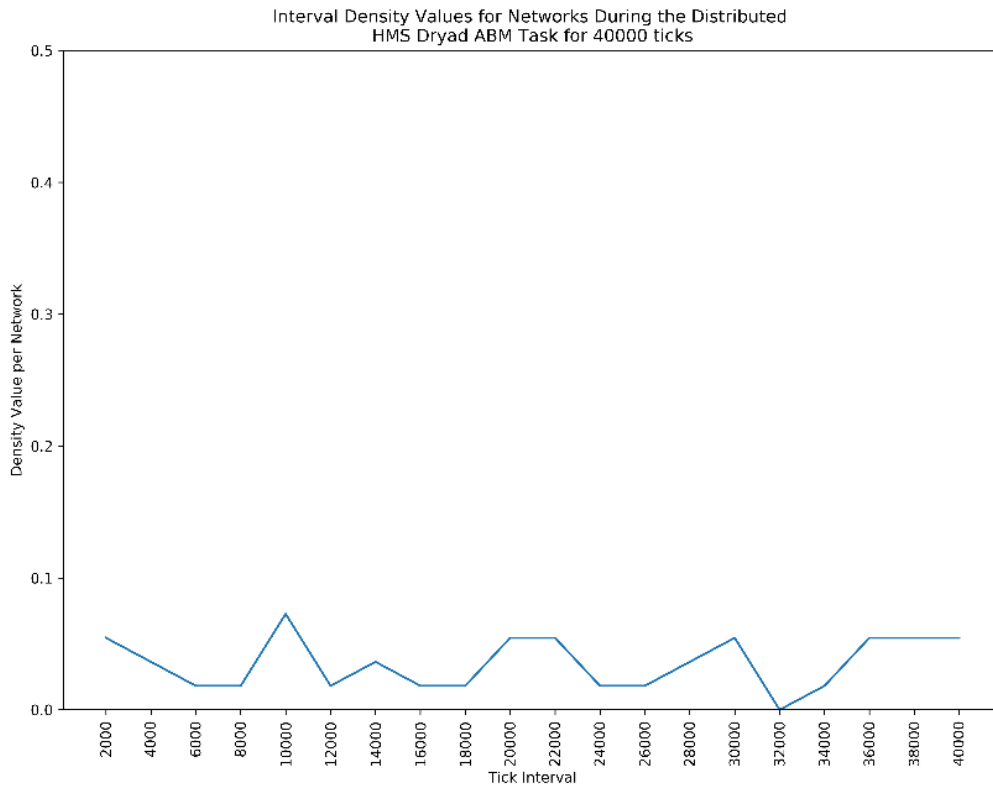
**Figure 43 - Interval Density Values During the Shared HMS Dryad ABM Task: 10000 tick intervals**



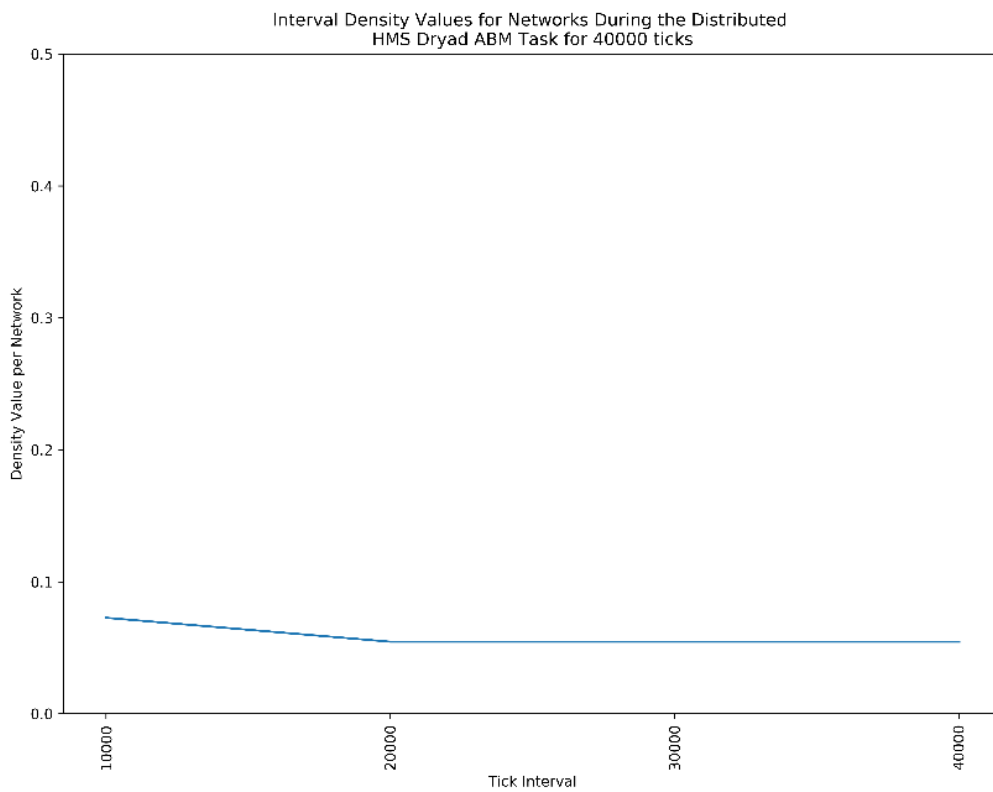
**Figure 44 - Interval Density Values During the Distributed HMS Dryad ABM Task: 500 tick intervals**



**Figure 45 - Interval Density Values During the Distributed HMS Dryad ABM Task: 1000 tick intervals**



**Figure 46 - Interval Density Values During the Distributed HMS Dryad ABM Task: 2000 tick intervals**



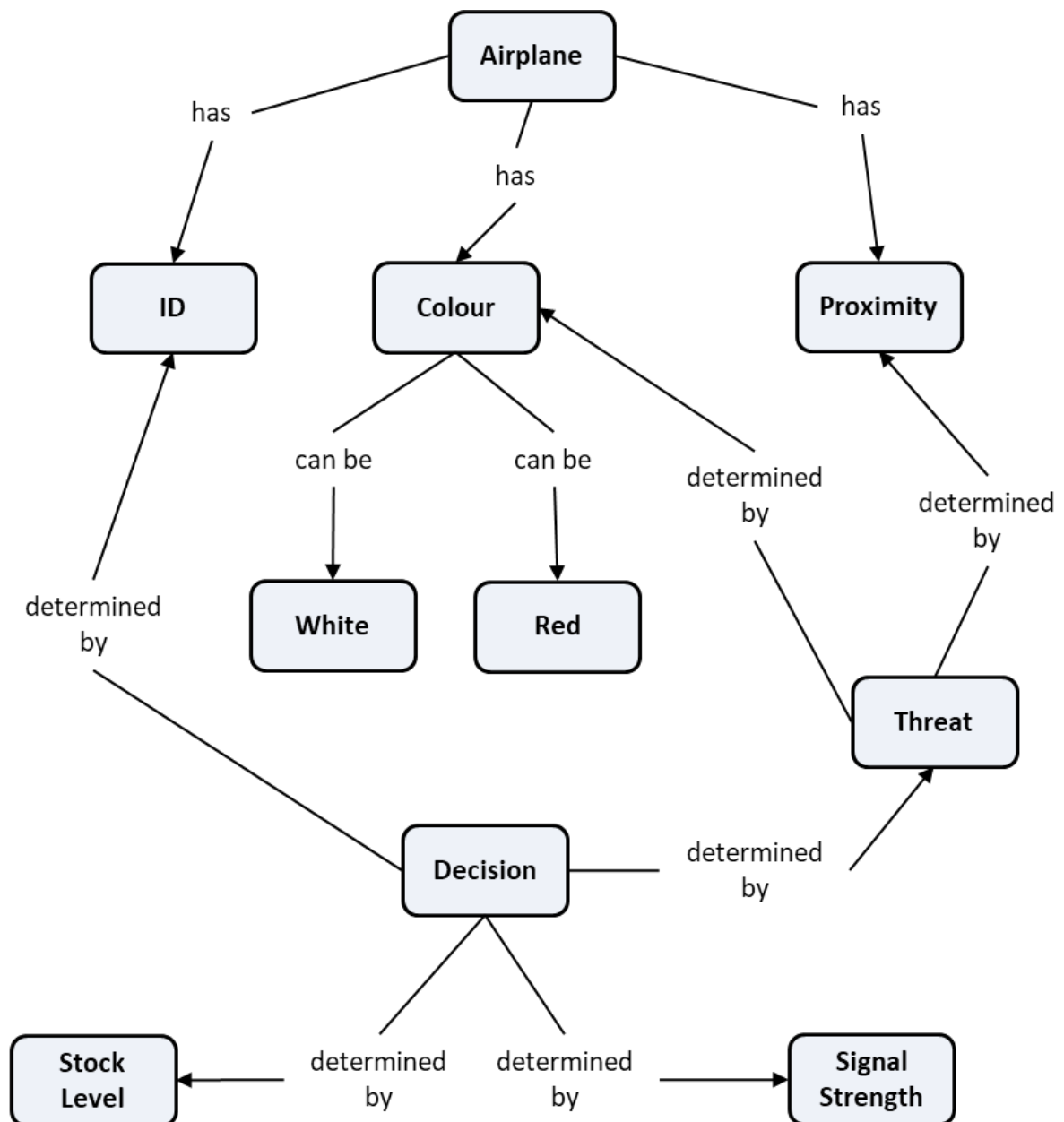
**Figure 47 - Interval Density Values During the Distributed HMS Dryad ABM Task: 10000 tick intervals**

It is clear from visual inspection of each of the figures (Figure 24 to Figure 47), that the selected interval greatly affects the overall outcome of the results and therefore the interpretation of those results. It is also clear that there is much variation in the SNA metrics over the course of the trial and therefore any results from a single snapshot could be misleading of the overall task. Another obvious problem with these results is that the greater the number of intervals used, the more complicated and difficult the results are to interpret. However, when comparing models like the ones in this chapter, this type of analysis can give a general overview of social network differences. The graphs show, regardless of the chosen interval, that the networks within the distributed with sharing model appear to be more complex and varied compared to those from the distributed without sharing model. This aside, the analysis does not give any insight into how the system came to the decisions made. One way of exploring this would be to develop concept maps for each agent to see how they used the available information. The next section explains how concept maps can be used to show how knowledge within the system.

### **3.2.3 Analysis of Agent Knowledge**

The concept maps in this chapter were created manually using the diagram features in Microsoft PowerPoint. At the end of each trial, the exported .csv file contains the information held by the agents in the system. Figure 48 shows the concept map of the 'system' in distributed without sharing and distributed with sharing version of the model. The "concepts" in the map represent the possible information that is present in the model (e.g. proximity or weapon stock level) and are shown as filled boxes. Links between the boxes represent the connections between the concepts, for example the "threat" concept is linked to the "colour" of the aircraft and the "proximity" of the aircraft to the ship. Note, the "decision" concept is linked to the "threat concept" but not vice versa. To represent this, the links have directed

arrows and text which defines the relationship between the two concepts. In this example, the “threat” concept is “determined by” the “colour” and the “proximity” concepts but not the “decision” concept, whereas the “decision” concept is “determined by” the “threat”, “ID”, “Electronic Signal Strength” and “Weapon Stock Level” concepts. The map provides a visual representation of how the overall goal of deciding what to do about a potential threat is achieved and the knowledge required to do so.



**Figure 48 – Concept map of the distributed without sharing and distributed with sharing networks**

To provide further insight into how each of agents work towards the end goal, each of the concepts is ringed to represent the agent which holds that piece of information. For example, in the distributed with sharing version of the model, all agents except for the Radar holds the “threat” knowledge, whereas in the distributed without sharing version of the model only the PWO holds this knowledge. In both versions, it is only the PWO that holds the “decision” knowledge. With this addition, it is possible to identify how key information is distributed throughout the system.

The information held by each agent in the distributed without sharing network can be seen in Table 4 which shows that the total information held by the agents is 53% of the systems total information storage capacity. The information held by each agent in the distributed with sharing network can be seen in Table 5 which shows that the total information held by the agents is 76% of the systems total information storage capacity. It can be argued that in the shared model, more of the systems information storage capacity is being used and this could potentially restrict the agents from reacting to new information in the system. Also, with all agents needing to have the same airplane ID information before the PWO agent makes a decision introduces a time delay in the decision-making process, and also restricts the system in “working” on more than one target at a time.

**Table 4 – Information held by each agent when a decision is made in the distributed without sharing version of the model**

	Airplane ID	Airplane Colour	Airplane Proximity to Ship	Electronic Signal Strength	Missile Stock Level	Threat Level
radar	X	X	X			
APS	X	X	X			
stock				X		
MD				X		
jam-status					X	
EWD					X	
captain					X	
AAWO	X	X	X	X	X	X
PWO	X	X	X	X	X	X
computer	X	X	X	X	X	X
threat-status	X	X	X	X	X	X

**Table 5 - Information held by each agent when a decision is made in the distributed with sharing version of the model**

	Airplane ID	Airplane Colour	Airplane Proximity to Ship	Missile Stock Level	Electronic Signal Strength	Threat Level
radar	X		X			
APS	X	X	X	X	X	X
stock				X		
MD	X	X	X	X	X	X
jam-status					X	
EWD	X	X	X		X	
captain	X	X	X	X	X	X
AAWO	X	X	X	X	X	X
PWO	X	X	X	X	X	X
computer	X	X	X	X	X	X
threat-status	X	X	X	X	X	X

Figure 49 and Figure 50 and show the concept maps for each of the networks at the time a decision is made, the thickness of the lines represent how often the information held is the same as the information held by the PWO. In the distributed with sharing network, the number of agents holding each of the knowledge objects (“Colour”, “ID”, “Proximity”, “Threat”, “Stock Level” and “Signal Strength”) is higher than in the distributed without sharing network. The aim of the distributed with sharing network is to generate a pool of information in which all agent can draw from, the concept map shows that the agents do indeed share this knowledge and have a larger pool of knowledge. Each of the agents hold more information each than in the distributed without sharing network. The line thickness indicates that apart from the “Signal Strength”, the agents have consistent knowledge of the targeted airplane as the PWO at the time a decision is made, indicating that the system of agents are working on the same airplane until the decision is made. The distributed without sharing concept map however shows that the system holds all the information required to make the decision, however each individual agent does not. It also shows that particular agents do not always have the same knowledge as the PWO at the time of decision making, in particular the “Signal Strength” knowledge and “Proximity”.

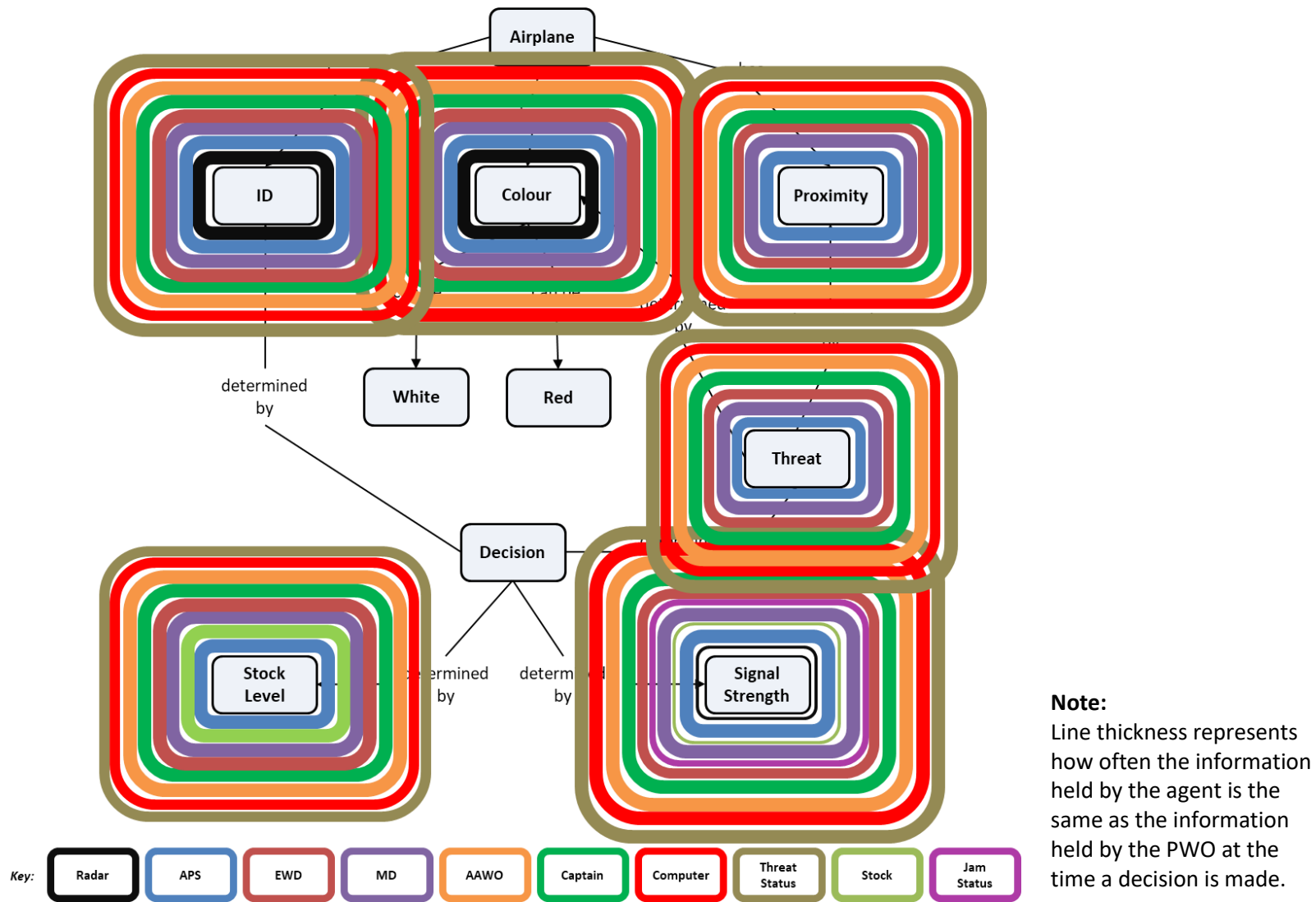


Figure 49 – Concept map with coloured rings showing agent knowledge for the distributed with sharing network

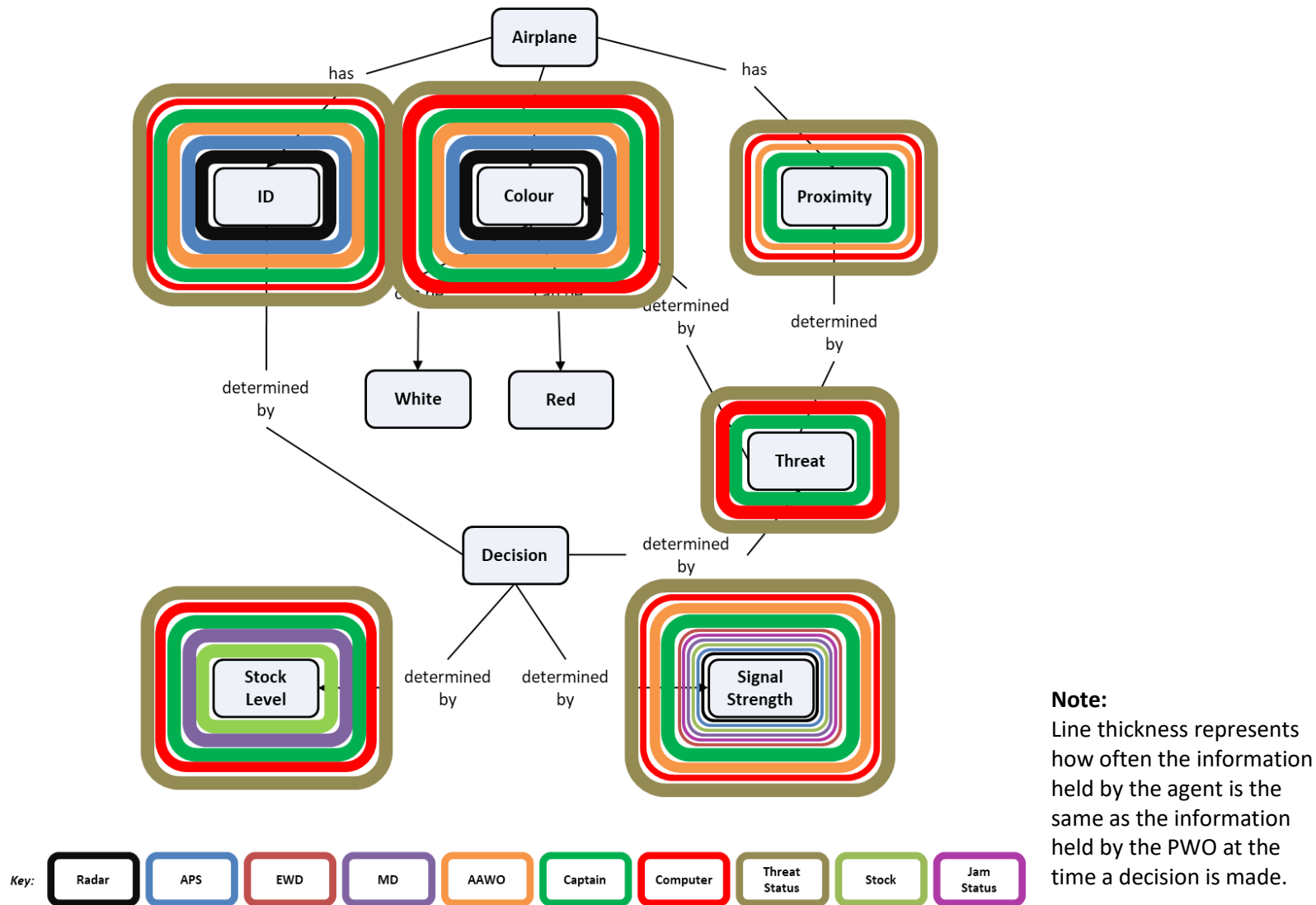


Figure 50 – Concept map with coloured rings showing agent knowledge for the distributed without sharing network

### 3.3 DISCUSSION

Agent based modelling has made the determination of agent knowledge and information possible, not only at the end of the simulations, but at any given point during the trial. The models also allow for this data to be displayed in the package itself or exported to a file for further analysis. Using this data it is possible to show what the agents know during the course of the simulation. Increasing model parameters such as the proportion of airplane threats or number of total airplanes in the radar, the total amount of information being transferred within and throughout the system also increases. As agents must perform tasks before receiving new information, it is possible that new information could be missed. This implies that the performance of the agents within the model can be affected in terms of decision making and information processing, and in turn the performance of the system as a whole.

The use of concept maps allows for a visual representation of how knowledge is organised throughout the model system and gives the opportunity to better understand how information is transferred and stored during the simulation. The models in this chapter were not given a limit to information storage as such, although only one aspect of each characteristic of the aircraft was stored. For example, only one value was stored for the proximity of the airplane at a time. If new information was received, this value was overridden, and the old value forgotten. With a small adjustment to the code conditions could have agents with limited memory, and therefore provide insight into agent workload. It could also be possible to identify whether the information that the agents are using and/or sharing is relevant to just their own task or if the information being shared is for the benefit of team members.

Interestingly, the concepts maps show that at the time of decision making it is not important for all agents to have the *same* information to ensure high performance. In fact, it can be the

case that when information is not shared the system performs better and with greater accuracy than when information is shared.

In terms of operational tempo and workload, the models manipulated aircraft speed. When the aircraft move too fast for the system to respond, the performance of that system is reduced.

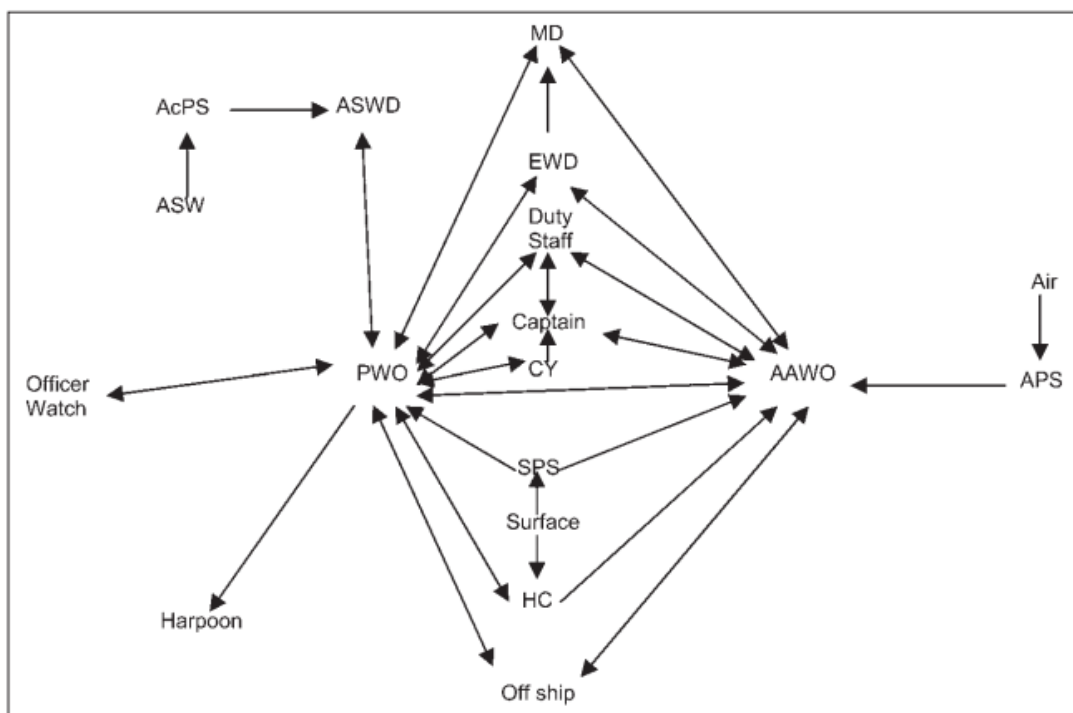
This higher level of system performance is not simply a matter of lower level agent cognition, but arises from the actions of the system as a whole. The results of this study show that, when given ample time, the structure of the system is not so important in terms of accuracy with both network structures providing correct decisions over 60% of the time, although the distributed without sharing network was more accurate than the distributed with sharing network overall (over 80%). With higher aircraft speeds and therefore system loads, it is clear that the distributed with sharing network cannot cope and fails to make any correct decisions, whereas the distributed without sharing network is able to make correct decisions with an accuracy of over 60% for the first three airplane speeds, after that performance drops to below 20% and, similarly to the distributed with sharing network, 0% with the fastest airplane speed. These results are comparable to Dekker's (2002), where a distributed without sharing network had higher performance than distributed with sharing network when the battle field tempo (i.e. workload/airplane speed) was high and the accuracy of the intelligence was also high. Sharing of information is therefore, not always beneficial to the success of a system. In this case, the act of sharing information hindered the system in making both correct decisions and the overall number of decisions. Even when the workload was low, focussing on task-work within the distributed without sharing model resulted in a higher overall number of decisions and a higher percentage of correct decisions than focussing on team work within the distributed with sharing model. It is, perhaps, the nature of the task itself that lends itself to such performance. Other time critical tasks have also been analysed in the literature, such as

the reactions to a chemical incident at a remote farm and a factory fire, both in the study by Houghton et al. (2006). The networks were also found to be distributed, and one can assume they have evolved as such to ensure the highest performance of those networks. More evidence that sharing is not always better.

The purpose of the work in this chapter is to demonstrate that agent-based modelling can be used to show that it is possible to model and simulate human-like behaviour as well as and discovering emergent system behaviours. Although the agents in the models do not have comparable cognitive features to humans, they do have comparable information sharing properties which mimic human-like information sharing behaviours. That said, the models do have a number of limitations, for example there the information being transmitted has no degradation which does not represent the very real property of human error. However, as previously mentioned, it is the system in which being studied and not the agents and therefore complex replication of human cognition is not required.

When reviewing the SNA within this chapter, it is important to note that they do not fully replicate the social networks seen in Case Study of HMS Dryad by Stanton et al. (2008) (see Figure 51). This could be due to several reasons. First, the models in this chapter do not utilize all the agents in the HMS Dryad case study (Stanton et al., 2008) and so there are interactions that could have taken place that are not shown in Figure 21. Secondly, although the models in this chapter follow similar rules to the ones in the HMS Dryad case study (Stanton et al., 2008) they were modified to replicate more extreme ways of working; focussing on independent working in the distributed model and team working in the shared model. This could explain why the networks in this chapter did not replicate the split network seen in Figure 51 **Error! Reference source not found.** One other reason could be that the social network constructed in Figure 51 utilised communications from the whole observed

scenario and input from subject matter experts. The social network results presented in Figure 21 to Figure 23 show a snapshot of interactions at the end of the model scenarios and Figure 24 to Figure 47 show snapshots of interactions throughout the model scenarios. These results do not show a cumulative social network analysis as seen in Figure 51 and the HMS Dryad case study (Stanton et al., 2008), instead they show how the social networks change from one point in the scenario and show differences in how the social networks from point in the



**Figure 51 - Excerpt from Stanton et al. (2008) showing the Social Network Analysis of the HMS Dryad Operations Room**

scenario to another.

Due to the limitations of many of the current SA measurement techniques highlighted in Chapter 2, the use of concept maps to gain a better understanding of what agents and systems know has been applied to the agent based models. However, like the SNA methods used in this chapter, the concept maps here only give an insight into system at a snapshot in time. For the SNA the snapshots are based on some arbitrary set intervals taken across the task; for the

concept maps, in order to obtain insight into how the system is working when specific actions are taken, the snapshots are when a decision is made by the PWO. A comparison of the interval values chosen shows that, depending on the value, the interpretation of how the system is performing may be very different, purely based when the results are taken. With methods such as freeze-time or real-time probes, the data gathered are also from snapshots in time, an interpretation of that data only gives insight into the individuals SA at that singular point in time, it does not show how the SA was formed or how it changed from one snapshot to the next. The SNA in this chapter suffers the same problem, it is not known how the systems change from one network analysis to the next. There may be time in-between the snapshots where the network is acting considerably different to the one observed and so changing the interval time and comparing the results from the different interval data could potentially provide conflicting interpretations of how that network is acting. However, SA needs to be dynamic and should be treated as such. Taking snapshots of the task is one step towards dynamically measuring SA, however these snapshots have proven insufficient. It is proposed that by instead taking snapshots, SNA could be analysed as a time series across the whole duration of the task instead, this would provide a set of data which could be analysed to detect and categorise patterns within the systems actions. Thanks to the nature of the models, it is possible to obtain such data.

Using such models also guarantee that when we ‘ask’ the agent what they know, the answer given will be true as there is no need to interpret the answer or the answer is not skewed by the agent giving the answer, another common criticism observed with freeze-time or real-time probe methods. These models also allow for conditions to be changed quickly and easily without the need to recruit more participants, this results in essentially having the same participants for as many experiments as are needed without the worry of fatigue or learning

affects. If the study in this chapter were to be carried out with human participants, 1000 naval personnel would be needed to obtain the same amount of data, all of which would have hold positions in operations room on a naval ship, a virtually impossible task for a project of this scale. Using ABM therefore gives us the opportunities to explore systems which previously were unattainable.

### **3.4 SUMMARY**

The model in this chapter is based on a case study previously carried out by and although the benefits of used an ABM have been highlighted, the information obtained is limited. For example, it is not known what is said by the agents on HMS Dryad in the operations room and it is known how they encode the information or how that information is interpreted in the real world. Therefore, the next step in this project is to carry out an experiment using human participants to explore how teams communicate and obtain the information required to reach a specific goal. This communication will prove a real-time series of data which can be analysed without the need to interrupt the participants or interfere with the task. As the DSA approach works on the assumption that 'knowledge' is externalised through communication, capturing the content of the communications can provide a proxy for what they know and how this might be used to inform DSA. As the task will be designed from start to finish, it can also be modelled and therefore simulations of the same task can be conducted post hoc.

# **CHAPTER 4 COMMUNICATION AS KNOWLEDGE: STUDY OF TEAMWORKING**

*Parts of this chapter have been published in:*

*[1] A comparison of shared and distributed situation awareness in teams through the use of agent-based modelling” in the Journal of Theoretical Issues in Ergonomics Science, 2016, 17(1), p 8-41*

*The sections: Distinguishing between SA Theories on Page 10 of [1], Hypotheses on Page 20 of [1], Design on Page 15 of [1], Participants on Page 15 of [1], Procedure on Page 15 of [1], Setup on Page 18 of [1], Experimental tasks on Page 16 of [1], Comparing Comments and Scores for High and Low Performance Teams on Page 23 of [1], Review of transcripts for high and low performing teams on Page 23 of [1], Information Held within the Network on Page 14 of [1] and Future Work on Page 38 of [1] have been reproduced in this chapter.*

*The chapter is based on the work in [1].*

## **4.1 INTRODUCTION**

When reviewing the Shared SA of a team one is looking at how the Individual SA (as the contents of each individual’s ‘internal’ representation of key information) of a team member is shared with all of the other members of that team, where all team members hold the same knowledge. However, when reviewing the Distributed SA of a system, one is looking at how each agent (human or non-human) within that system contributes to the overall SA (as the content of the ‘external’ representations communicated through the system) of that system

and how the SA of the system emerges via the interactions and individual actions of the agents within it.

The primary difference between the SA theories to be explored is the extent to which sharing of information facilitates SA in a team and how communication aids the systems performance. This difference is explored through a simple scenario in which a team is required to identify a target by agreeing on the features which can be used to distinguish it from not target objects. The team members either view the situation using the same visual display, or each team member will have a unique display. In the former case, one might expect communication to rely on highlighting information-in-common, perhaps checking that each team member was looking at the same part of the display. One might expect communication to rely on highlighting differences in information, perhaps checking for overlaps in the information available to each team member or trying to reach a consensus on the information being used. In this case, the displays become the focus of communication and one might expect higher levels of communication to reflect Shared SA. In each condition, it is possible that no one member of the team draws on all of the information but that this information is essentially held in the system, i.e., distributed through the team members and the displays they are using. This will reflect Distributed SA.

The previous chapter utilised ABM to observe how agents (human and non-human) interact together in order for the system to achieve a goal. Due to the nature of ABM it was possible to record what knowledge the agents had at any given time during the simulated trials. A concept map, where the knowledge objects within the map owned by the agents are visually represented, was presented as a way of exploring the DSA of the system at a given point in time. This method allowed for the system to be mapped and the activated knowledge to be shown.

The previous chapter highlighted the benefits of using ABM, however the model itself was based on a case study and not on experimental data. Therefore, in this chapter a study was carried out to observe how team members work together to achieve a common goal. Due to the limitations of the project, it was not possible to recruit naval personnel and so for the simple target detection task, students from the University of Birmingham were recruited. The study is concerned with the information sharing within a team and how this affects the performance of that team.

## 4.2 HYPOTHESES

Figure 52 summarises the hypotheses explored in this chapter, contrasting Shared versus Distributed knowledge and Separate versus Common Displays. Shared knowledge is obtained via a Distributed with Sharing network, where distributed knowledge is obtained via a Distributed without Sharing network. Thus, when information needs to be Shared and there are Separate Displays we might expect relatively low performance (in comparison with the other conditions) because team members will need to expend effort on reaching consensus on

<i>Expert Literature</i>	Shared Knowledge	Distributed Knowledge
Separate Displays	Team SA Low Performance	Distributed SA High Performance
Common Displays	Shared SA High Performance	Individual SA Low Performance

Figure 52 - Comparing Shared and Distributed knowledge

the value and meaning of the content of their separate displays. In contrast, when team members work individually and do not communicate there might be a higher level of performance; not only due to the reduced need to communicate but also due to the impact of individual decision making on collaborative performance. Likewise, when team members have information-in-common (through Common Displays), then one might expect higher performance when information is Shared (because the team members work from the basis of common ground in their discussions), and this could be better than when team members work individually with a Common Display (because the performance of the team could be affected by unresolved conflict in interpreting the display).

In this chapter, depicting the knowledge that agents might hold during the development of a given situation is of interest. The content of messages sent by the participants in the experimental trials and by analysing the content of the messages exchanged by agents in the models will be analysed. This means that we make the assumption that external communication (e.g. verbally or written) of information indicates (but need not directly correspond to) the knowledge held by people or agents. This means that we are describing information flow within a team performing a task in order to reflect the manner in which information might inform SA. We realise that this skirts a number of deeper philosophical discussions of epistemology and the nature of cognition and reasoning, but feel that the use of concept maps in this paper is analogous with other uses to reflect knowledge required to understand a domain or situation (Novak, 1991, Williams, 1998, Hoffman et al., 2002a, Hoffman et al., 2002b, Hoffman et al., 2004, Novak & Cañas, 2006, Coffey et al., 2006, Novak & Cañas, 2008).

It is hypothesised that condition 2 (Separate Displays) will be more difficult than condition 3 (Common Displays), and that this will be reflected in the scores in each condition and the

number of messages passed between participants. We allowed teams to communicate as they felt appropriate, rather than imposing a form of communication on them. This allow us to explore whether teams spontaneously adopt a ‘shared’ or ‘distributed’ approach to the task (see Figure 52).

## **4.3 METHOD**

### **4.3.1 Experiment Design**

In this experiment, an A-B-A design was used. An initial condition (A), referred to as the practice condition or condition 1, is used to introduce the experimental task and equipment. This is followed by an experimental condition (B), referred to as condition 2, in which a variant of the task is presented, and then repetition of the initial condition, referred to as condition 3. This allows us to consider the potential impact of learning effects on a repeated measures design. If performance improves between the two A conditions (first and third), then there is a learning effect, but if the performance on B does not follow this trend, then this condition has disrupted the ability to learn the task. A-B-A is useful as a means of testing the impact of a variable on performance. In the case of this experiment, the independent variable was the type of information presented to participants, i.e., information-in-common versus individual information. While the experiment is presented as an exploration of the effect of information presentation on communication, it was also intended to provide input to the development of the models developed in the next chapter.

The experiment involved teams of three participants working together to identify a ‘target’. In this case, the target was defined by a specific type of vehicle crossing a specific location on the display provided. The task involved a team watching a video and communicating (via typed messages) to define the ‘target’.

### 4.3.2 Participants

The experiment was approved by the University of Birmingham ethical review process. Twenty-seven participants were recruited from the School of Electronic, Electrical and Systems Engineering (participants were Undergraduate students, mean age 21; with 14 males and 7 female). Participants were randomly assigned to teams of three before each session. All teams took part in each of the conditions, resulting in a repeated measures design.

### 4.3.3 Procedure

Each participant was given an information sheet which explained the purpose of the experiment and was asked to sign a form of consent (see Appendix B and Appendix C). Participants were free to withdraw at any point during the conduct of the experiment and within two weeks of the end of the experimental sessions (i.e., they could request their results to be withdrawn from analysis).

The experimental task was described as follows (both verbally and in the form of a crib sheet given to participants):

*Vehicles are on a toll road and certain vehicles have not paid their annual road subscription. These illegal vehicles are detected automatically based on multiple different characteristics. These characteristics are known by the experimenter and the team will be informed when all characteristics have been identified. There will be more than one illegal vehicle, but they will share the same characteristics. Your task is to monitor the screen which shows the vehicles on the road. You must work as a team to identify the characteristics which make the vehicle illegal using the instant messenger on the display. Each team member will work from their own individual display. Once the team has come to a decision, a member of the team must ask the experimenter if this determination is correct, using the following form: **The illegal vehicle is...**The experimenter will provide feedback to the team in response to this phrase. All communication must be performed using the instant messenger. Any*

member of the team can ask for feedback, using the phrase *The illegal vehicle is... as often as they like.*

#### 4.3.4 Task Development

Due to the familiarity of NetLogo and the seamless integration of the task into the ABM in chapter 3, it was decided that the videos used in the experiment would be made using this platform. The videos are taken from simple animations which are coded in such a way that vehicles spawn at either side of a road background comprising of three two-way lanes and a vertical colour representing a grey “zone”. A screenshot of this animation can be seen in Figure 53. In the code the vehicles are set to randomly choose the colours red or blue as well as the shape of a bus or car. The frequency of vehicle generation, colour, shape and background can all be easily modified within the NetLogo code by changing several basic

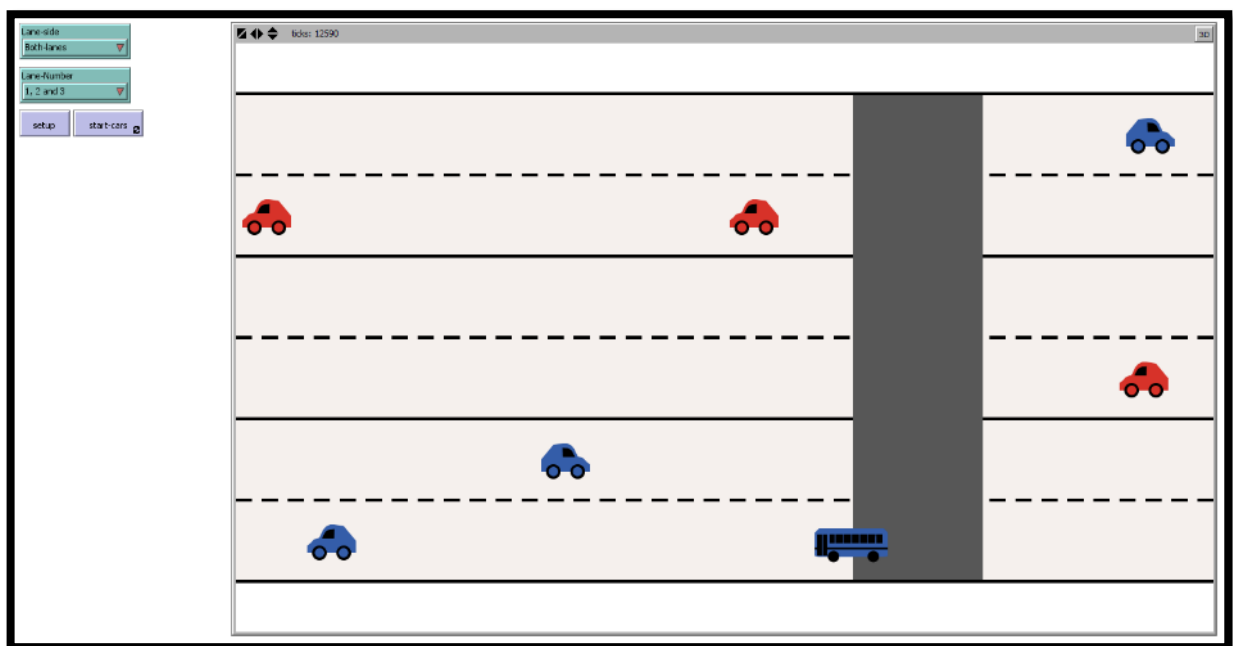
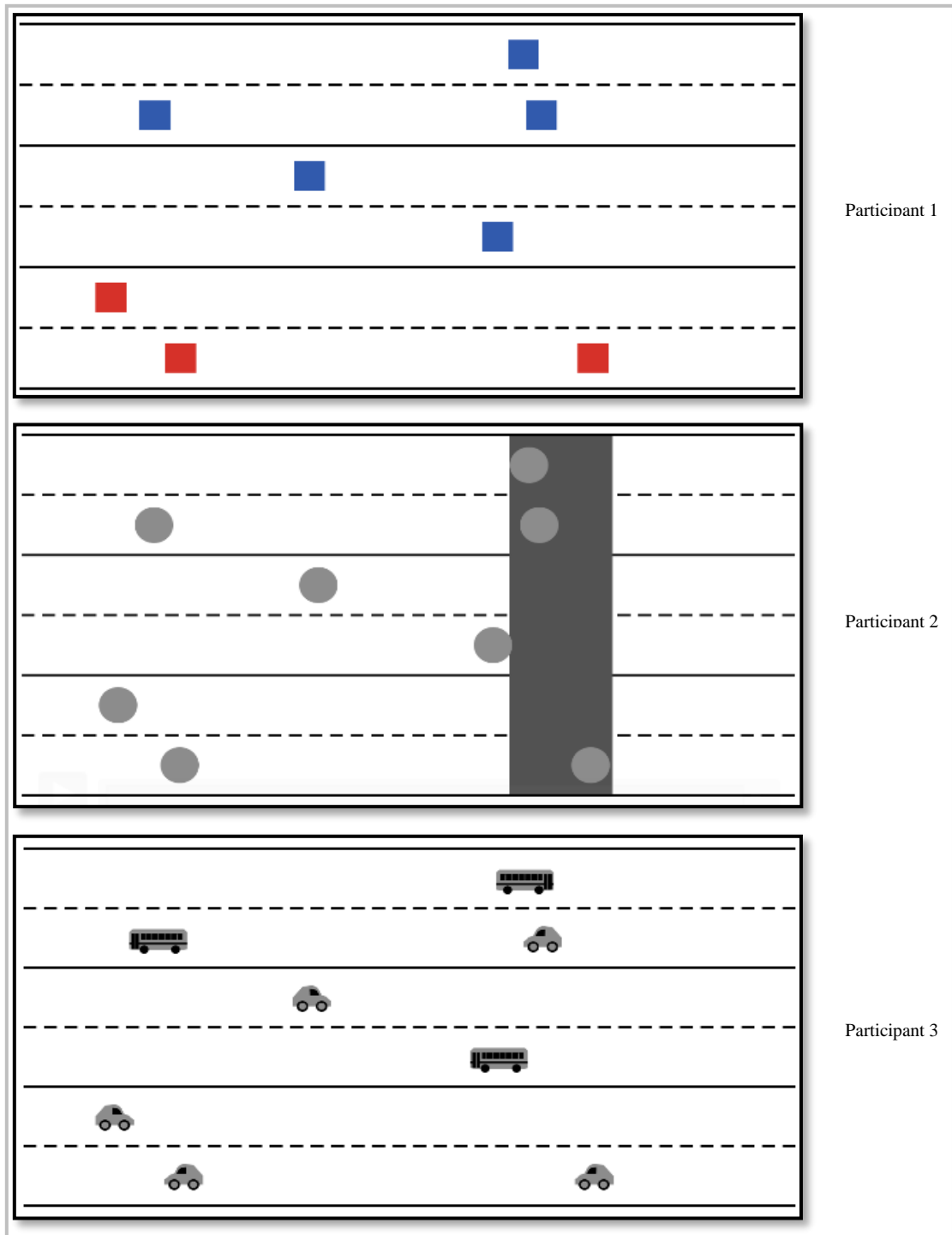


Figure 53 - Screenshot of the traffic animation used in the experiment

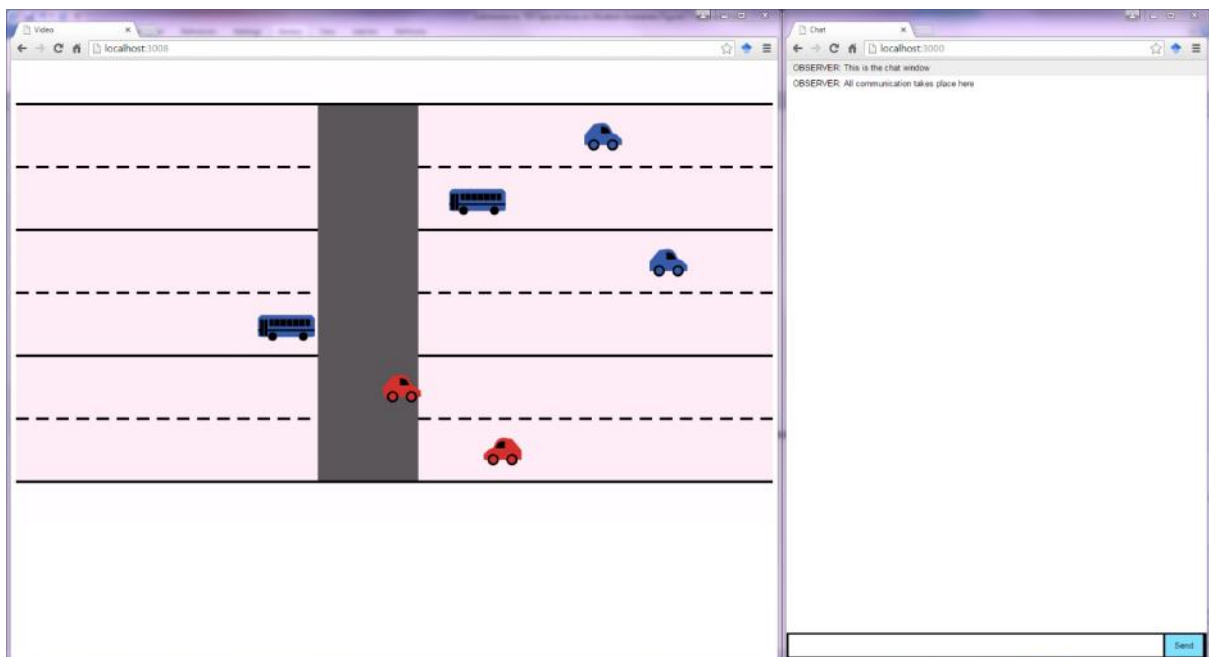


**Figure 54 – Screenshots of the separate displays created from the animation code**

variables. These modifications to the code enabled the animations used in condition 2 (separate display condition) to be created (see Figure 54). The animations were recorded using the screen capture software TinyTake and saved as .mp4 video files to be used during

the experiment. A computer lab at the University of Birmingham was used for the experiment and four identical desktop computers were chosen, each using the Windows 7 operating system. Through the use of a server, the videos and chat windows were made accessible via two separate web-pages displayed in Google Chrome, which were positioned side by side on the screen (see Figure 55). The Internet Protocol address (IP address) of each computer identified the participants throughout the experiment, the participant ID (e.g. participant 1, participant 2, participant 3 and operator) were assigned in order of the webpage being accessed, i.e. the first participant to access the webpage was given the ID participant 1 for the duration of the experiment. This setup was carried out by the experimenter at the beginning of each experiment.

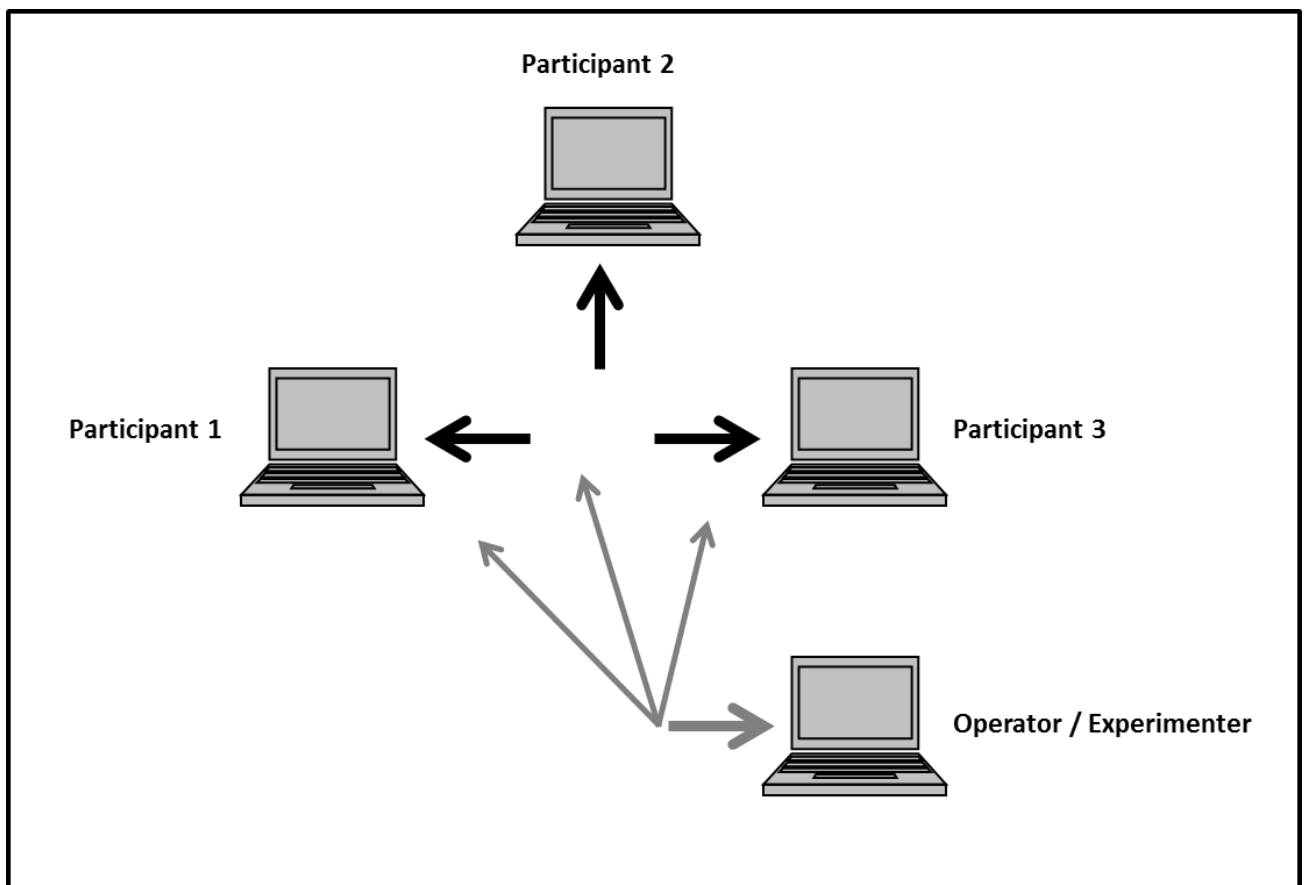
The screens had a video of the cars on the road as well as a chat window. The chat window was the only source of communication throughout the experiment. Each input into the chat window was preceded by the participant ID; this allowed the operator and other participants in the team to know who was talking. The observer was the experimenter in each experiment



**Figure 55 – Video display and chat window**

and provided feedback to the participants using the same chat window. The outputs from the chat window were exported in real time to a .csv file in a transcript format and stored the following data points for each message typed: participant ID, text from chat window message and the date and time stamp. At the beginning of each condition a new .csv file was created and stored in a specific folder in the experimenter's computer account, resulting in 3 files at the end of each experiment. Those files were collated resulting in one .csv file containing all the communication from each condition in the experiment.

The computer layout can be seen in Figure 56, the participants were arranged in such a way that they could not see each other's computer screens, however the operator was positioned so that they could see all computer screens if necessary. The experimental task was explained in



**Figure 56 – Layout of computers and participants**

the same manner and at the same time in each experiment and a crib sheet was also given to each participant for reference throughout the experiment.

#### **4.3.5 Concept Map Application**

In this chapter, concept maps were created manually using Microsoft PowerPoint, this method was time consuming and unscalable. Therefore, a concept map application was created using the NetLogo programming language which allows for the maps to be created automatically. As NetLogo has been used throughout this thesis it was an obvious choice for creating the application.

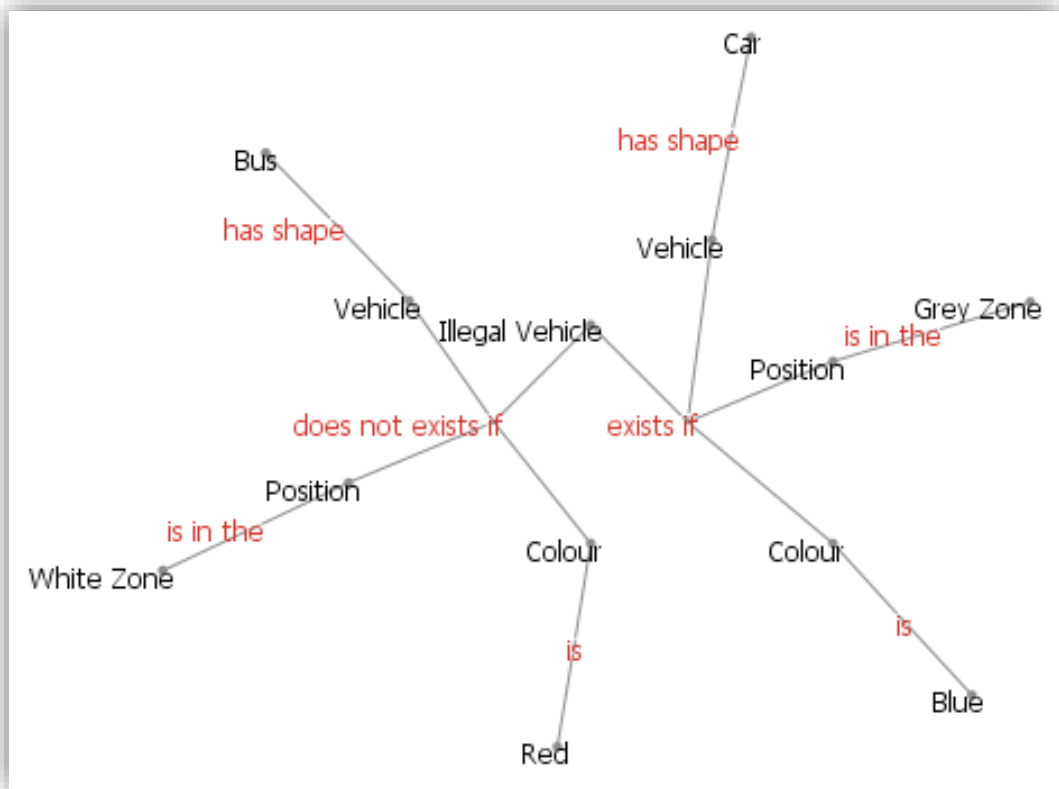
After reviewing the transcripts and messages exchanged between the team members in each team, the characteristics that were mentioned in relation to the vehicle were grouped into three concept categories; colour, position and shape. Each of the characteristics in these categories was used as the concepts within the map. In condition 2, the colour concepts of the vehicle could be either; <red>, <blue>, <grey>, <not red>, <not blue> or <not grey>, the position concepts could be either in the <grey zone>, in the <white zone>, in the <not grey zone> or in the <not white zone> and the shape concepts could be either a <bus>, <car>, <circle>, <square>, <not bus>, <not car>, <not circle> or <not square>. In condition 3 the colour concepts of the vehicle could be either <red>, <blue>, <not red> or <not blue>, the position concepts could be either in the <grey zone>, in the <white zone>, in the <not grey zone> or in the <not white zone> and the shape concepts could be either a <bus>, <car>, <not bus> or <not car>.

The construction of the maps consisted of nodes and links, arranged in a hierarchal tree structure, with the left side of the tree showing the concepts that are not classed as illegal and the right side showing the illegal concepts. The concept map application visualised the

concepts for the illegal and illegal vehicles in either condition 2 or condition 3 using propositions to connect them. For example, one branch of the concept map could read “Illegal vehicle exists if colour is red” with <red> being a concept, <colour> being a concept category and <exists if> and <is> being propositions. The program created 6 identical concept maps (for each condition) with the title Interval 1 through to Interval 6 at the top of each map, identifying which interval of information the map was showing.

Due to the information used in the concept map application deriving from a manual post hoc analysis of the communication transcripts, the setup of the concept maps were programmed manually meaning that maps used in this chapter could also be used in chapter 5 with no additional programming, setup or analysis. These maps can be seen in Figure 57, the yellow areas highlight the difference in the two maps.

## Condition 2 Concept Map



## Condition 3 Concept Map

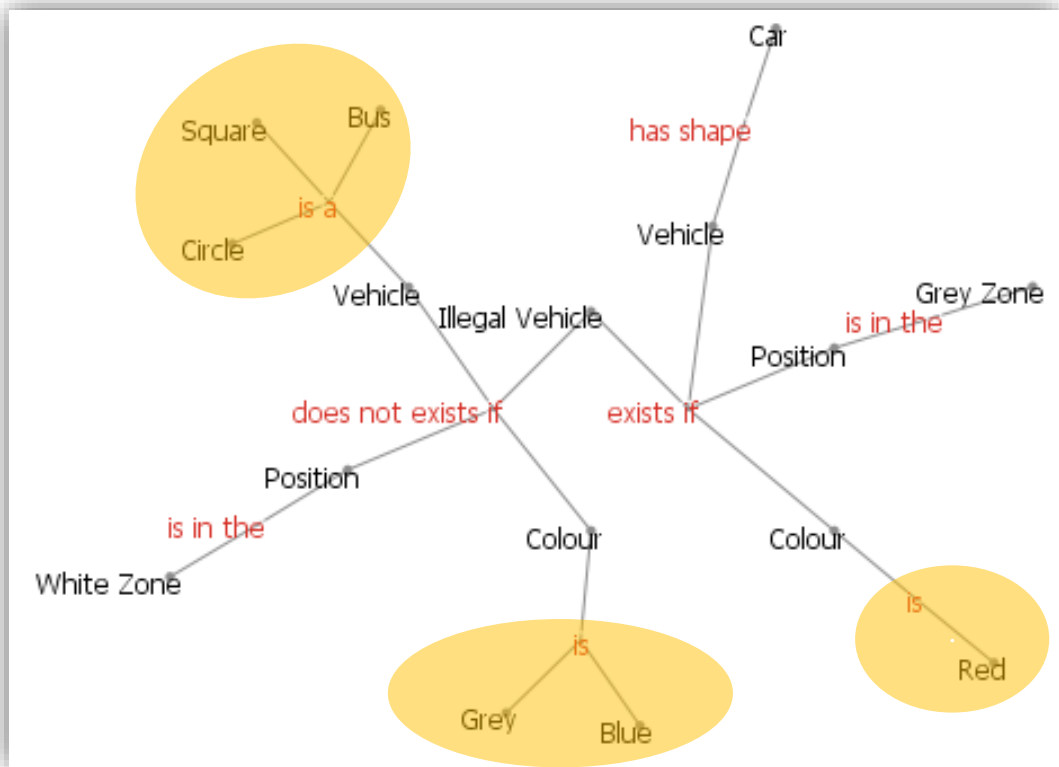


Figure 57 – Concept maps of condition 2 and 3 created using data from the transcript analysis

#### 4.3.6 Experimental tasks

In the experiment, there was a practice condition (condition 1) in which participants had Common Displays, an experimental condition (condition 2) in which participants had Separate Displays, and a repetition of the practice condition (condition 3) (although it was decided to introduce a slight variation in this third condition by adjusting the rules so that the team still needed to discover these rather than simply recall what they had done in the first condition). The practice condition (condition 1) provided an opportunity for participants to become familiar with the displays, the instant messaging and the concept of defining rules for illegal vehicles.

In the practice condition (condition 1), the display shows cars and buses in six lanes. The vehicles moved from one side of the screen to the other at different speeds and were coloured red or blue. Figure 53 shows this display. There is also a grey line which represented the toll area. In order to identify an illegal vehicle participants had to identify it as a <car> that was <blue> and <in the grey zone>. This results in a correct answer which involves three elements and the team needed to identify all three elements for a successful target detection. Each participant had their own individual computer screen in each condition, with either common or different displays depending on the experimental condition.

Condition 2 presented each participant with a different display. While the displays had lanes and objects across the screen, each display showed different features (Figure 54). Thus, one participant saw coloured squares, another saw grey circles and the grey line, the third saw grey vehicles. This meant that the correct answer had to be arrived at through combining the colour from one participant, the grey zone from another, and the vehicle shape from the third. Condition 3 presented all participants with the same view (as in the practice condition (condition 1)) but used a different set of rules. The objects were synchronised with each other

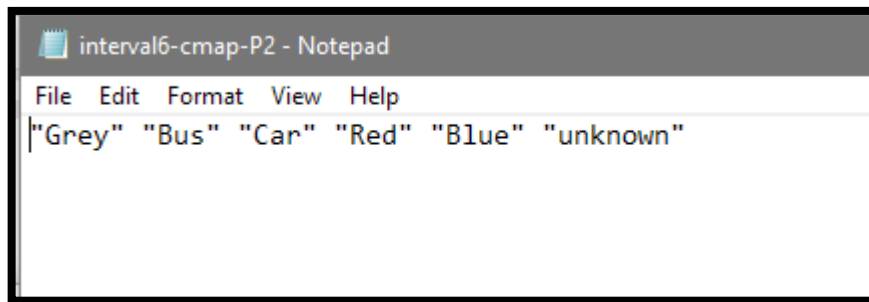
on all displays, so that the participants saw the objects in the same position on each display regardless of the objects characteristics.

### 4.3.7 Creating Concept Maps from Participant Messages

To overlay the knowledge of each participant in the experiment the transcripts of messages they sent were analysed post-hoc by the lead author. The video duration (6 minutes 42 seconds) was divided by 6 to generate the interval time (every 1 minute 7 seconds). The content of messages sent by a participant was coded using the concept categories for legal vehicles (e.g. <blue>, <not red>, <grey zone>) for each block of 1 minute and 7 seconds, by

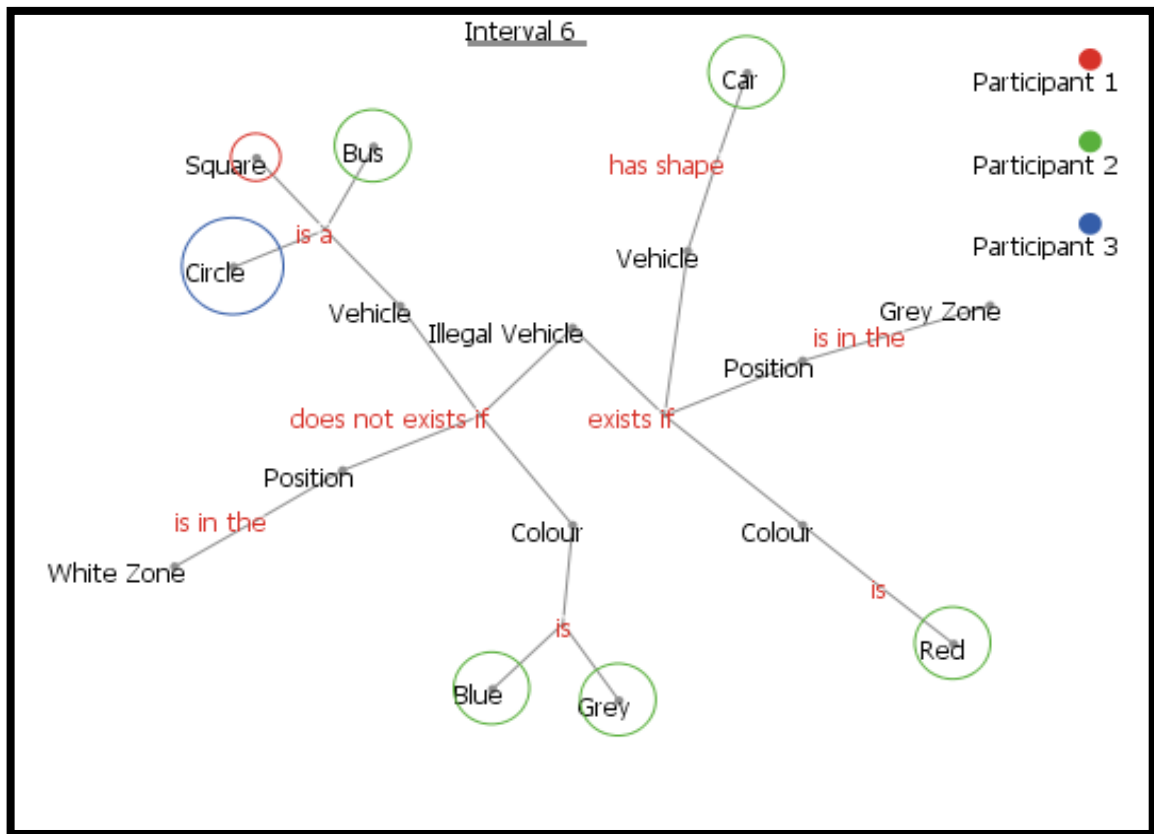
	A	B	D
1	Group 6		
2			
3	Condition 1		
4	VIDEO STAR	Tue Mar 17 2015 10:52:14 GMT+0000 (GMT Standard Time)	
5	Condition 2		
6	VIDEO STAR	Tue Mar 17 2015 11:00:04 GMT+0000 (GMT Standard Time)	
7	Condition 3		
8	VIDEO STAR	Tue Mar 17 2015 11:07:24 GMT+0000 (GMT Standard Time)	
9			
10	Condition 1		
11	operator2	hi	Tue Mar 17 2015 10:51:13 GMT+0000 (GMT Standard Time)
12	operator3	boysw	Tue Mar 17 2015 10:51:20 GMT+0000 (GMT Standard Time)
13	operator1	hey m9	Tue Mar 17 2015 10:51:21 GMT+0000 (GMT Standard Time)
14	operator2	busy road lol	Tue Mar 17 2015 10:51:36 GMT+0000 (GMT Standard Time)
15	operator3	road is clear	Tue Mar 17 2015 10:51:39 GMT+0000 (GMT Standard Time)
16	operator2	where the traffic	Tue Mar 17 2015 10:51:55 GMT+0000 (GMT Standard Time)
17	operator3	blue buses look dodgy	Tue Mar 17 2015 10:52:42 GMT+0000 (GMT Standard Time)
18	operator2	i think blue in genral is a very suspicious colour	Tue Mar 17 2015 10:52:58 GMT+0000 (GMT Standard Time)
19	operator1	ok guuys	Tue Mar 17 2015 10:53:16 GMT+0000 (GMT Standard Time)
20	operator2	the illegal vechile is a blue bus	Tue Mar 17 2015 10:53:28 GMT+0000 (GMT Standard Time)
21	OBSERVER	The illegal vehicle is not a blue bus	Tue Mar 17 2015 10:53:44 GMT+0000 (GMT Standard Time)
22	operator1	damn	Tue Mar 17 2015 10:53:49 GMT+0000 (GMT Standard Time)
23	operator1	though we had her	Tue Mar 17 2015 10:53:52 GMT+0000 (GMT Standard Time)
24	operator3	then it's either the red or the blue car	Tue Mar 17 2015 10:54:12 GMT+0000 (GMT Standard Time)
25	operator1	the illegal vehicle is a red car	Tue Mar 17 2015 10:54:17 GMT+0000 (GMT Standard Time)
26	operator2	so far i have just seen red and blue cars and blue bus..what about you guys?	Tue Mar 17 2015 10:54:22 GMT+0000 (GMT Standard Time)
27	operator1	same here	Tue Mar 17 2015 10:54:28 GMT+0000 (GMT Standard Time)
28	operator3	same	Tue Mar 17 2015 10:54:28 GMT+0000 (GMT Standard Time)
29	operator3	the illegal vehicle is a blue car?	Tue Mar 17 2015 10:54:44 GMT+0000 (GMT Standard Time)
30	OBSERVER	The illegal vehicle is red $18 - 6 = 12$	Tue Mar 17 2015 10:54:46 GMT+0000 (GMT Standard Time)
31	operator2	wooooo	Tue Mar 17 2015 10:54:52 GMT+0000 (GMT Standard Time)
32	OBSERVER	The illegal vehicle is a car $19 - 6 = 13$	Tue Mar 17 2015 10:54:53 GMT+0000 (GMT Standard Time)
33	operator3	WINNNNNER	Tue Mar 17 2015 10:54:55 GMT+0000 (GMT Standard Time)
34	operator1	yea boys	Tue Mar 17 2015 10:55:01 GMT+0000 (GMT Standard Time)
35	operator1	so now we just need to figure out the colour of the illegal car?	Tue Mar 17 2015 10:55:22 GMT+0000 (GMT Standard Time)
36	operator2	what sort of car..im calling vauxhall corsa	Tue Mar 17 2015 10:55:30 GMT+0000 (GMT Standard Time)
37	operator3	JUST SAW A RED BUS	Tue Mar 17 2015 10:56:07 GMT+0000 (GMT Standard Time)
38	operator1	me too	Tue Mar 17 2015 10:56:12 GMT+0000 (GMT Standard Time)
39	operator1	speeding?	Tue Mar 17 2015 10:56:21 GMT+0000 (GMT Standard Time)
40	OBSERVER	Reminder - There are multiple characteristics for the illegal vehicles.	Tue Mar 17 2015 10:56:25 GMT+0000 (GMT Standard Time)
41	operator2	does the illegal vechile have 2 wheels?	Tue Mar 17 2015 10:56:28 GMT+0000 (GMT Standard Time)
42	operator3	that's irrelevant actually cause the illegal one is a car right?	Tue Mar 17 2015 10:56:37 GMT+0000 (GMT Standard Time)
43	operator2	yeah	Tue Mar 17 2015 10:56:49 GMT+0000 (GMT Standard Time)

Figure 58 - Example of one of the raw transcript files for group 6



**Figure 59 - A .txt file of knowledge from group 6**

referring to the time stamp next to each message in the transcript. A text document (.txt) was created in Notepad for each participant for each time interval; a total of 18 .txt files per condition. Figure 58 - Example of one of the raw transcript files for group 6 shows an example of one of the raw transcript files for group 6 and Figure 59 - A .txt file of knowledge from group 6 shows a .txt file of knowledge from the same transcript at time interval 6 for participant 2. The knowledge of each participant was manually entered into these text files in a format that could be imported into the concept map application. The concept program contained three nodes which represented the participants in the study. When the text file was imported into the program, the information for each participant was stored in each participant node. A coloured ring which represents one of these nodes circles a concept if at that interval that participant is holding that particular bit of information. For example, if participant 2 knows that the illegal vehicle is red and participant 2 is represented by a small green ring, a small green ring will be applied over the concept <red> in the concept map (see Figure 60 – Concept map using knowledge extracted from the group 6 transcripts).



**Figure 60 – Concept map using knowledge extracted from the group 6 transcripts**

#### 4.3.8 Data Analysed

Three variables were obtained from the experiment:

- Number of identified characteristics
- Number of comments
- Participant knowledge

The number of identified characteristics were identified via post-hoc analysis of the communication transcripts. Each time the observer (i.e. the experimenter) confirmed an illegal characteristic following the phrase “*The illegal vehicle is...*” made by one of the participants it was considered identified by the group. The communication transcripts also allowed for the number of comments to be counted for each condition and the content of the transcripts

allowed for the knowledge of the participants to be recorded. When a participant used the phrase “*The illegal vehicle is...*” and the observer (i.e. the experimenter) provided a response that participant was considered to have that knowledge. For example, if the participant said, “*The illegal vehicle is a car*” and the observer replied with “*Correct, the illegal vehicle is a car*” it was assumed that the participant had the knowledge that the illegal vehicle had the shape of a car. Similarly, if the participant said, “*The illegal vehicle is a blue*” and the observer replied with “*Incorrect, the illegal vehicle is not blue*” it was assumed that the participant had the knowledge that the illegal vehicle was not blue in colour.

#### **4.4 RESULTS**

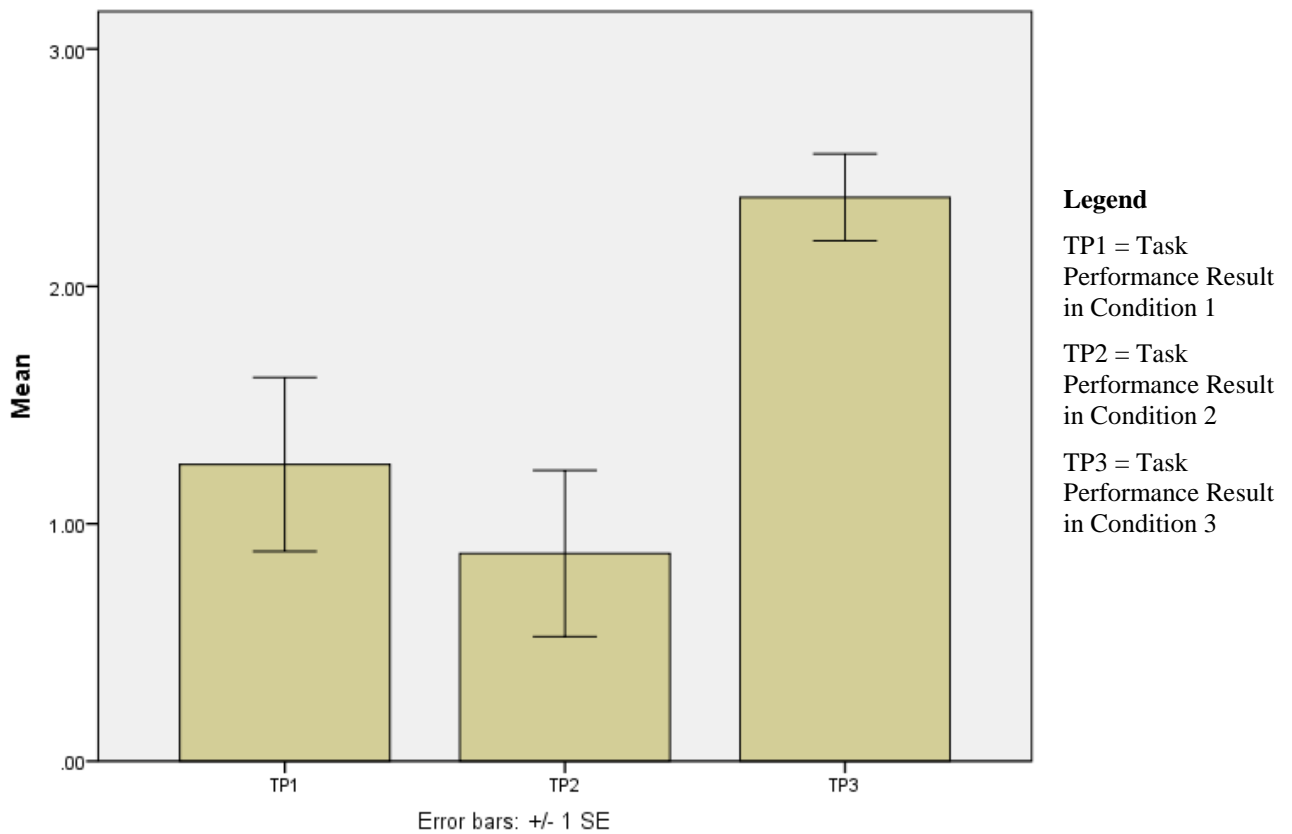
Following initial review of the results, it was apparent that team 1 had failed to complete the task in any of the conditions, i.e., they failed to mention any of the concept categories in their messages. This data was excluded from the analysis because it was clear that they were not following the experiment instructions, therefore the data from the remaining eight teams were used. A combination of quantitative analysis, using SPSS V23, and qualitative analysis of the results was carried out on the data obtained from these eight teams. Results presented are:

- Performance
- Total comments
- Task relevant comments
  - Task relevant comments are the comments pertaining to the task and exclude any miscellaneous utterances.
- Total comments against performance
- Task relevant comments against performance
- Qualitative comparison of high and low performance teams

#### 4.4.1 Performance

The tests for normal distribution can be found in Appendix H & Appendix I and show that the performance data was not parametric. Therefore, a Friedman test was conducted to compare the performance over each of the three conditions. As there was a statistically significant differences between group means as determined by the Friedman test ( $\chi^2(2) = 11.217, p = 0.004$ ) a post-hoc Wilcoxon Signed Ranks Test was conducted to compare the results further, the results of which can be seen in Figure 61 and the statistical results for the Friedman test and post-hoc Wilcoxon Signed Ranks Test can be found in Appendix J and Appendix K, respectively. There was a not a significant difference in the scores for condition 1 and condition 2; ( $Z = -1.089, p > 0.05$ ). However, there was a significant difference in the scores for condition 1 and condition 3; ( $Z = -2.251, p = 0.024$ ) and for condition 2 and condition 3;

*Comparison of Mean Performance Over the Three Experimental Conditions*



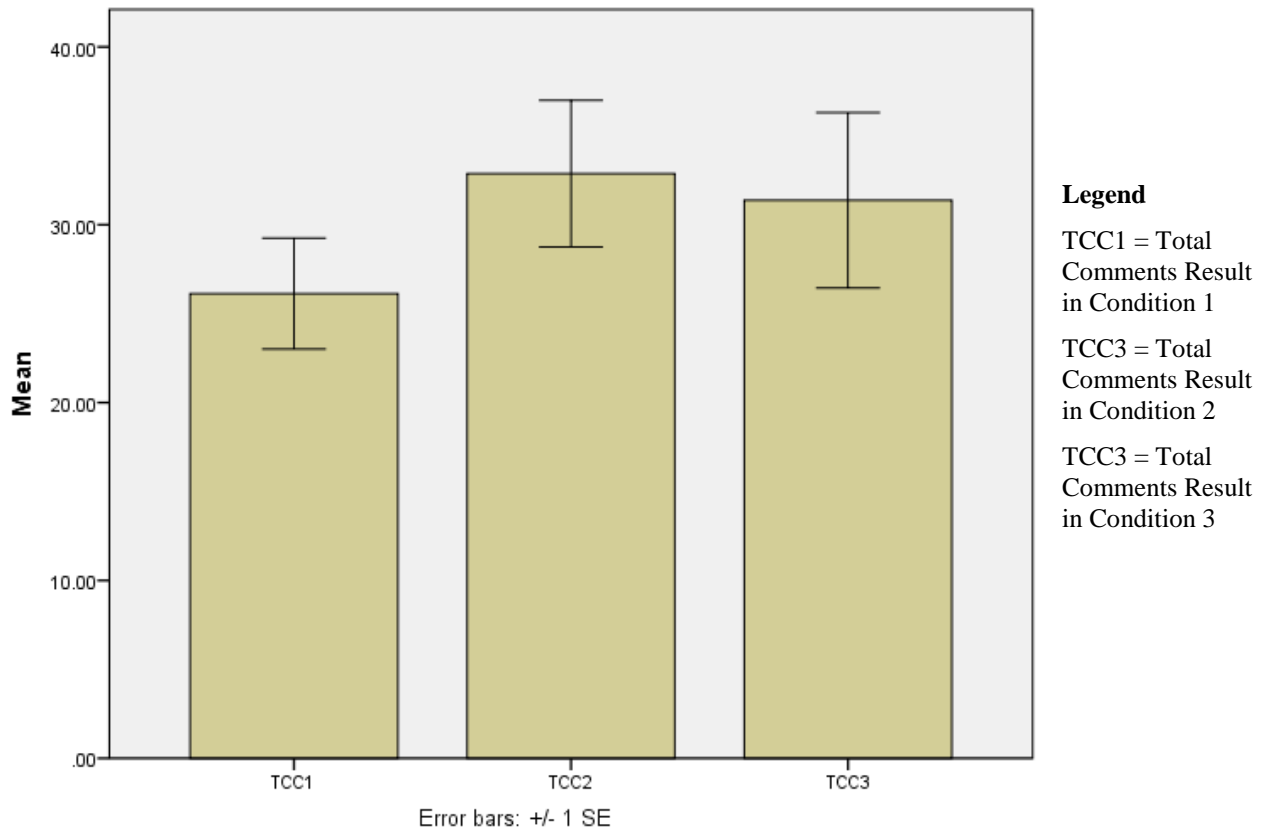
**Figure 61 - Comparison of Mean Performance Over the Three Experimental Conditions**

( $Z = -2.401$ ,  $p = 0.016$ ). The results here suggest a learning effect took place over the three conditions, with there being no significant decrease in scores between condition 1 and 2 but an increase between 1 and 3.

#### 4.4.2 Total Comments

The tests for normal distribution can be found in Appendix L & Appendix M and show that the performance data was parametric. Therefore, a one-way ANOVA was conducted to compare the total comments over each of the three conditions, the results of which can be seen in Figure 62 and the statistical results can be found in Appendix N. There were no statistically significant differences between group means as determined by the one-way ANOVA ( $F(2,21) = 0.74$ ,  $p = 0.490$ ) and therefore no post-hoc analysis was conducted.

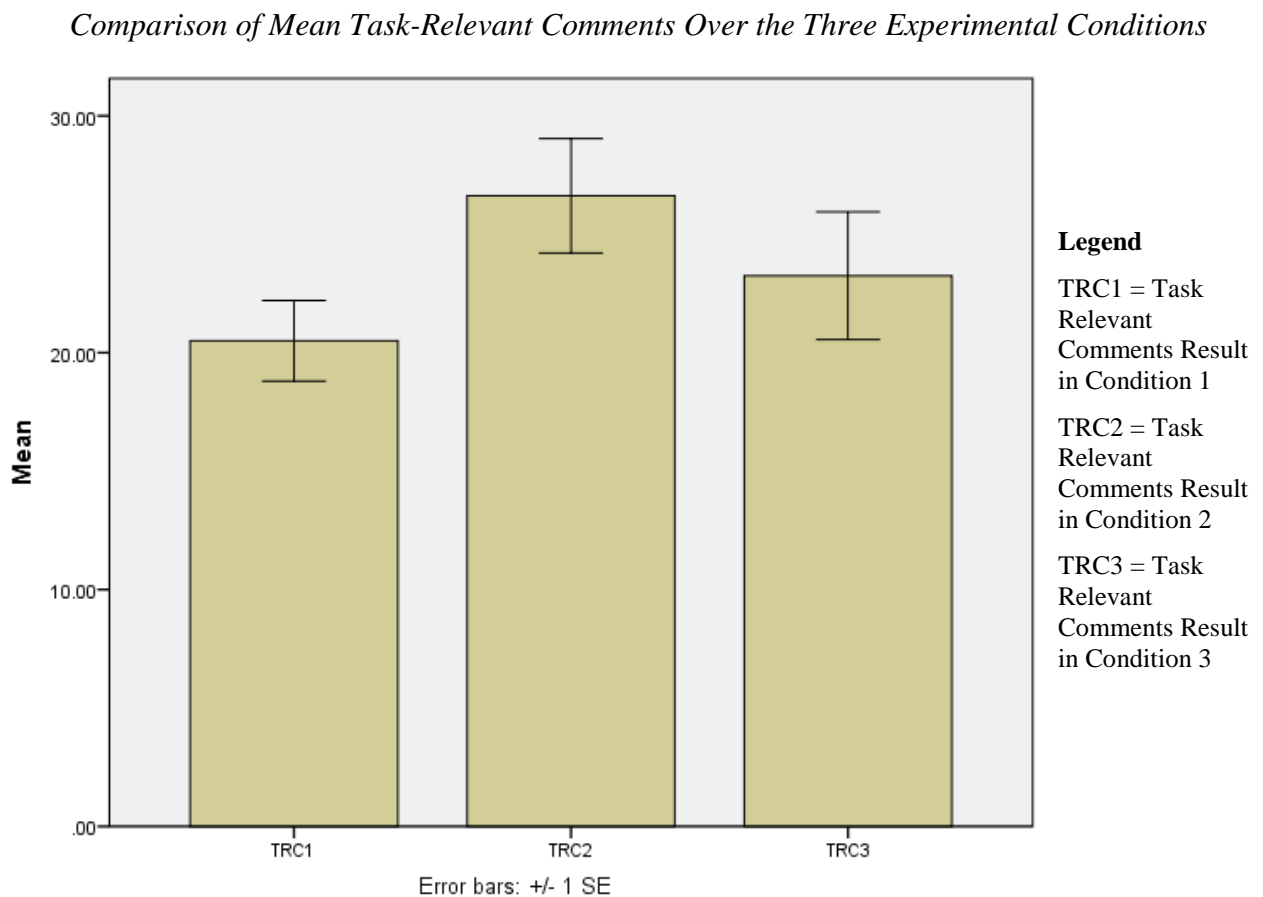
*Comparison of Mean Overall Comments Over the Three Experimental Conditions*



**Figure 62 - Comparison of Mean Overall Comments Over the Three Experimental Conditions**

### 4.4.3 Task Relevant comments

The tests for normal distribution can be found in Appendix O & Appendix P and show that the performance data was parametric. Therefore, a one-way ANOVA was conducted to compare the task relevant comments over each of the three conditions, the results of which can be seen in Figure 63 and the statistical results can be found in Appendix Q. There were no statistically significant differences between group means as determined by the one-way ANOVA ( $F(2,21) = 1.77, p = 0.196$ ) and therefore no post-hoc analysis was conducted.



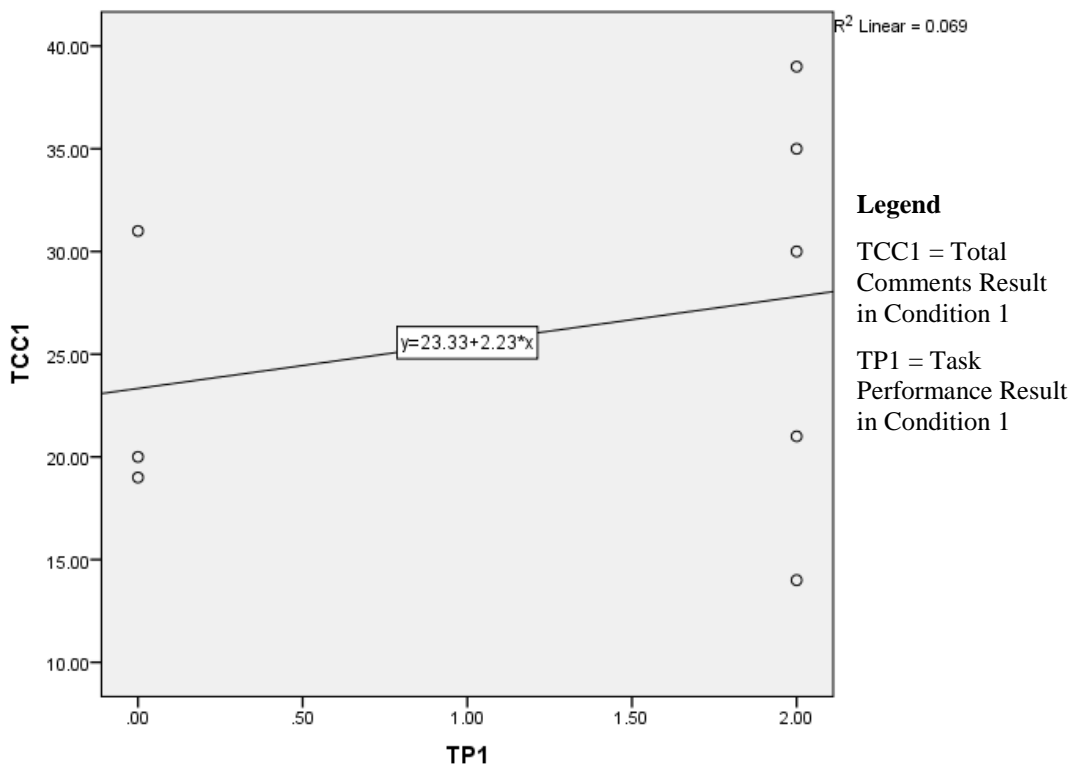
**Figure 63 - Comparison of Mean Task-Relevant Comments Over the Three Experimental Conditions**

#### 4.4.4 Comments against performance

##### 4.4.4.1 Total Comments Made

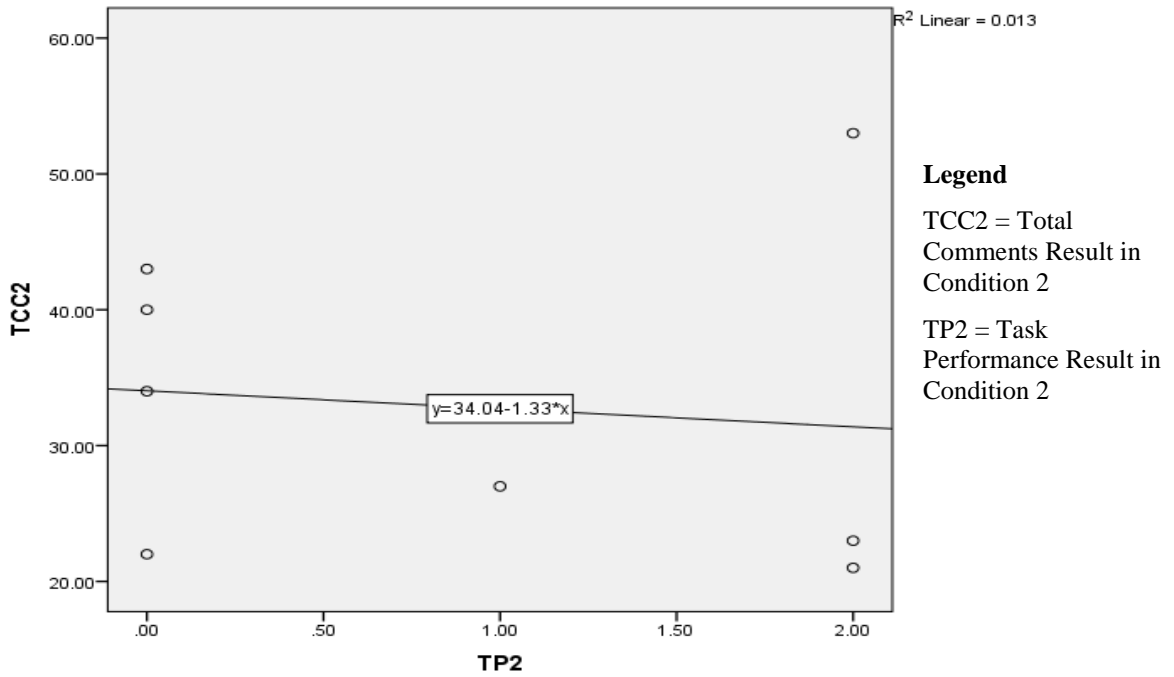
A Pearson product-moment correlation coefficient was computed to assess the relationship between the team performance scores and the comments made for each condition. The results of which can be seen in Figure 64, Figure 65 & Figure 66 and the statistical results can be found in Appendix R. The analysis showed that there was no correlation between the team performance scores and the total number of comments made in any of the three conditions; Condition 1:  $r = 0.262$ ,  $n = 8$ ,  $p = 0.531$ , Condition 2:  $r = -0.113$ ,  $n = 8$ ,  $p = 0.790$ , Condition 3:  $r = 0.295$ ,  $n = 8$ ,  $p = 0.497$ .

*Relationship Between Overall Comments and Performance for Condition 1*



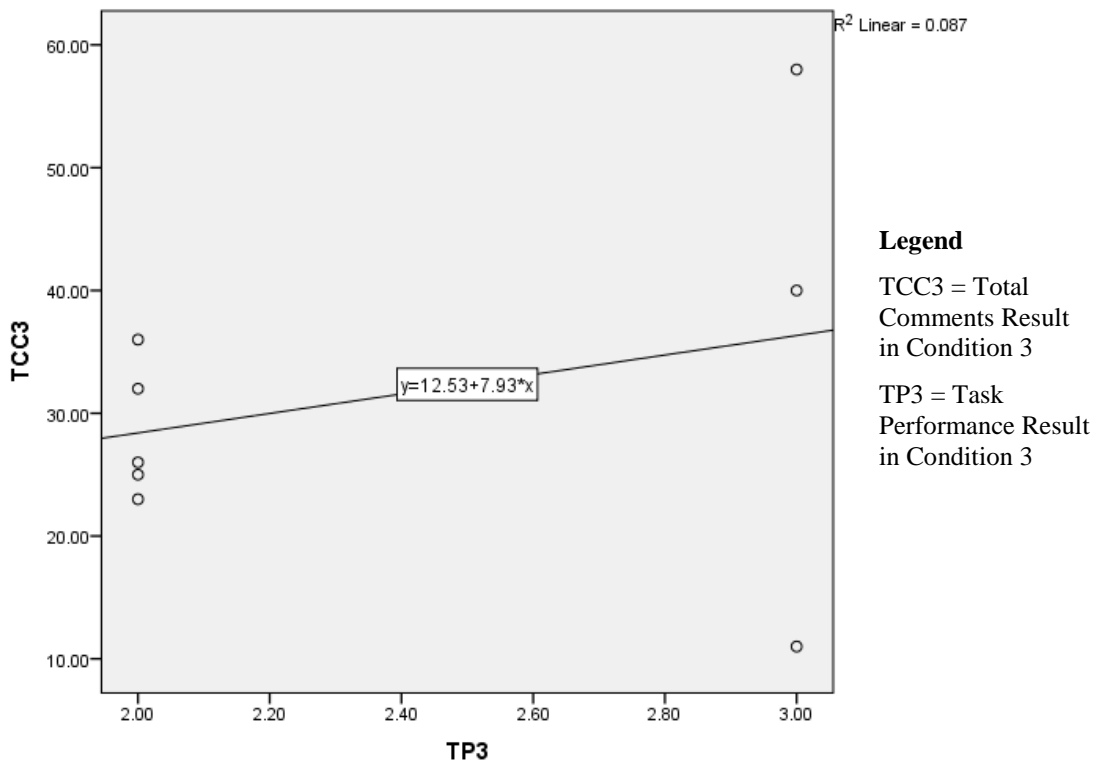
**Figure 64 - Relationship Between Overall Comments and Performance for Condition 1**

*Relationship Between Overall Comments and Performance for Condition 2*



**Figure 65 - Relationship Between Overall Comments and Performance for Condition 2**

*Relationship Between Overall Comments and Performance for Condition 3*

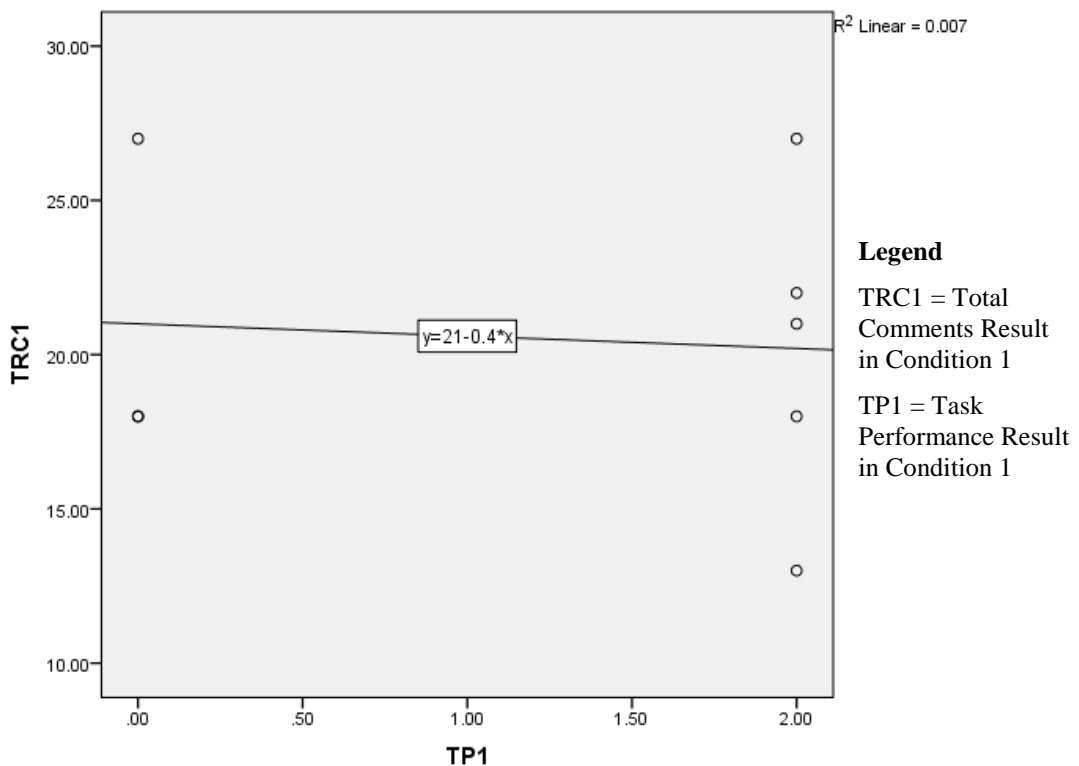


**Figure 66 - Relationship Between Overall Comments and Performance for Condition 3**

#### 4.4.4.2 Task Relevant Comments

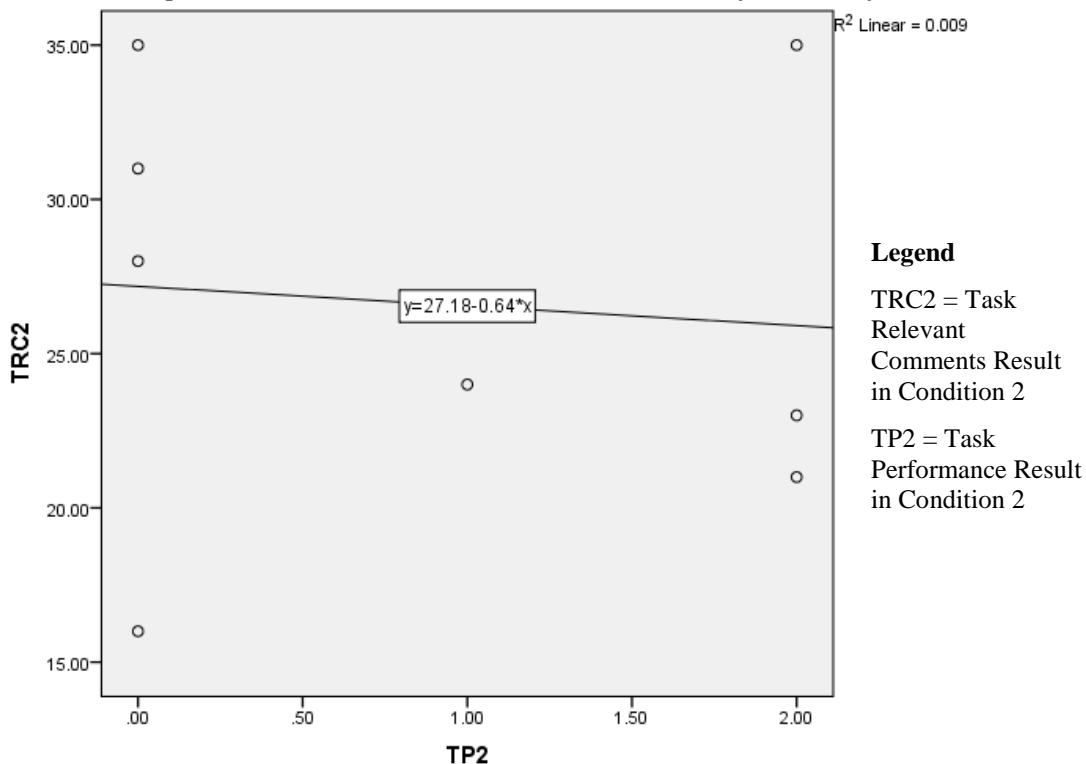
A Pearson product-moment correlation coefficient was computed to assess the relationship between the team performance scores and the number of task relevant comments made for each condition. The results of which can be seen in Figure 67, Figure 69 & Figure 68 and the statistical results can be found in Appendix S. There was no correlation between the team performance scores and the number of task relevant comments made in any of the three conditions; Condition 1:  $r = -0.086$ ,  $n = 8$ ,  $p = 0.839$ , Condition 2:  $r = -0.092$ ,  $n = 8$ ,  $p = 0.828$ , Condition 3:  $r = -0.244$ ,  $n = 8$ ,  $p = 0.560$ .

*Relationship Between Task Relevant Comments and Performance for Condition 1*



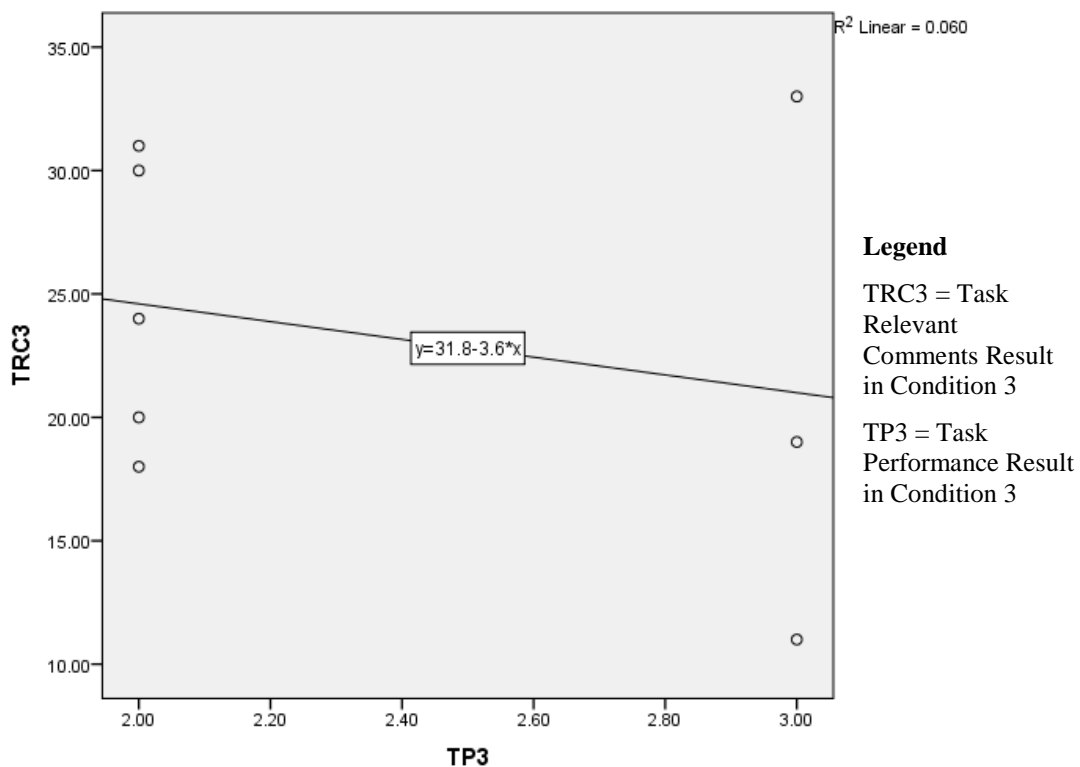
**Figure 67 - Relationship Between Task Relevant Comments and Performance for Condition 1**

*Relationship Between Task Relevant Comments and Performance for Condition 2*



**Figure 69 - Relationship Between Task Relevant Comments and Performance for Condition 2**

*Relationship Between Task Relevant Comments and Performance for Condition 3*



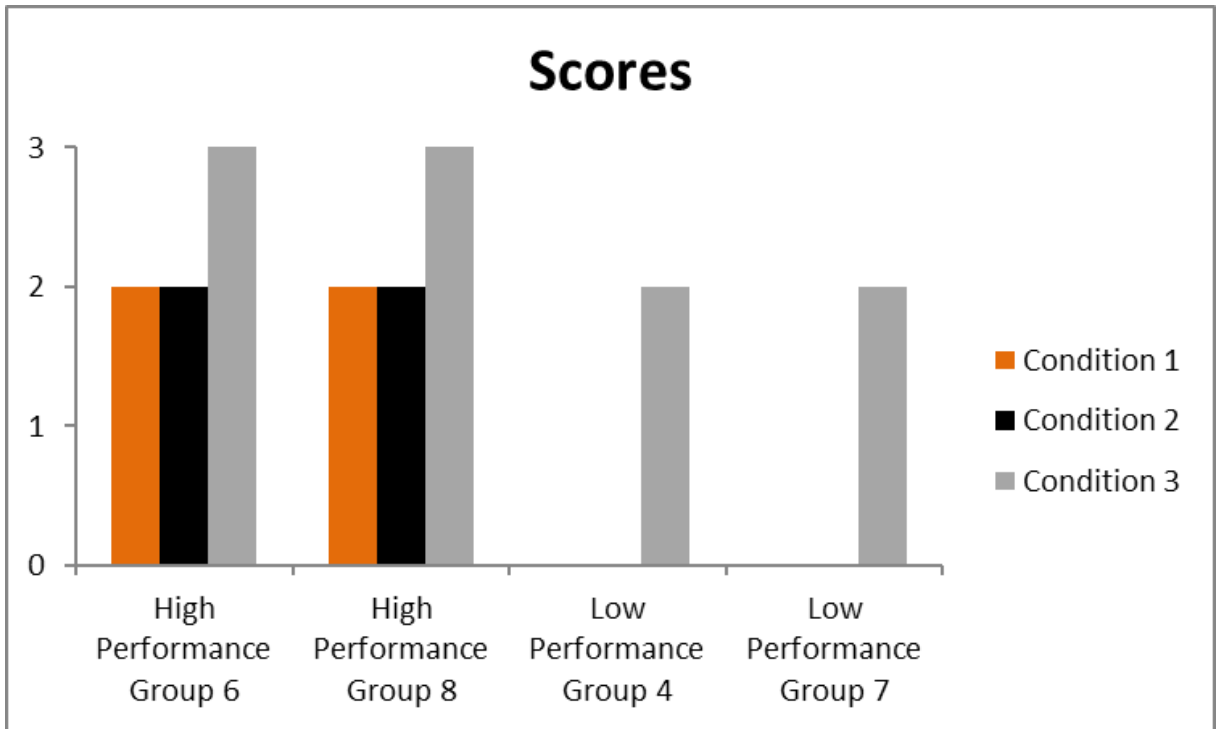
**Figure 68 - Relationship Between Task Relevant Comments and Performance for Condition 3**

#### **4.4.5 Comparing Scores for High and Low Performance Teams**

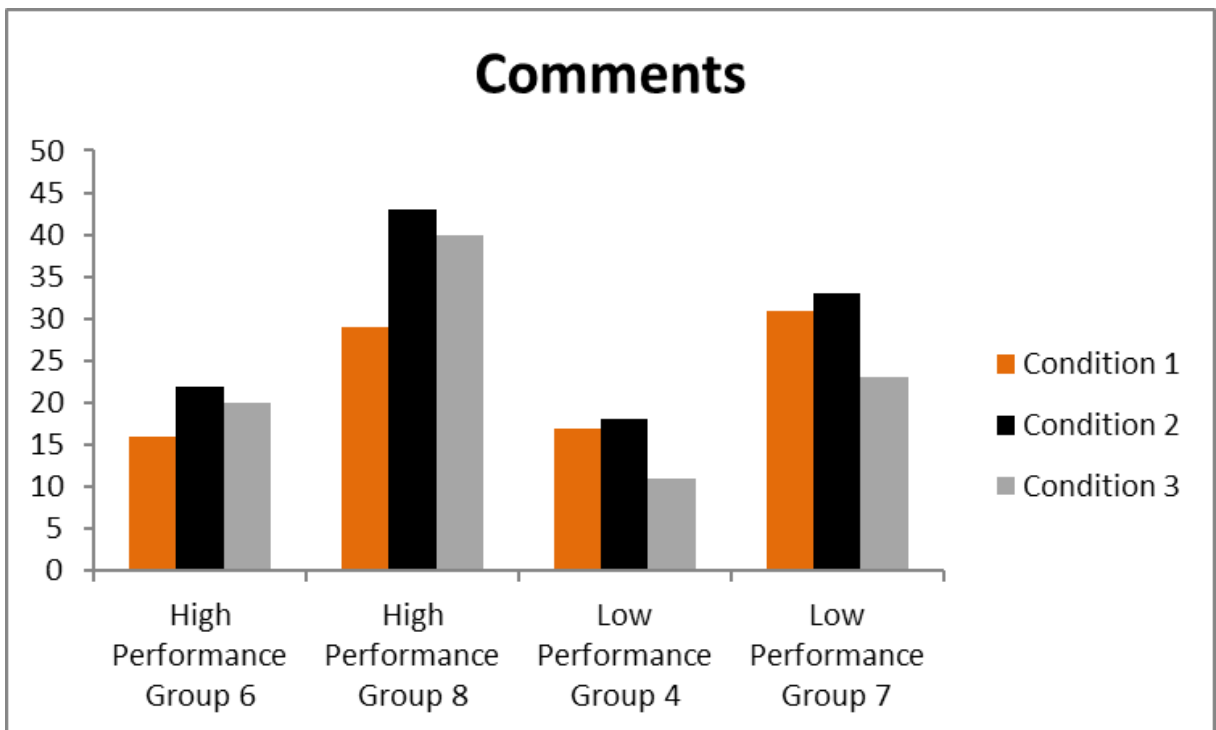
By taking the average number of characteristics identified for each team over the 3 conditions (4.5) along with the standard deviation (2.07), a high performing team was classified as having a score of 6.57 (average plus the standard deviation) or above and a low performing team would be classified as having a score less than 2.43 (average minus the standard deviation). On these criteria, teams 6 and 8 were classed as high performing and teams 4 and 7 were classed as low performing. The comments and scores of the high and low performing teams were compared.

No statistical inference could be made on these results due to only 4 teams being analysed, however some qualitative observations can be presented. Figure 70 shows the scores achieved for the teams for conditions 1, 2 and 3. First it can be seen that both of the low performance teams were unable to identify any characteristics in condition 2 where both of the high performance teams were able to identify 2 out of the maximum 3 characteristics. Note also that both of the high performance teams were able to identify all 3 of the characteristics required in condition 3.

Comparing the comments made (Figure 71), it can be seen that the high performing teams exhibit similar patterns in both conditions. Team 6 had around 20 comments in both conditions, team 8 had around 40 comments in both conditions. While these differ between team, each team seems to have a consistent approach to the task. In contrast, the low performing teams have lower numbers of comments in condition 3 (even if they have different total numbers of comments). This implies a change in approach from the two conditions. It is interesting to note that the low performance teams made more comments in the Separate Displays condition.



**Figure 70 - Comparison of scores between high performing and low performing groups**



**Figure 71 – Comparison of comments made between high performing and low performing groups**

#### **4.4.6 Review of high and low performing teams' transcript content**

The transcript for team 4, a low performing team, in condition 2 (see Figure 72 – Team 4 transcript for condition 2 and 3) reveals that there was a high concentration of communication about what could be seen on their individual screens with an emphasis on sharing information. However, none of the team members attempted to identify a characteristic of an illegal vehicle. This implies emphasis on achieving common ground for the task rather than actually performing the task. This emphasis on sharing information was replicated in condition 3. The content of the messages gave no indication that the team members knew each other before the experiment. This team attempted to create their own vocabulary, using words such as “Op 1” which replaced “Operator 1”. A review of the transcript for team 7 (also a low performing team) revealed a similar approach to the task, having an emphasis on sharing what they could see. Again, this can be said for both condition 2 and condition 3. The messages gave no impression that the team members knew each other before the experiment. This team did not attempt to create their own vocabulary.

In contrast, the transcript for team 6, a high performing team, (see Figure 73 & Figure 74) shows team members, for both condition 2 and condition 3, working independently and attempting to identify characteristics before conversing with the other team members. The messages were friendly and gave the impression that these team members knew each other. This team attempted to create their own vocabulary, using words such as “IV” which replaced “illegal vehicle”. Team 8's transcript (also high performing) showed the same emphasis on working independently with no comments showing an attempt to share information in condition 3, and minimal attempts in condition 2. The conversation gave no impression that the team members knew each other before the experiment and they did not attempt to create their own vocabulary.

## Team 4 Transcripts

Condition 2	Condition 3
operator3 operator1	operator1 operator3
3 dual lanes not middle partition no grey line in centre	3 dual lanes, grey partician 3/4 left 3 dual lanes, grey reservation 3/4 left
operator1	operator2
Op 2 same?	Same set up, partition now 3/4 left, same width, back to red and blue vehicles
operator2 operator3	operator1 operator3
Same set up, central block shifted to right all vehicles grey	red and blue cars red and blue cars
operator1	operator2
Op 2 has different display	I have busses also
operator1	operator3
I have three dual lanes no partition	buses also]
operator3	operator1
same as op 1	top lane left to right, bottom right to left
operator1	operator1
cars are now blocks	buses as well
operator1	operator3
Red and blue	same
operator2	operator2
I have grey circles	Rgr
operator1	operator3
w here?	middle lane now slower
operator3	operator1
same cars and buses from before, all grey	ok i think the 2 vehicle rule may be true
operator1	operator1
Cars all grey?	red illegal vehical
operator2	operator2
My central partition is 3/4 to right, same width as previous	It might be two vehicles of same colour in the partition at a time
operator3	operator1
yes	entered middle lane with two vehicles already present
operator1	OBSERVER
w here are the circles Op 3?	No - the illegal vehicle is not red
operator3	operator1
no circles	illegal vehicle is blue bus
operator1	OBSERVER
sorry Op 2	Yes - the illegal vehicle is a blue bus
operator2	operator2
Might be worth counting how many get into partition area at the same time?	Why??
operator3	OBSERVER
op 2 are all vehicles now circle?	Reminder: there are multiple conditions for an illegal vehicle
operator1	operator1
roger	illegal vehicle is blue car
operator2	operator2
Ye	Blue bus again
operator3	operator2
op 1 they are circles for you?	*illegal vehicle
operator1	operator1
so we have circle and square vehicles	*****OBSERVER: No - the illegal vehicle is not red*****
operator1	OBSERVER
?	No - the illegal vehicle is not a blue car.
operator2	operator1
Illegal vehical just left screen middle lane, bottom	it has to be blue
operator1	OBSERVER
no mine are square, colours red and blue	Reminder: Yes - the illegal vehicle is a blue bus
OBSERVER	
Information supplied not sufficient.	
operator1	
Op 1: square vehicles red and blue	
operator1	
Op2: circles vehicles grey	
operator1	
op 3:?	
operator3	
normal vehicles but all grey	
operator1	
Op 2 has partition 3/4 right?	
OBSERVER	
Reminder: there are multiple characteristics which make the vehicle illegal	
Pattern seems to be that it has max of 2 vehicles per partition at a time, and yes partition located theree4	

**Figure 72 – Team 4 transcript for condition 2 and 3**

## Team 6 Transcripts

Condition 2	Condition 3
operator2 w e meet again	operator2 hola
operator1 back on-the-line boyz	operator1 cant wait to get a sandwich IRL
operator3 let's catch these filthy criminals	operator2 road is clear
operator2 same road same goal	operator3 sandwich* lol
operator1 workin hard or hardly workin?	operator2 blue and red bastards again for me
operator1 what.	operator3 blue and red cars flying all over the shop
operator2 grey.....	operator3 blue bus spotted
operator3 curveball	operator2 bus has just arrived
operator3 the illegal vehicle is a grey circle	operator2 im behind 3
operator1 what kind of road is this??	operator3 red bus spotted
operator2 m25	operator2 is the iv a bus?
operator1 the illegal vehicle (IV) is a square?	operator1 i have red and blue cars and and a grey area (presumably a traffic collision hotspot) right of centre
operator2 is the vehicle a grey?	operator2 im the same as 1
operator2 is the vehicle a car?	operator3 my grey is left of centre
operator3 all i have is grey circles	operator3 a bit like my politics
operator2 ids the vehicle a bus?	operator1 sorry i was AFK for 2 secs
operator2 no way i have cars and buses	operator1 was messaging the gf
operator3 lots and lots of grey circles	operator1 you know how it is
operator1 i have squares!!!	operator2 im left of centre as well
OBSERVER The illegal vehicle is not grey	operator2 operator answer my q please
operator2 operator one come in	operator1 damn sass
operator3 trippy road	operator3 i think i just saw a blue bus go under the grey bit
operator1 Operator 2	operator2 observer*
OBSERVER The illegal vehicle is a car 22 - 6 =	operator2 focus!
operator2 i have cars and buses	operator3 is it the illegal one a blue bus?
OBSERVER The illegal vehicle is not a circle	OBSERVER The illegal vehicle is a blue bus
operator1 The IV is a square!!	operator2 w oooooooooooooo
OBSERVER The illegal vehicle is not a bus	operator3 YESSSSSS
operator3 ok my road is clear	operator1 YEAAA !!!
operator1 The IV is a square	operator1 thats just how we do
operator2 i havnt seen anything but grey stuff	operator1 he's going away for along time
operator1 i have red and blue squares	operator2 is the illegal vehicle heading east?
operator3 still just grey circles going back and forth and here :s :s xD	OBSERVER The direction of the vehicle is not relevant
operator2 is the illegal vehicle red?	operator2 damn
operator2 is the illegal vehicle blue?	operator1 blue bus over grey zone
OBSERVER The illegal vehicle is not red	operator2 is the illegal vehicle travelling too fast?
operator1 what connecting characteristics can we locate?	operator3 yeah i think i was just seeing things lol
operator2 wise ^	OBSERVER Correct! The illegal vehicle is a blue bus which is over the grey zone.
OBSERVER The illegal vehicle is blue 33 - 6 = 27	operator1 this job can do that to you
operator1 oh shush	operator3 oops
operator1 are any vehicles tailgating?	OBSERVER All characteristics have been identified
operator2 blue and and a car so far!	operator1 ah
operator1 The grey bit in the middle has gone for you guys too??	operator1 so we win?

**Figure 73 - Team 6 transcript for condition 2 and 3**

## Team 6 Transcripts continued

### Condition 2

### Condition 3

<p>operator1      sorry oddly w orderd questikon</p> <p>operator3      is my road meant to be just grey circles????? i'm freakin out</p> <p>operator2      i have seen none</p> <p>operator2      its a trip observer 3</p> <p>operator1      The illegal vehicle is a blue square</p> <p>operator3      my grey bit has moved to the right</p> <p>OBSERVER      The illegal vehicle is not a square</p> <p>operator1      mine has gone totally</p> <p>operator2      my road is so dull</p> <p>operator2      Does the illegal vechile have any mates?</p> <p>operator1      The ilegal vehicle is 'blue' as a concept</p> <p>operator1      w ho has a grey zone?</p> <p>OBSERVER      The illegal vehicle has friends, they are also illegal</p> <p>operator3      my road is way too law abiding</p> <p>operator1      i'm assuming thats the toll part of the bridge</p> <p>operator1      and we all have different sections of this bridge</p> <p>operator3      i have a grey zone</p> <p>operator1      its a gang</p> <p>operator1      w ho is op 3 IRL?</p> <p>operator2      is the IV a bus ?</p> <p>operator2      isaac is 2</p>	<p>operator2      w oooooooooooooooooooooooooooooooooooooo oo</p> <p>operator2      party</p> <p>operator1      I hate crime</p> <p>operator2      w e are the champions</p> <p>operator3      pmsl</p> <p>OBSERVER      You Win</p> <p>operator3      sorry</p> <p>operator2      observer 3 is well chuffed</p> <p>operator1      op 3 cool your engines</p> <p>operator1      that op 3 for ya</p> <p>operator3      can't control myself w hen i'm otk</p> <p>operator1      i w ant this job IRL</p> <p>operator3      afk i'm normal i sw ear</p> <p>operator1      otk? On the ket?</p> <p>operator2      cant w ait for fabios task</p> <p>operator3      any choomahs?</p> <p>operator3      i think i just saw one</p> <p>operator1      haha</p> <p>operator1      so how about that airplane food?</p> <p>operator3      can't w ait for next ep of TBLS</p>
---	--

**Figure 74 - Team 6 transcript for condition 2 and 3 continued...**

#### **4.4.7 Information Held within the Network**

To represent the knowledge held by each participant (in relation to the characteristics in the study) a circle of a different size and colour was allocated to that participant for each concept map (a set of 6 per condition, due to the recordings taking place over 6 intervals) and was applied to each bit of knowledge that that participant had at the given interval. Figure 75, Figure 76, Figure 77 & Figure 78 show examples of the interval concept maps results, however all results can be seen in Appendix T - Condition 2: Separate Display, Group 2 to Appendix AA - Condition 2: Separate Display, Group 9 for groups 2 to 9 in condition 2 and Appendix BB - Condition 3: Same Videos, Group 2 to Appendix II - Condition 3: Same Videos, Group 9 for groups 2 to 9 in condition 3. Due to the large performance difference between condition 2 and 3, only these conditions were compared. Each set of 6 concept maps represents the knowledge data for a given group over the course of the task.

In condition 2 (Appendix T - Condition 2: Separate Display, Group 2 to Appendix AA - Condition 2: Separate Display, Group 9) teams 2, 4, 5 and 7 showed either no team member knowledge or very little (e.g. one bit of knowledge for only one participant). In condition 3 (Appendix BB - Condition 3: Same Videos, Group 2 to Appendix II - Condition 3: Same Videos, Group 9) teams 4, 5 and 7 also showed no team member knowledge or very little, similar to that in condition 2. Team 9 showed that only one team member held information in both condition 2 and condition 3. For team 6, one of the team members can be seen to hold most of the information in condition 2. However, in condition 3, it is less apparent that a single team member is collating the information. Teams 3, 8 and 9 showed similar results to team 6.

## Group 6 – Condition 2

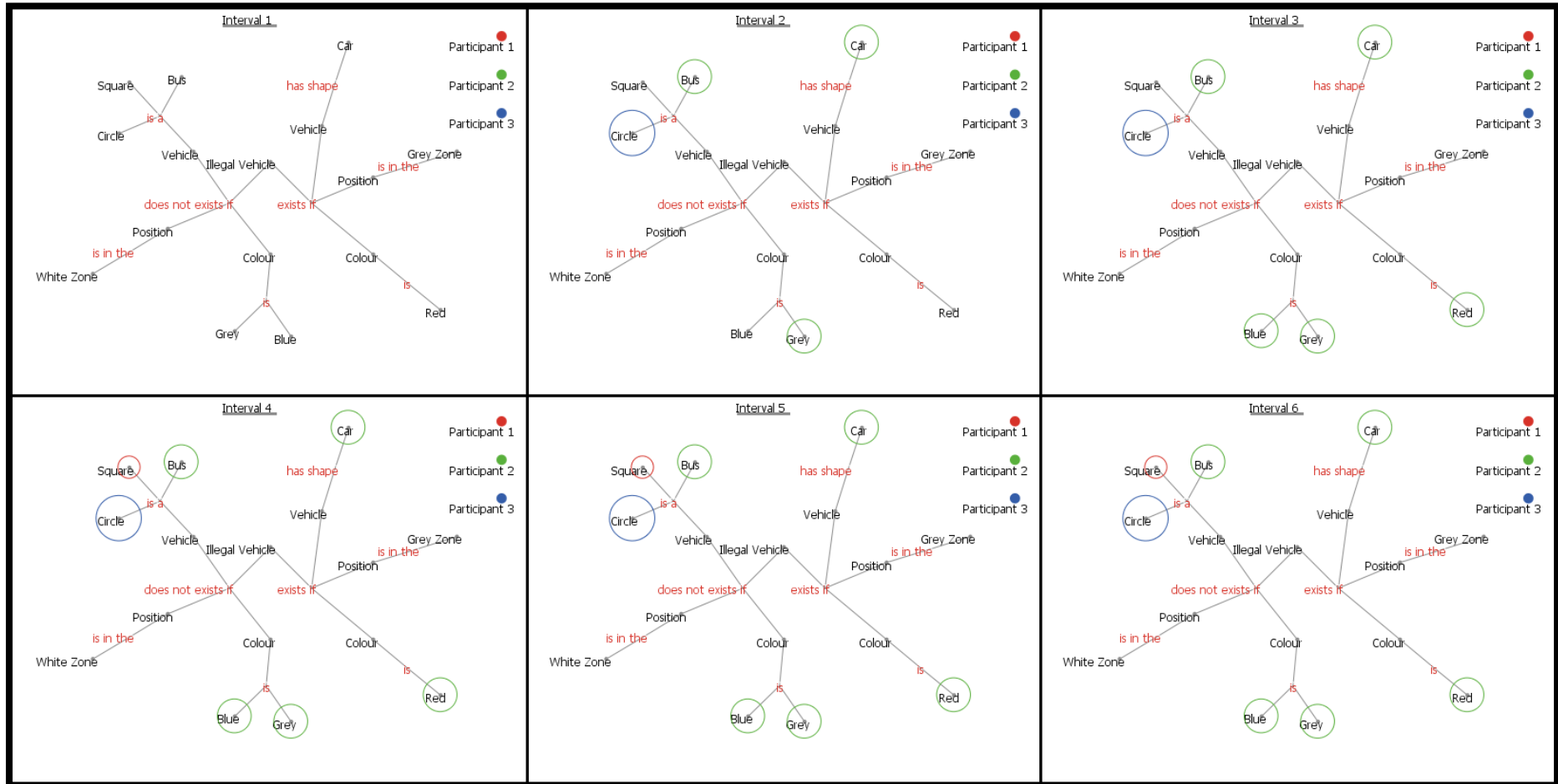


Figure 75 - Concept map example for Group 6 in Condition 2

## Group 8 – Condition 2

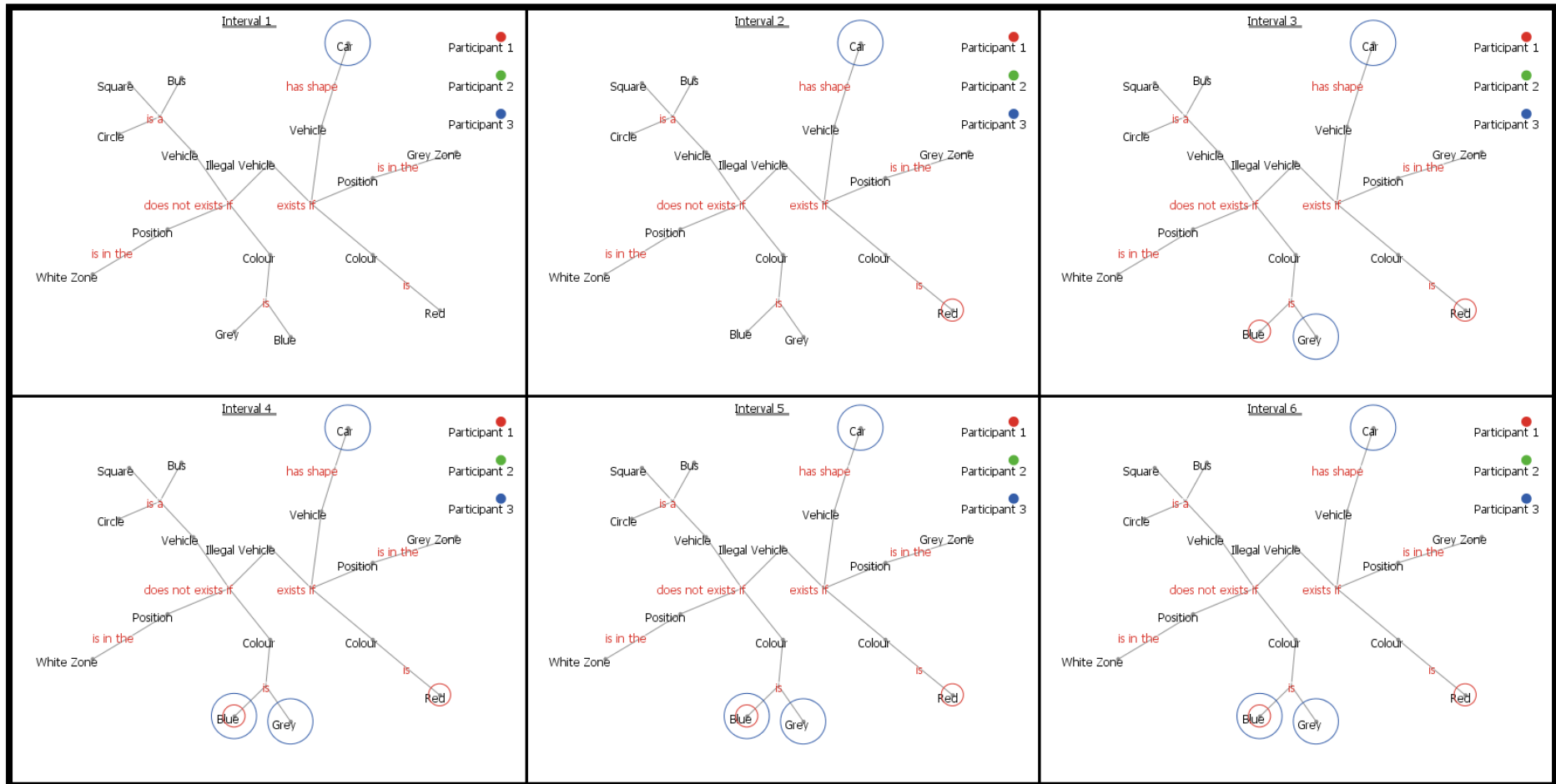
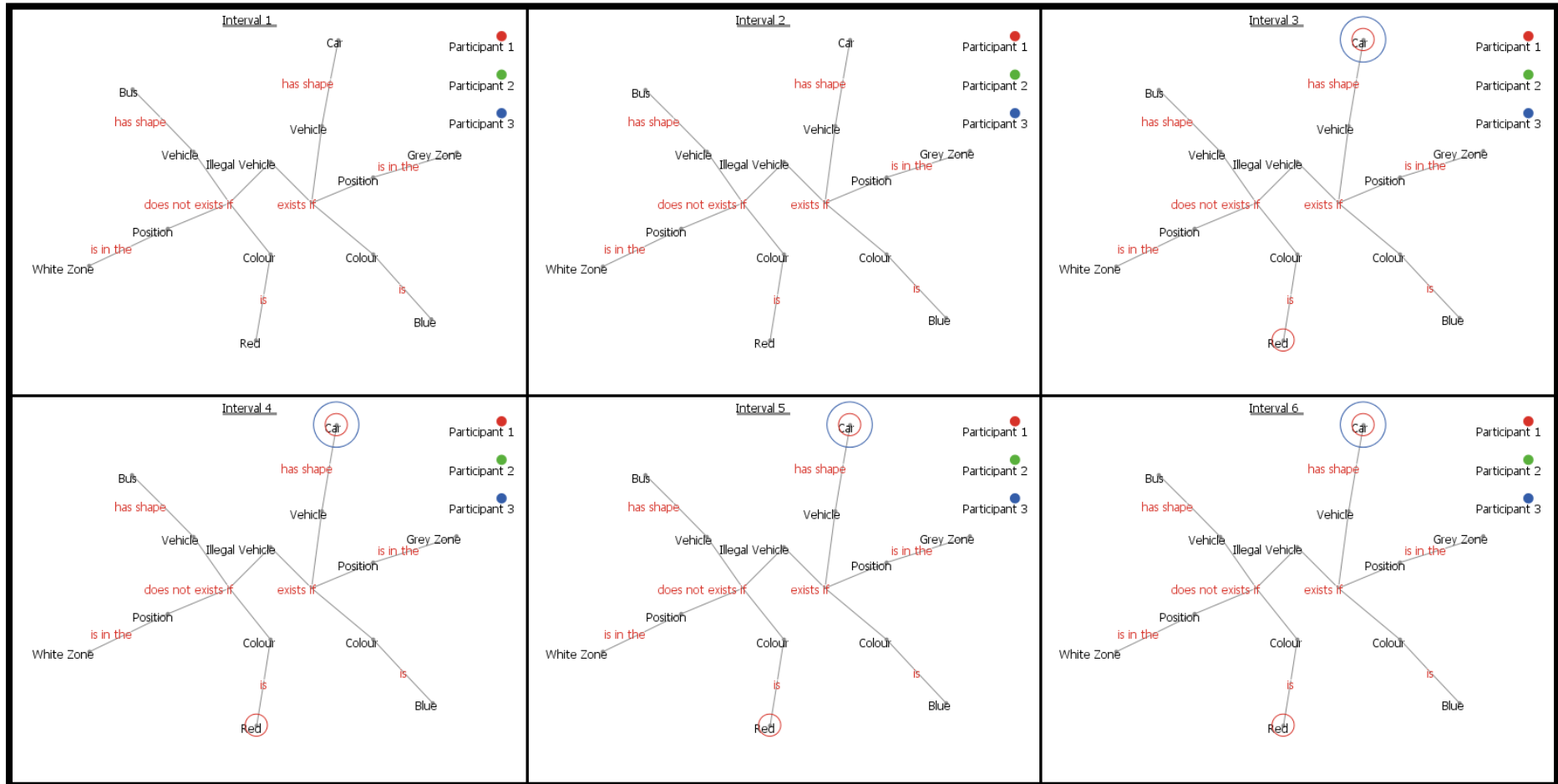


Figure 76 - Concept map example for Group 8 in Condition 2

## Group 6 – Condition 3



**Figure 77 - Concept map example for Group 6 in Condition 3**

## Group 8 – Condition 3

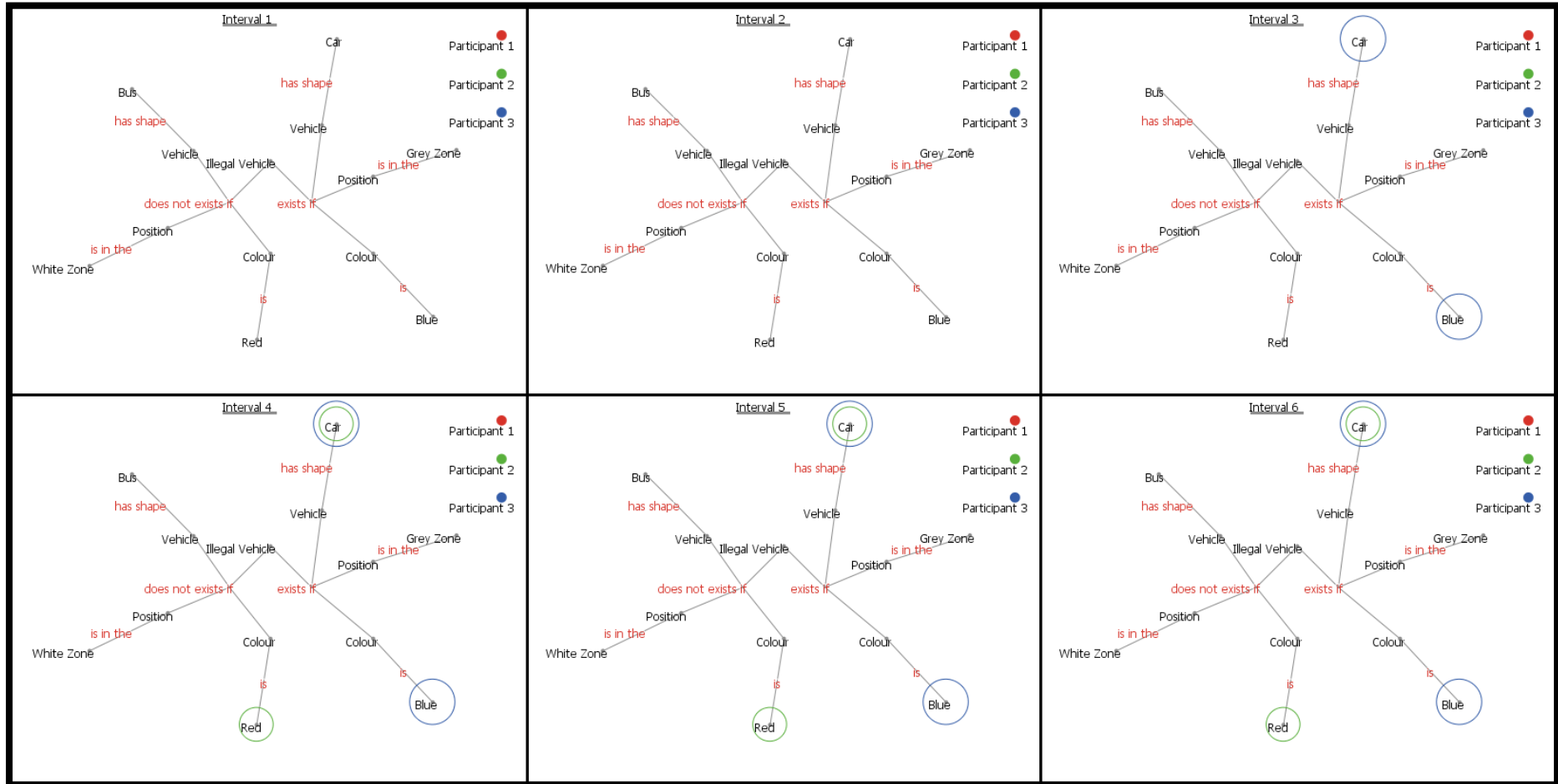


Figure 78 - Concept map example for Group 8 in Condition 3

## 4.5 CONCLUSIONS

Despite a learning effect, the results imply that performance was higher in condition 3 compared to condition 2, that is the Common Display aided the teams to reach the end goal more than the Separate Display or the teams were able to work better together when they were provided the same information. From the results in this chapter imply that performance does not change from condition 1 to condition 2, but there is improvement from condition 1 to condition 3. Due to the nature of an ABA experimental design, this tells us that there was no impact on the experimental condition (condition B), and there was difference in condition 3 (condition A). This could be explained by Tuckman's (1965) forming–storming–norming–performing model of group development. The model suggests that for a group to fully develop into one that can perform at its best it must transition through each of these phases. As participants were randomly assigned to the groups carrying out the tasks and due to the short task time, one could argue that the teams were still forming, storming and norming over the first two conditions and that it took until the third condition to reach the performing phase. Further experiments would be needed to test this hypothesis further and could be done by either increasing the task time during each condition and comparing performance over different task times or comparing already formed groups to randomly selected groups.

When it comes to communication, interestingly there was no overall difference in the number of comments made between the two conditions however, when comparing high and low performance teams, the number of comments were fewer in condition 3 for the high-performance teams. Low performance teams had a similar number of comments for both conditions, the content of these comments indicated that there was a focus on teamwork and reaching a consensus which resulted in a distraction from the main task. Content of the

comments suggests that higher performance teams focussed on task work and were more willing to act independently.

In conjunction with the performance results, teams 6 and 8 performed highest and also used the most amount of information as seen in the concept maps. Teams 4 and 7 performed the worse and also used very little information as seen in the concept maps. As the information used in the concept maps was taken from the transcripts it is clear that information sharing is key to system performance, however it is the content of that communication that is of importance and task relevant communications provide the information required for high performance. Although communication is important, the concept maps how that information is contained within the system. Group 6 in condition 2 (Figure 75 - Concept map example for Group 6 in Condition 2), where information is limited for each participant, information is distributed throughout the system, implying that even when the task requires sharing information it is not necessary to duplicate that information.

Duplication would occur if team members were repeating or confirming comments made by other team members, that is if they were trying to reach a consensus on the information being used. Concept maps which show agents holding the same information would imply that they were focusing on teamwork and reaching a consensus, where when agents have different information one could suggest that they are focusing on task work and that reaching a consensus is not necessary in order to achieve the common goal. Concept map results of the high performing teams reflect this teamworking behaviour.

Therefore, the conclusion is that more knowledge within the system promotes better performance, however that knowledge does not need to be duplicated, and suggests that completing the task is not reliant on sharing everything, just what is required for the system to perform. When low performance teams tried to reach a consensus, they did not achieve

sufficient SA and in turn were not able to complete the task. Therefore, teams did not gain awareness through simply sharing, it emerged via the distribution of participant knowledge. Although the concept maps provide some insight into when the knowledge concepts were obtained during the task, and which participants held that knowledge it is still not clear how the system used this knowledge or when the knowledge was truly gained. While obtaining the knowledge from transcripts eliminates the problem of intrusion or influence, it is a second-hand account of what the participants knew. It is possible that the participants knew considerably more, but it was not communicated and therefore not available to us as an analyst. However, as previously shown, with ABM it is possible to record exactly when that agent receives information and stores it to memory. Using the performance results and transcript content, it is possible to model the experiment in this chapter and therefore provide a more accurate account of what the system knows and when during the task. The following chapter takes this data and provides such a model, simulations from this model are then analysed in the form of concept maps.

#### **4.6 EXPERIMENT CRITIQUE**

Although the main purpose of the experiment was to provide results to both create and validate the model used in chapter 5, the results themselves raised questions and provided interesting results in relation to communication and situation awareness. With this in mind, the following modifications and improvements to the experiment are considered for future research.

Due to the varied nature of the participants themselves a question was raised about the familiarity between participants and the effect on the experiment. Therefore a control over the level of familiarity between participants could be implemented in future variations of the

experiment with a focus on whether this familiarity has an impact on overall performance and task implementation style. This raises questions such as, “does language style and/or communication amount differ between teams who know each other?”, “does how much the participants know each other affect the SA/performance of the team?” and “does the type of relationship (social or professional) affect how the teams work together and the overall SA/performance?” This could provide insights into the focus and usefulness of team building and training. If this version of the experiment were to be implemented a larger sample size would be necessary to gain the reliable results.

Increasing the number of characteristics to identify may also give a greater resolution in the data. These characteristics could be split into different categories such as vehicle specific (e.g. colour, shape, size, number of wheels, number of windows, etc.) and environmental (e.g. background/zone colour, lane number, direction of travel, etc.). With more characteristics and types of characteristics to identify, we could see if the teams allocate roles to each other or focus on one type of characteristic over another. Any modifications to the experiment would need to be carried over to the model/s used in Study 2, for example the increase in characteristics and role allocation (if necessary) again using the results from the experiment to validate the model.

A countdown timer could also be available on the screen for all team members (or perhaps only one during the separate display condition) to see if this has an effect on the amount teams communicate, how they communicate and again if this has an effect on overall performance. The increase in characteristics could also give a richer form of the concept maps, allowing for a greater understanding of how an individual team builds up their knowledge during the task. Coupling this with teams who have different levels of familiarity could also give insight into

how these different types of teams build up knowledge, work together and also work independently.

#### **4.7 SUMMARY**

The work in presented a target detection experiment using teams of three participants. The experiment captured communications between the team members through written transcripts, the content of these transcripts are used to extract participant knowledge. Concept maps were used to display the organisation of knowledge throughout the team system. A discussion of how effective the use of concept maps are in this case and a critique of the experiment is presented. The next step is to use the experiment design and results from this chapter and create a model of the team structure and task. The development and design of the model will be outlined in the next chapter, and simulations carried out to explore the information flow and knowledge acquisition of the agents within the system. Concept maps will be used again to display the temporal nature of the organisation of knowledge throughout the team.

# CHAPTER 5 TEAM TRAFFIC MODEL: COMMUNICATION AS KNOWLEDGE

*Parts of this chapter have been published in:*

*[1] A comparison of shared and distributed situation awareness in teams through the use of agent-based modelling” in the Journal of Theoretical Issues in Ergonomics Science, 2016, 17(1), p 8-41*

*The sections: Study 2: modelling SA on Page 26 of [1], Conclusion on Page 26 of [1], Program Structure on Page 27 of [1], Setup on Page 28 of [1], Questions and Comments in Agent Messages on Page 31 of [1], ‘Go’ - Main Operating Loop on Page 32 of [1], Distributed Model on Page 32 of [1], Shared Model on Page 33 of [1], Export - Illegal Characteristic Identification on Page 33 of [1], Export – Interval Agent Knowledge on Page 33 of [1] and Conclusions on Page 36 of [1] have been reproduced in this chapter.*

*The work in this chapter is based on the work in [1].*

## **5.1 AGENT BASED MODEL OF TEAMWORKING**

The experiment in the previous chapter illustrated differences in the ways in which display influences behaviour of teams in a Situation Awareness task. In order to explore those differences in more detail, and to consider how SA might vary under different conditions, two ABM were developed, again using NetLogo. Once the models produced comparable results to the experimental data, they were manipulated to explore the effects of different conditions.

The advantage of using the models is that level of performance can be set for team members, e.g., novice or expert, or type of SA that teams employ, e.g., Distributed Situation Awareness,

where the agents only know their own knowledge and do not share this with the other agents, or Shared Situation Awareness, where agents share knowledge once they acquire it. An expert team is described as compromising of agents that were more likely to ask task-relevant questions, where a novice team was more likely to ask non task-related questions.

The first of the two models used common and separate video outputs (common video outputs used in the practice condition (condition 1) and 2<sup>nd</sup> condition the experiment and separate video outputs used in the 1<sup>st</sup> condition [experimental condition]). When using either the common or separate video outputs the agents had distributed information, i.e. the agents asked a question they kept any relevant information output for themselves only.

The second model differed only in that when using either the common or separate video outputs the agents had shared information, i.e. when the agent asked a question they shared all relevant information, which took priority over additional questions being asked. The sharing of information took the same amount of time as one agent cycle through the video, screen and output window, during this time no other questions or comments were made.

## **5.2 METHOD**

### **5.2.1 Program Structure**

Facilitated by the direction of the experimental task, the actions of the agents reflect Boyd's Observe-Orient-Decide-Act (OODA) loop principles (Brehmer, 2005), where:

- [1] Agent<sub>i</sub> (a participant) *observes* an information source (the video or output window) and
- [2] Then *orients* to it, interpreting what that information source is displaying. Agent<sub>i</sub> (a participant) then communicates information to Agent<sub>ii</sub> (the observer) via an interface (the output window).

[3] Agent<sub>ii</sub> makes a *decision* about the information and communicates that information to Agent<sub>iii</sub> (either one or all participants) via an interface (the output window).

[4] Agent<sub>iii</sub> (either one or all participants) then performs an *action* (i.e. stores information communicated via the observer).

Once the action has been performed the loop begins again with a new observation.

It is important to note here that it is not possible to know from the results whether only one or all participants stored the information given ([4] *action* phase) by the observer during the [3] *decision* phase at any point during each of the trials. It was observed during some trials that participants had to remind their fellow team members that a certain characteristic had been made, indicating that although the information had been displayed to them, they either a) did not orient to the window output when the information was being communicated or b) they did not store the information communicated. As one cannot see into the participants mind one cannot say how often this occurred during the experiment and so the development of the models in this chapter allows the opportunity to isolate this variable.

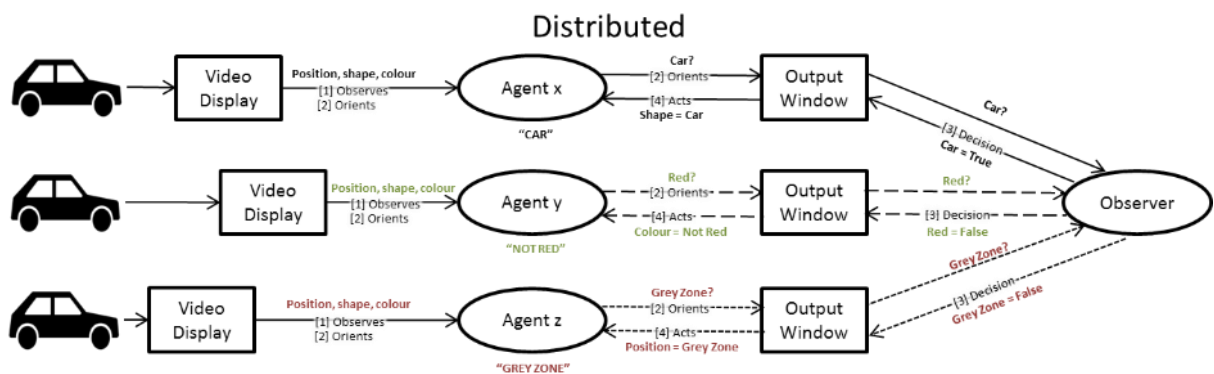
The model follows the OODA principles in the following way:

[1] Agent x (a `randomAgent`) *observes* an information source (the video) and

[2] Then *orients* to it, interpreting what that information source is displaying. Agent x then communicates information to the Observer (`observerAgent`) via an interface (the output window).

[3] The Observer (`observerAgent`) makes a *decision* about the information and communicates that information to Agent x via an interface (the output window).

[4] Agent x then performs an *action* (i.e. stores information communicated via the observer and either stops or continues the task).



**Figure 79 - The OODA principles in the model**

Figure 79 - The OODA principles in the model visually represents the principles in the model.

The spatial distribution (people and displays positioning) is the same for the model, however in reality although the positioning of people and displays are the same there may be some differences, such as the angle or distance from those displays. The structural distribution is the same for both models, the agents make the same links and the information flows in the same manner. No new links or information emerges from one model to the other. However functional distribution (i.e. roles or task allocation) is different. In the common displays model a random agent asks a question, shares the answer to that question to the other agents and then all agents store that information. All agents must be carrying out the same role (i.e. *acts*) to complete this task. Therefore, their roles or functions are shared. In the separate display model, a random agent still asks a question and receives an answer, however only that agent stores the information (i.e. *acts*). The other agents are allowed to carry out other roles during this time, such as *observe* or *orient*. Therefore, their roles or functions are distributed.

### 5.2.1.1 Design

The code of model has been shown in the form of a flowchart (see Figure 80 – Flowchart of the model code for the distributed model).

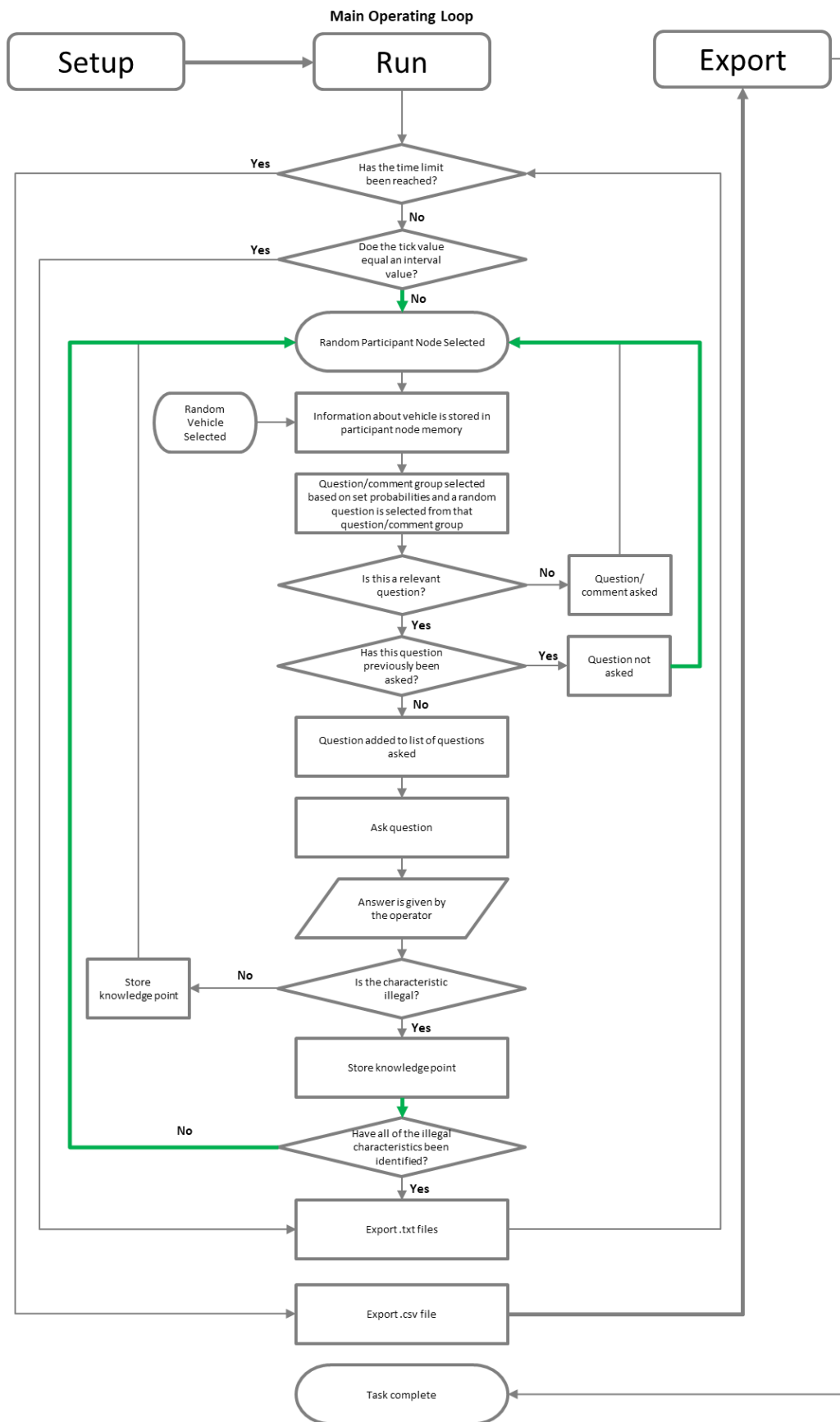


Figure 80 – Flowchart of the model code for the distributed model

The agents have a set of 5 rules: watchVideo, sendVideoInformationFromVideo, typeToWindow, readWindow and getInfoFromWindow. Figure 81 gives a summary of each of these rules, how they are activated and carried out during the task.

The agent rules can be described as active and reactive. The rules watchVideo, readWindow and typeToWindow are active rules and gainInfoFromWindow and sendVideoInformationFromVideo are reactive rules. For example, when the watchVideo rule is activated the agent sends a “request” to the video for information in the form of an arrow. When the video receives this request the reactive rule sendVideoInformationFromVideo is activated and the agent receives one piece of information about the video, i.e. the vehicle type, colour or position. Once the agent receives the information, the action loop is closed and a new active rule can be activated. This may be the same rule as before, watchVideo, or a new active rule, for example readWindow or typeToWindow. Each of these action loops consist of four actions, two from the active rule and two from the reactive rule. Each of these action loops can be seen in Figure 81 - Summary of agent rules, how they are activated and carried out during the task

, in the form of numbers from 1 to 4.

Although the agents are not communicated with each other directly, that is they are not requesting information from each other rather from the artefacts within their environment, the processes of active and reactive actions within the model can be described as analogous to the push/pull actions described by Demir et al. (2018b). The pushing and pulling of information described by Demir et al. (2018b) explains how information is requested and provided by agents via particular individual behaviours. In this model the agents do not replicate these specific behaviours, however the pushing and pulling of information is still carried out, that is between the artefacts within the system, i.e. the video and chat window. Agents themselves

push information to the chat window and pull information from both the chat window and video.

For the two models, using the common and separate displays, these actions remain the same. To replicate the experiment conditions in chapter 4, what does change is the information provided by the videos. In condition 1, the information of the videos is separated, that is each of the agents have access to one type of characteristic, either: the colour of the vehicle, the shape of the vehicle or the position of the vehicle. In the 2<sup>nd</sup> condition agents receive all this information, that is the videos are identical for each agent.

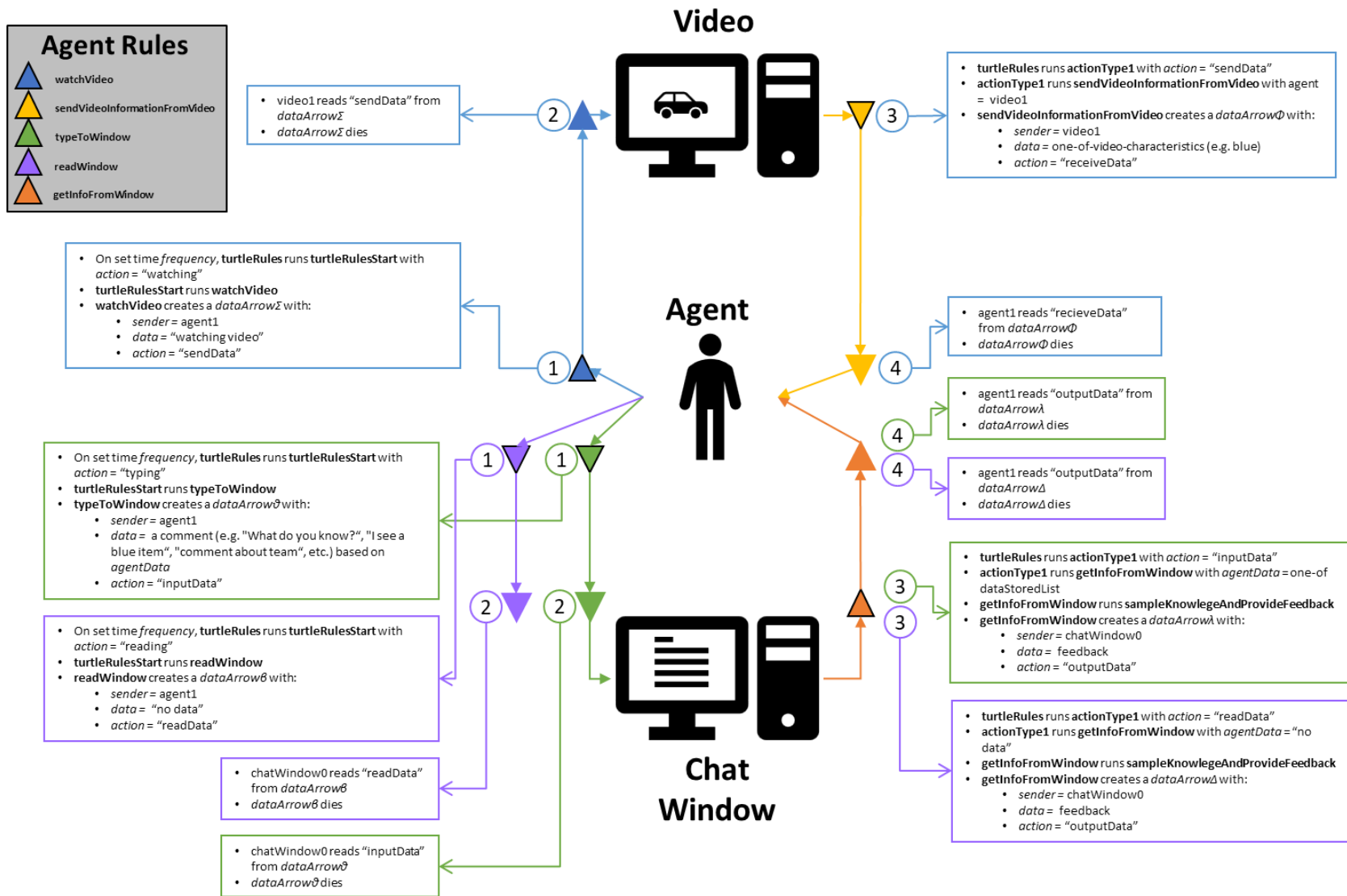


Figure 81 - Summary of agent rules, how they are activated and carried out during the task

### 5.2.1.2 Setup

All programs start with a setup procedure which involves the creation of the graphics on the screen (③ in Figure 82), the loading of the videos to be used (common or different videos) (① in Figure 18) and the creation of the export files, the status of which can be seen in the output window (② in Figure 82). The last part of the setup procedure requires the user to set the number of cycles, i.e. how many times the model will be run, (④ in Figure 82) and set the probability values for question types to be selected, using the sliders (⑤ in Figure 82). Once this is complete the user starts the *main operating loop* by pressing the ‘go button’ (⑥ in Figure 82), this button starts the main operating loop and can also pause the model while the main operating loop is running.

#### 5.2.1.2.1 Parameters

The model parameters were set to create three different types of teams; calibrated to replicate the experiment teams, expert teams and novice teams. Each of the three model settings were based on the types of questions available, via the question type sliders (⑤ in Figure 82). The calibrated model was based on a percentage of task-related comments and non-task related comments. This was modified until the performance of the model matched the performance of the teams in the experiment. Once this calibration was complete, the same parameters were modified to simulate expert and novice teams, following the premise that expert teams would be more likely to make task-relevant comments and novice teams would be less likely to.

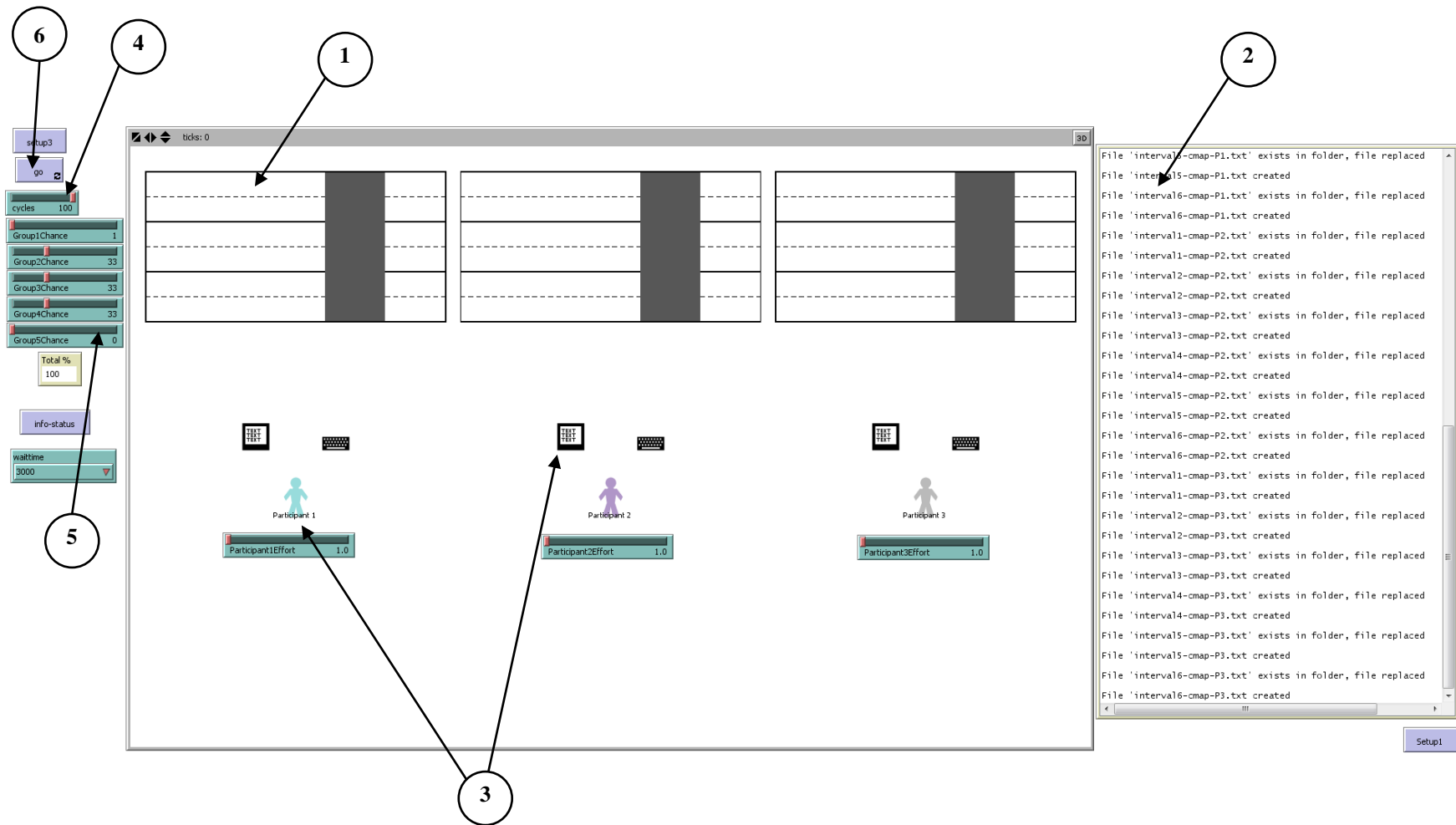


Figure 82 – Model interface

### 5.2.1.3 *Questions and Comments in Agent Messages*

In addition to the programs simulating the SA task in the experiment, they were also designed to simulate agents asking questions or making comments. Relevant questions would generate a reply from the operator, confirming whether a characteristic represents an illegal vehicle. At the beginning of each “turn” an agent was selected at random and this agent would select a question or comment to “type” into the chat window, which would then prompt a reply from the operator. The lists of questions used in the models were created by reviewing the transcripts from Study 1 and taking the questions that were asked by the participants and classifying them as either; Non Relevant Questions, Relevant Questions – Vehicle Colour Related, Relevant Questions – Vehicle Shape Related, Relevant Questions – Background Colour Related and Non Relevant Comments. For example:

- Non Relevant Questions
  - E.g. “Is the illegal vehicle in the top lane?”
- Relevant Questions – Vehicle Colour Related
  - E.g. “Is the illegal vehicle blue?”
- Relevant Questions – Vehicle Shape Related
  - E.g. “Is the illegal vehicle a bus?”
- Relevant Questions – Background Colour Related
  - E.g. “Is the illegal vehicle in the grey zone?”
- Non Relevant Comments
  - E.g. “I think I'm finished”

The probability of a type of questions/comments being selected during the model experiment was set before the model was run, using the sliders in the user interface. For example, if the

Non Relevant Questions was set to 40, then there was a 40% chance that a question would be asked from that group of questions. A random question would then be asked from that set of questions/comments, if the question had already been asked, the question would not be asked again and no questions would be asked during that turn. The questions/comments allocated to these groups were taken from the transcripts obtained during the experiment outlined in Study 1.

#### ***5.2.1.4 'Go' - Main Operating Loop***

In all programs, the video is played and each agent attends to objects in the video. The objects represented moving vehicles with different characteristics (e.g. vehicle shape, vehicle colour and background colour). On attending to an object, one of the characteristics was perceived by the agent who then raised a question about that characteristic via the output window. For example, if the agent attended to a blue car, it could ask 'Is the illegal vehicle a car?' or 'Is the illegal vehicle blue?'. Feedback was then provided via the same output window as to whether the answer to the question is correct or false. In addition to asking questions about the video, agents can ask questions which are directed to the other agents, such as 'how long is left?' and 'what can you see?'.

#### ***5.2.1.5 Model***

In the model, the main operating loop continues for 8000 ticks (model counter = 8000) of the model code. If all the characteristics are identified before the time limit, the main operating loop stops at that model counter value. A random agent is chosen for this run of the main operating loop, along with a random car from the agents' allocated video. Based on the chosen question group probabilities a question group is selected and a question (or comment) from that group is selected. If the question is regarded as relevant (i.e. in relation to the

characteristics in question: vehicle shape, vehicle colour and colour of vehicle background/zone) and that question had not previously been asked the agent “asks” this question via text to the output window. An answer is then given by the operator, which is stored in the agents’ memory. If all of the illegal characteristics have been identified, then the main operating loop exits and the illegal characteristic identification export function is carried out. If all of the illegal characteristics have not been identified, then a new random agent is selected and the main operating loop continues as before. If the model counter is equal to any of the interval values, then the interval agent knowledge export function is carried out.

### **5.2.2 Export - Illegal Characteristic Identification**

Once a characteristic was identified, it is saved together with the counter value in a list within the code. The first value in this list represents the time when the first characteristic is identified, the second value in this list represents the time when the second characteristic is identified and the third value in this list represents the time when the third characteristic is identified. Once the main operating loop had been exited (due to reaching the tick limit or identifying all of the characteristics) the list is exported to a .csv file, which can be opened directly in Microsoft Excel. If the model reached the end of the run (model counter = 8000) and the characteristic had not been identified, then that would be exported as model counter = 8000 also. E.g. if the first characteristic had been identified but the other two had not, then the output may read something similar to: 4555, 8000, 8000. If all three characteristics had been identified then the output may read something similar to: 4555, 5654, 7589.

### **5.2.3 Export – Interval Agent Knowledge**

If the model counter equals an interval value (e.g. 6000), the knowledge of each agent is exported to a .txt file for each agent. These files are imported into the concept map application once all of the main operating loop cycles have been complete. The main operating loop does not exit.

### **5.2.4 Export – Total comments made, and task relevant comments made**

### **5.2.5 Model Concept Maps**

The same concept map application that was used in chapter 4 was also used here. The model files exported the knowledge of the model agents at regular intervals in the same format that was manually written in chapter 4. The concept map application read the .txt files and overlay the agent knowledge over the relevant concepts on the map. The .txt files in this chapter were automatically created and exported by the models.

## **5.3 RESULTS**

The models were run 100 times each, supplying 100 data exports per model simulates a total of 300 participants or 100 groups. The calibrated real world model results provided two sets of data, along with expert and novice results providing a further two more sets each.

A combination of quantitative analysis, using SPSS V23, and qualitative analysis of the results was carried out on the data obtained from these eight teams. Results presented are:

- Performance
- Total comments
- Task relevant comments
  - Task relevant comments are the comments pertaining to the task and exclude any miscellaneous utterances.
- Total comments against performance
- Task relevant comments against performance
- Information held within the network (concept maps)

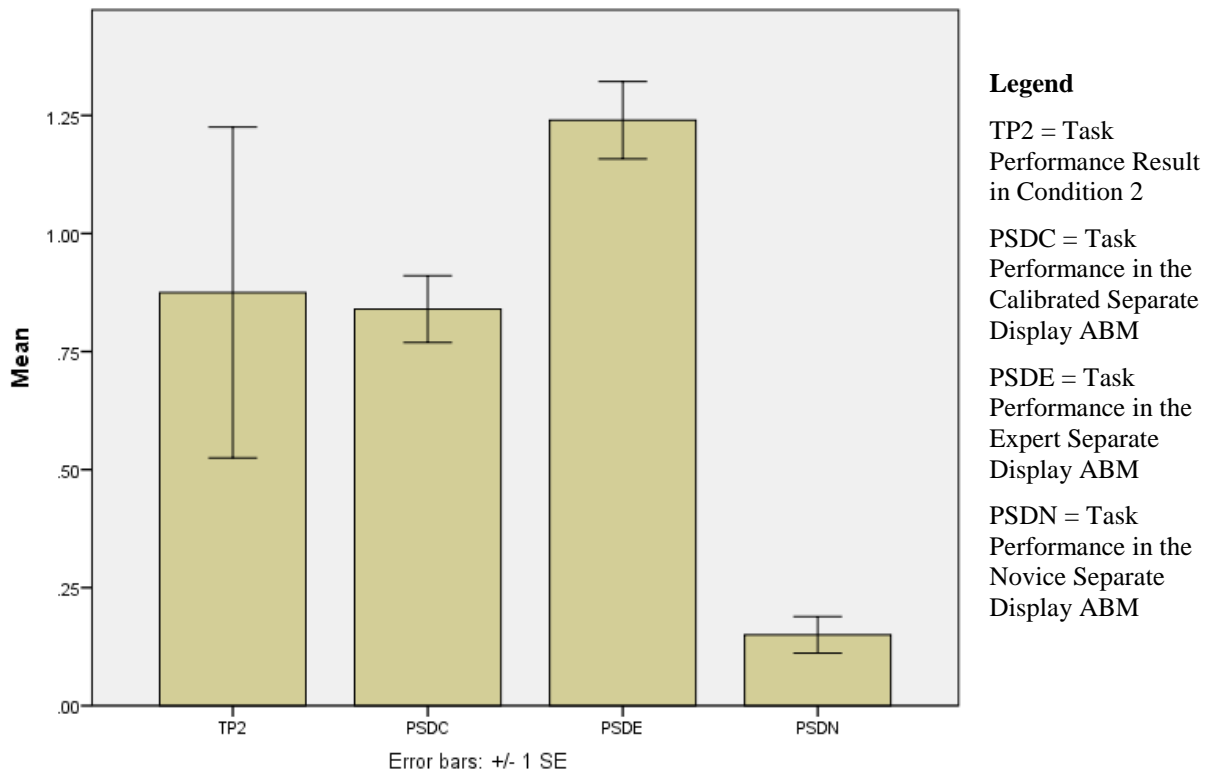
### **5.3.1 Performance**

The tests for normal distribution can be found in Appendix JJ and show that the performance data for the models was not parametric. Therefore, a Kruskal-Wallis test was conducted to compare the performance of the models and experiment for the separate display and common display conditions, followed by a Man-Witney post hoc test.

### 5.3.1.1 Condition 2

As there was a statistically significant differences between group means as determined by the Kruskal-Wallis test ( $\chi^2(3) = 102880$ ,  $p < 0.001$ ). A post-hoc Mann-Whitney Test was conducted to compare the results further, the results of which can be seen in Figure 83 and the statistical results for the Kruskal-Wallis and post-hoc Mann-Whitney Test can be found in Appendix KK

*Comparison of Mean Performance Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display*



**Figure 83 - Comparison of Mean Performance Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display**

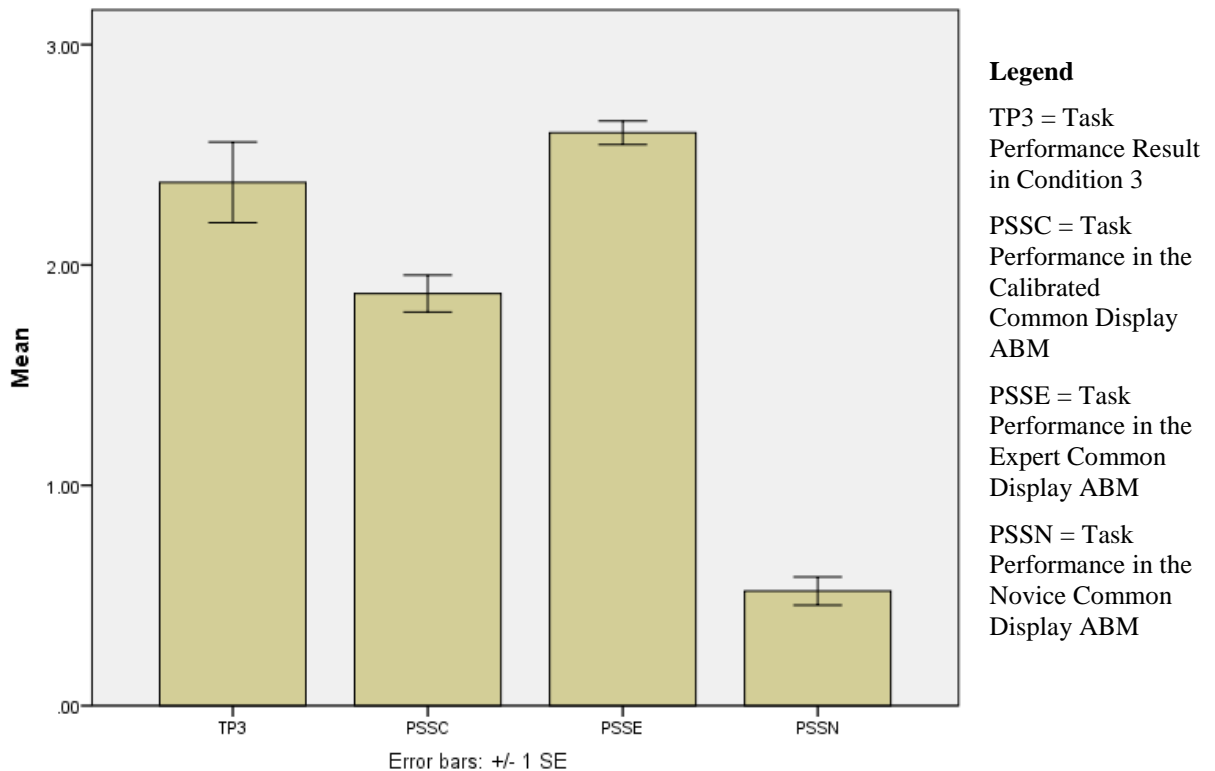
Appendix KK There was a not a significant difference in the performance scores between the experiment and the calibrated model ( $U = 399, p = 0.990$ ) or the experiment and the expert model ( $U = 314, p = 0.280$ ).

There was a significant difference in the scores for all other comparisons: the experiment and the novice model ( $U = 237, p = 0.003$ ), calibrated model and expert model ( $U = 3712, p = 0.001$ ), calibrated model and novice ( $U = 2307, p < 0.001$ ) and expert model and novice model ( $U = 1350, p < 0.001$ ).

### 5.3.1.2 Condition 3

As there was a statistically significant differences between group means as determined by the Kruskal-Wallis test ( $\chi^2(3) = 186.361, p < 0.001$ ). A post-hoc Mann-Whitney Test was conducted to compare the results further, the results of which can be seen in Figure 84 and the statistical results for the Kruskal-Wallis and post-hoc Mann-Whitney Test can be found in Appendix KK

*Comparison of Mean Performance Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display*



**Figure 84 - Comparison of Mean Performance Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display**

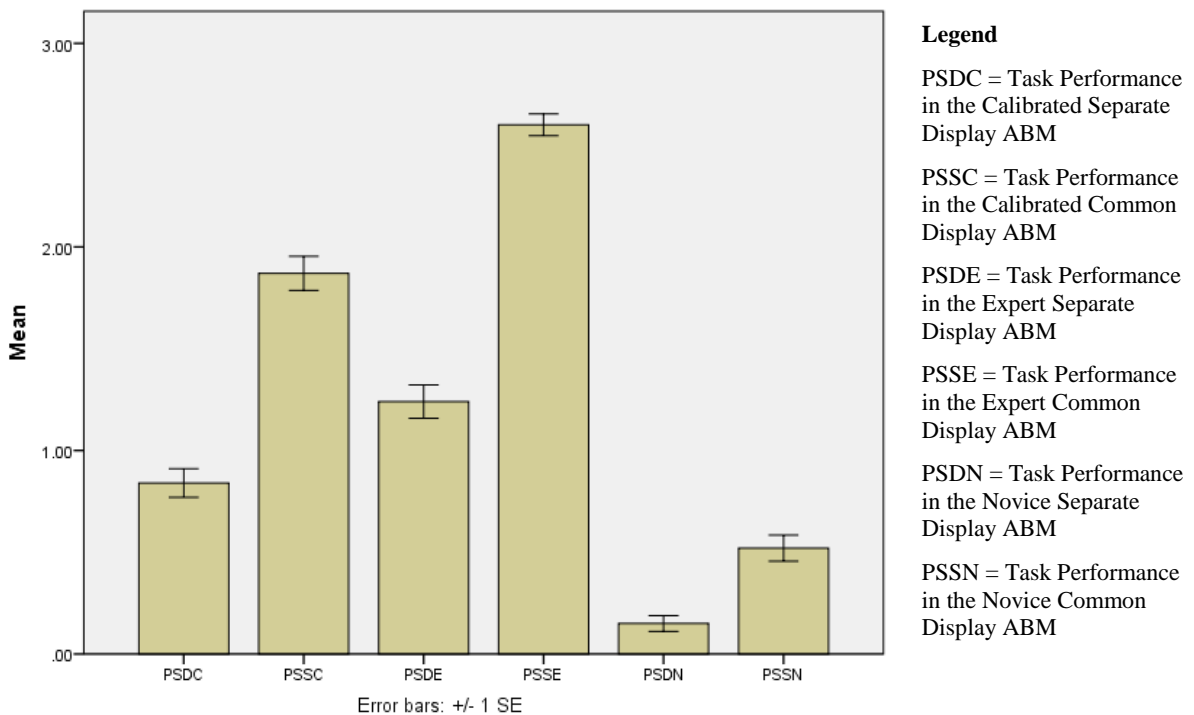
Appendix KK There was a not a significant difference in the performance scores between the experiment and the calibrated model ( $U = 267, p = 0.093$ ) or the experiment and the expert model ( $U = 307, p = 0.201$ ).

There was a significant difference in the scores for all other comparisons: the experiment and the novice model ( $U = 20, p < 0.001$ ). calibrated model and expert model ( $U = 2551, p < 0.001$ ) calibrated model and novice ( $U = 1244, p < 0.001$ ) and expert model and novice model ( $U = 196, p < 0.001$ ).

### 5.3.1.3 Model comparisons

A Paired Samples t-test was conducted to compare each of the model results over the two conditions and can be seen in Figure 85. The statistical results can be found in Appendix MM.

*Comparison of Mean Performance Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model*



**Figure 85 - Comparison of Mean Performance Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model**

There was a significant difference in the performance scores for all comparisons: condition 2 ( $M = 0.84$ ,  $SD = 0.707$ ) and condition 3 ( $M = 1.87$ ,  $SD = 0.837$ ) for the calibrated model;  $t(99)=-9.24$ ,  $p < 0.001$ , condition 2 ( $M = 1.24$ ,  $SD = 0.818$ ) and condition 3 ( $M = 2.60$ ,  $SD = 0.532$ ) for the expert model;  $t(99)=-14.34$ ,  $p < 0.001$  and condition 2 ( $M = 0.15$ ,  $SD = 0.386$ ) and condition 3 ( $M = 0.52$ ,  $SD = 0.643$ ) for the novice model;  $t(99)=-5.14$ ,  $p < 0.001$ .

### **5.3.2 Communication**

The tests for normal distribution can be found in Appendix NN for the total comments results and Appendix RR for the task-relevant comments results. It was determined that the results were parametric and therefore a One-Way ANOVA with a post-hoc Independent Samples t-test would be conducted for these results.

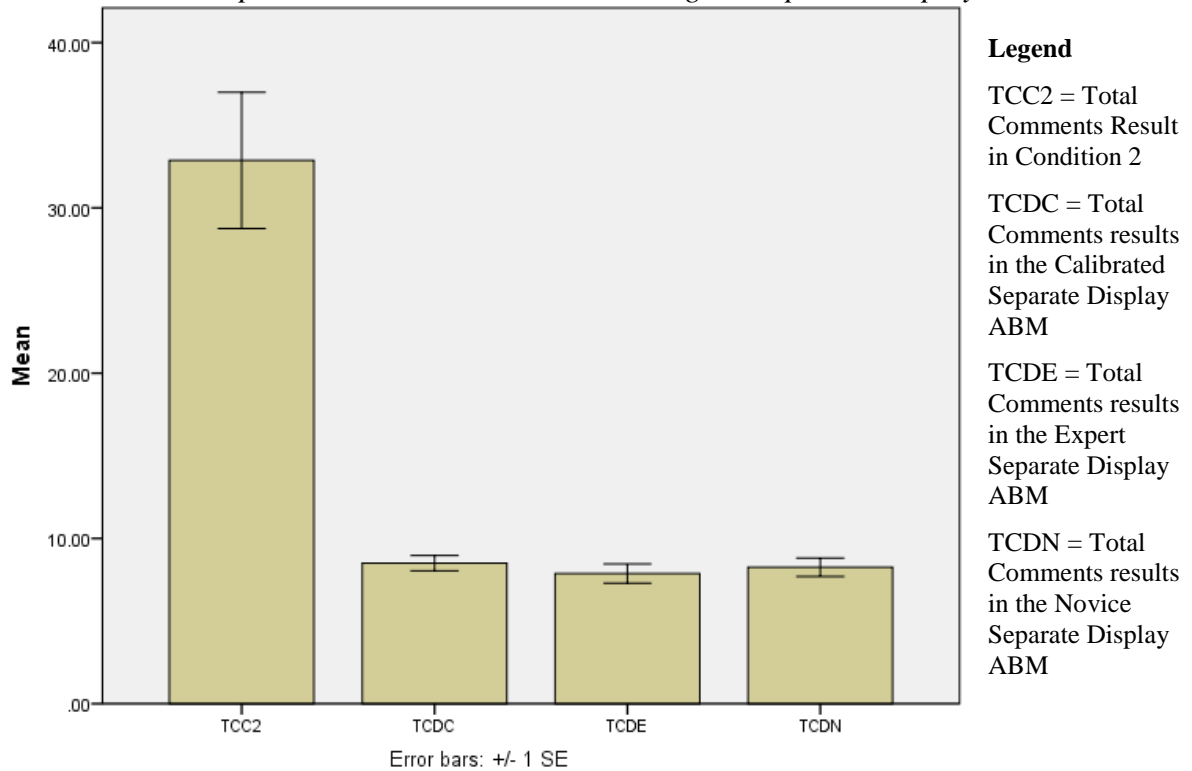
#### **5.3.2.1 Total comments**

##### 5.3.2.1.1 Condition 2

As there was a statistically significant differences between group means as determined by the One-Way ANOVA [ $F(3,304) = 269.88$ ,  $p < 0.001$ ]. A post-hoc Independent Samples T-Test was conducted to compare the results further, the results of which can be seen in Figure 86 and the statistical results for the One-Way ANOVA and post-hoc Independent Samples T-Test can be found in Appendix OO and Appendix PP, respectively.

The post-hoc Independent Samples T-Test showed that there was a significant difference in the total comments made between the experiment ( $M=32.88$ ,  $SD=11.66$ ) and all of the model results: calibrated model ( $M=8.53$ ,  $SD=1.58$ );  $t(106)=19.71$ ,  $p < 0.001$ , expert model ( $M=8.10$ ,  $SD=1.60$ );  $t(106)=19.99$ ,  $p < 0.001$  and novice model ( $M=8.25$ ,  $SD=1.79$ );  $t(106)=19.37$ ,  $p < 0.001$ .

*Comparison of Mean Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display*



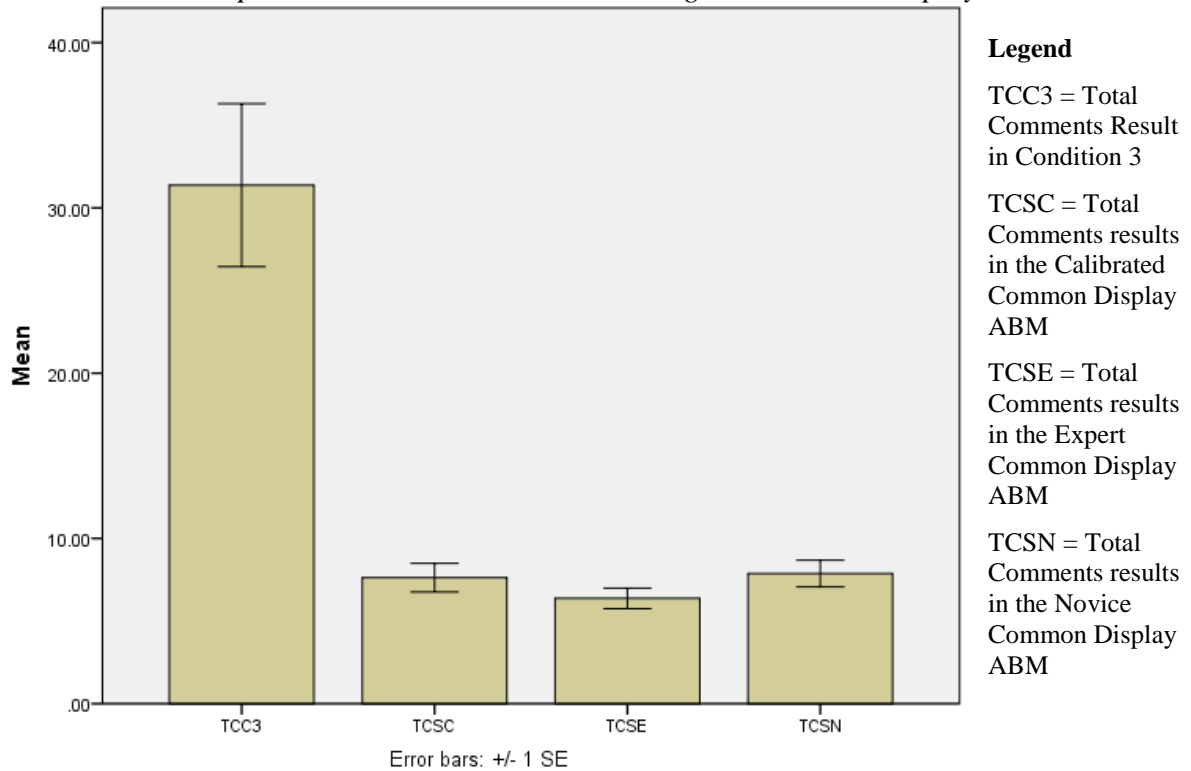
**Figure 86 - Comparison of Mean Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display**

The post-hoc Independent Samples T-Test showed that there was a not a significant difference in the total comments made between any of the model results: the calibrated model (M=8.53, SD=1.58) and expert model (M=8.10, SD=1.60);  $t(198)=1.910$ ,  $p = 0.058$ , the calibrated model (M=8.53, SD=1.58) and novice model (M=8.25, SD=1.79);  $t(198)=1.17$ ,  $p = 0.243$  and the expert model (M=8.10, SD=1.60) and novice model (M=8.25, SD=1.79);  $t(198)=-0.623$ ,  $p = 0.534$ .

5.3.2.1.2 Condition 3

As there was a statistically significant differences between group means as determined by the One-Way ANOVA [ $F(3,304) = 178.16$ ,  $p < 0.001$ ]. A post-hoc Independent Samples T-Test was conducted to compare the results further, the results of which can be seen in Figure 87

*Comparison of Mean Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display*



**Figure 87 - Comparison of Mean Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display**

and the statistical results for the One-Way ANOVA and post-hoc Independent Samples T-Test can be found in Appendix OO and Appendix PP, respectively.

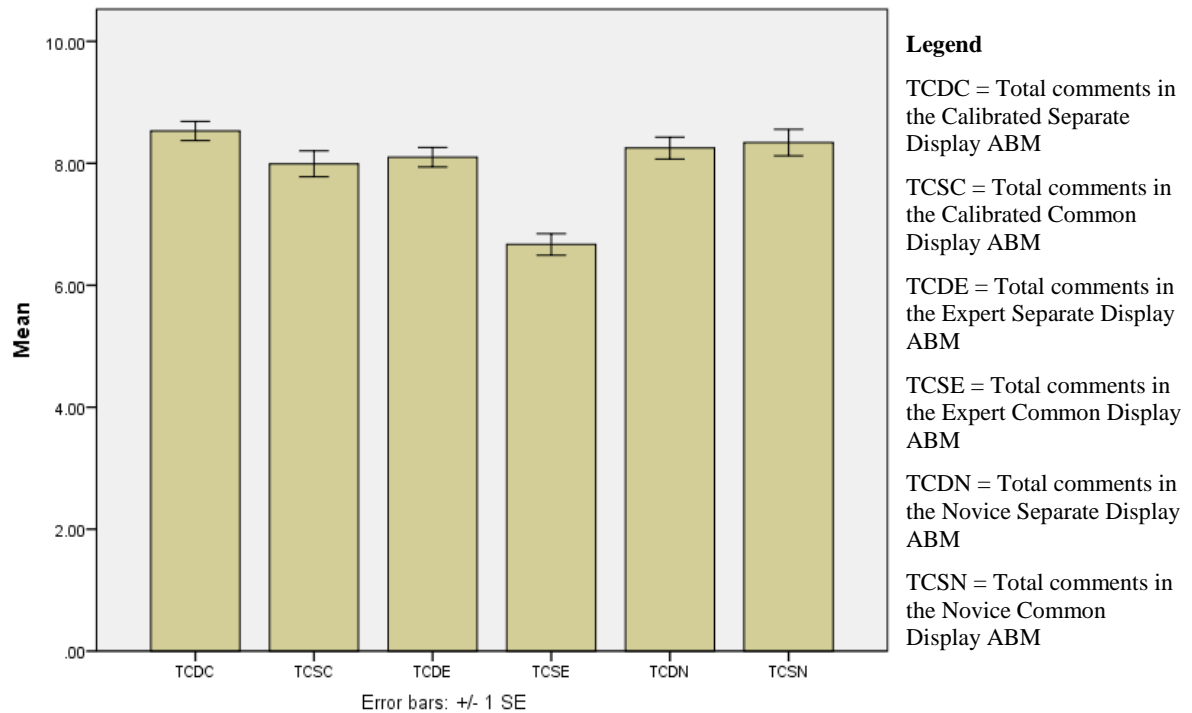
The post-hoc Independent Samples T-Test showed that there was a significant difference in the total comments made between the experiment ( $M=31.38$ ,  $SD=13.94$ ) and all of the model results: calibrated model ( $M=7.99$ ,  $SD=2.12$ );  $t(106)=15.42$ ,  $p < 0.001$ , expert model ( $M=6.67$ ,  $SD=1.77$ );  $t(106)=16.94$ ,  $p < 0.001$  and novice model ( $M=8.34$ ,  $SD=2.17$ );  $t(106)=15.11$ ,  $p < 0.001$ . There was also a significant difference in the total comments made between the calibrated model ( $M=7.99$ ,  $SD=2.12$ ) and expert model ( $M=6.67$ ,  $SD=1.77$ );  $t(198)=4.78$ ,  $p < 0.001$  and the expert model ( $M=6.67$ ,  $SD=1.77$ ) and novice model ( $M=8.34$ ,  $SD=2.17$ );  $t(198)=-5.97$ ,  $p < 0.001$ .

The post-hoc Independent Samples T-Test showed that there was not a significant difference in the total comments made between the calibrated model (M=7.99, SD=2.12) and novice model (M=8.34, SD=2.17);  $t(198)=-1.16, p = 0.250$ .

### 5.3.2.1.3 Model Comparisons

A Paired Samples t-test was conducted to compare each of the model results over the two conditions and can be seen in Figure 88. The statistical results can be found in Appendix QQ. There was a significant difference in the total comments results between condition 2 (M = 8.10, SD = 1.60) and condition 3 (M = 6.67, SD = 1.77) for the expert model;  $t(99)=6.18, p < 0.001$ , however there was no significant difference between condition 2 (M = 8.53, SD = 1.58) and condition 3 (M = 7.99, SD = 2.12) for the calibrated model;  $t(99)=1.97, p =0.051$  or

*Comparison of Mean Communication Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model*



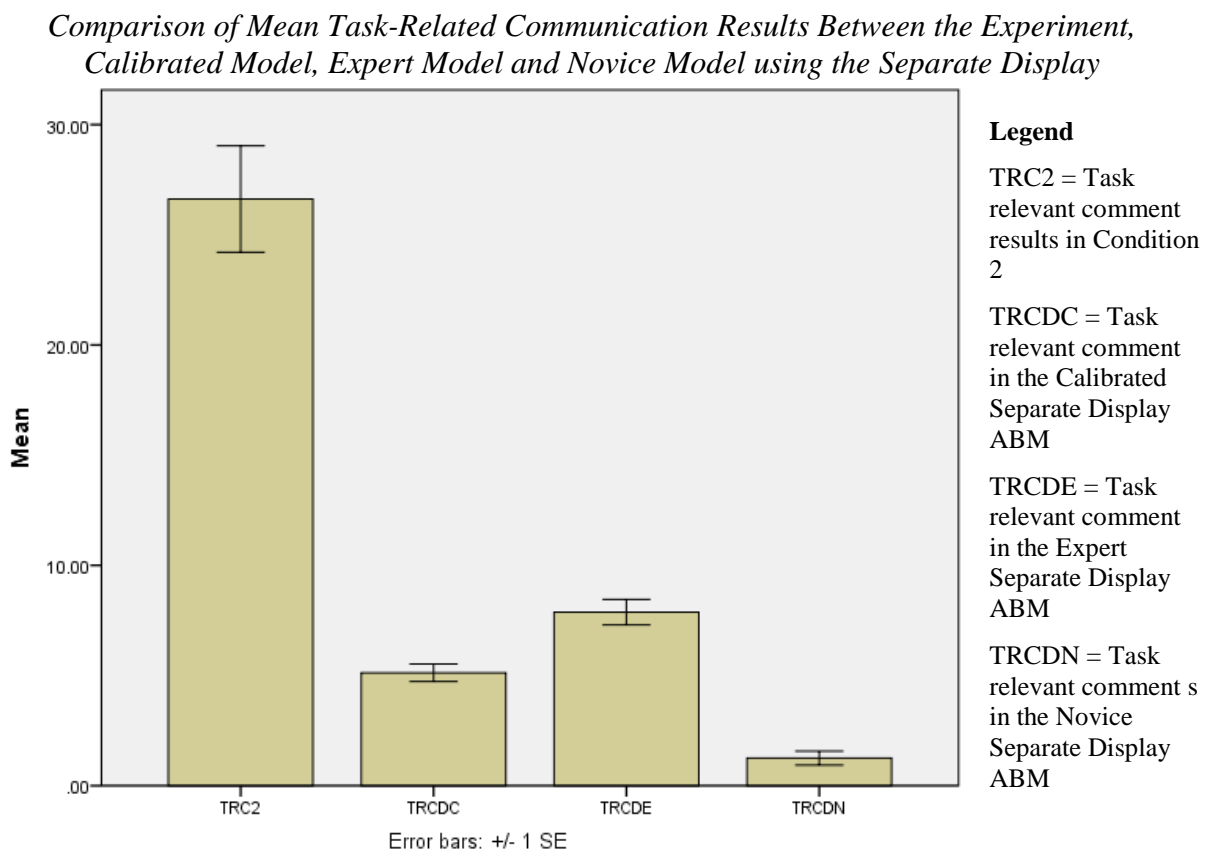
**Figure 88 - Comparison of Mean Communication Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model**

condition 2 (M = 8.25, SD = 1.79) and condition 3 (M = 8.34, SD = 2.17) for the novice model;  $t(99) = -0.31, p = 0.757$ .

### 5.3.2.2 Task Relevant comments

#### 5.3.2.2.1 Condition 2

As there was a statistically significant difference between group means as determined by the One-Way ANOVA [ $F(3,304) = 636.19, p < 0.001$ ]. A post-hoc Independent Samples T-Test was conducted to compare the results further, the results of which can be seen in Figure 89 and the statistical results for the One-Way ANOVA and post-hoc Independent Samples T-Test can be found in



**Figure 89 - Comparison of Mean Task-Related Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Separate Display**

Appendix SS and Appendix TT, respectively.

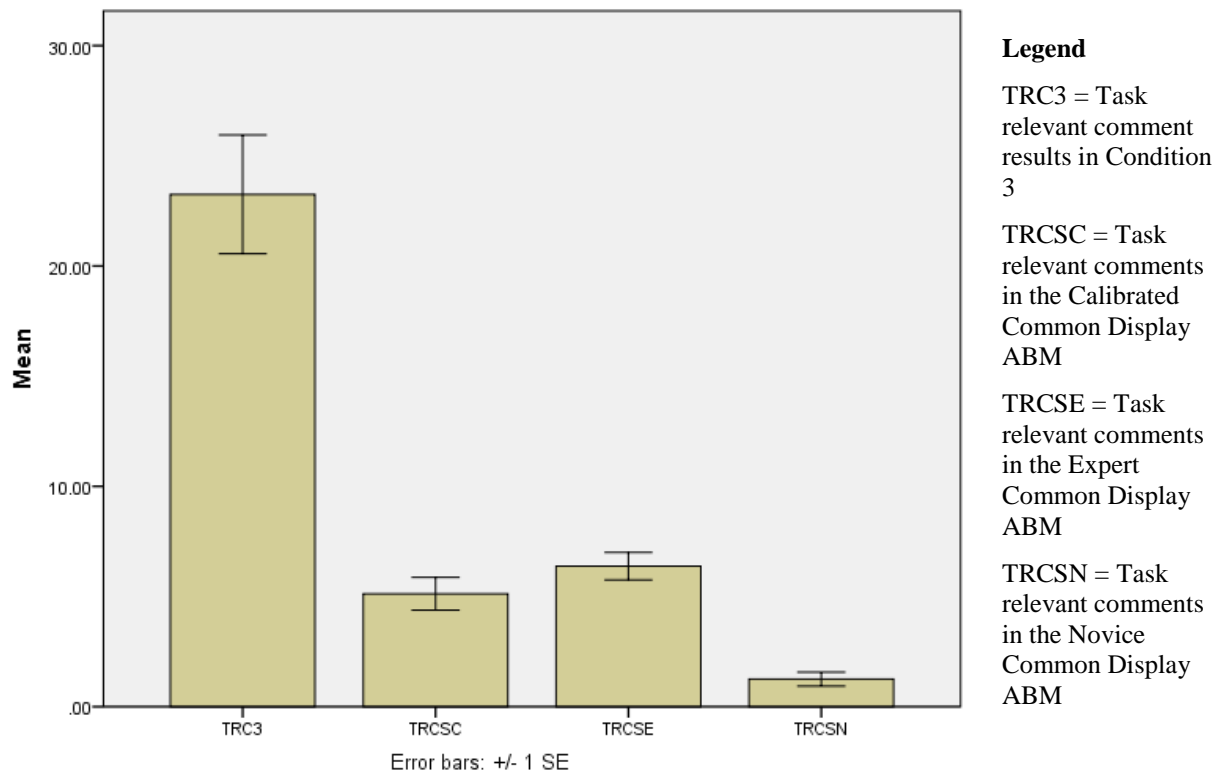
The post-hoc Independent Samples T-Test showed there was a significant difference in the number of task relevant comments made between the experiment ( $M=26.63$ ,  $SD=6.82$ ) and all of the model results: calibrated model ( $M=5.44$ ,  $SD=1.79$ );  $t(106)=23.42$ ,  $p < 0.001$ , expert model ( $M=8.03$ ,  $SD=1.63$ );  $t(106)=21.47$ ,  $p < 0.001$  and novice model ( $M=1.12$ ,  $SD=0.844$ );  $t(106)=35.89$ ,  $p < 0.001$ .

The post-hoc Independent Samples T-Test also showed there was a significant difference in the number of task relevant comments made between all of the model results: the calibrated model ( $M=5.44$ ,  $SD=1.79$ ) and expert model ( $M=8.03$ ,  $SD=1.63$ );  $t(198)=-10.71$ ,  $p < 0.001$ , the calibrated model ( $M=5.44$ ,  $SD=1.79$ ) and novice model ( $M=1.12$ ,  $SD=0.84$ );  $t(198)=21.84$ ,  $p < 0.001$  and the expert model ( $M=8.03$ ,  $SD=1.63$ ) and novice model ( $M=1.12$ ,  $SD=0.84$ );  $t(198)=37.65$ ,  $p < 0.001$ .

#### 5.3.2.2.2 Condition 3

As there was a statistically significant difference between group means as determined by the One-Way ANOVA [ $F(3,304) = 383.29$ ,  $p < 0.001$ ]. A post-hoc Independent Samples T-Test was conducted to compare the results further, the results of which can be seen in Figure 90 and the statistical results for the One-Way ANOVA and post-hoc Independent Samples T-Test can be found in

*Comparison of Mean Task-Related Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display*



**Figure 90 - Comparison of Mean Task-Related Communication Results Between the Experiment, Calibrated Model, Expert Model and Novice Model using the Common Display**

Appendix SS and Appendix TT, respectively.

The post-hoc Independent Samples T-Test showed there was a significant difference in the number of task relevant comments made between the experiment ( $M=23.25$ ,  $SD=7.63$ ) and all of the model results: calibrated model ( $M=4.88$ ,  $SD=7.63$ );  $t(106)=19.57$ ,  $p < 0.001$ , expert model ( $M=6.60$ ,  $SD=1.80$ );  $t(106)=17.30$ ,  $p < 0.001$  and novice model ( $M=1.32$ ,  $SD=1.07$ );  $t(106)=26.92$ ,  $p < 0.001$ .

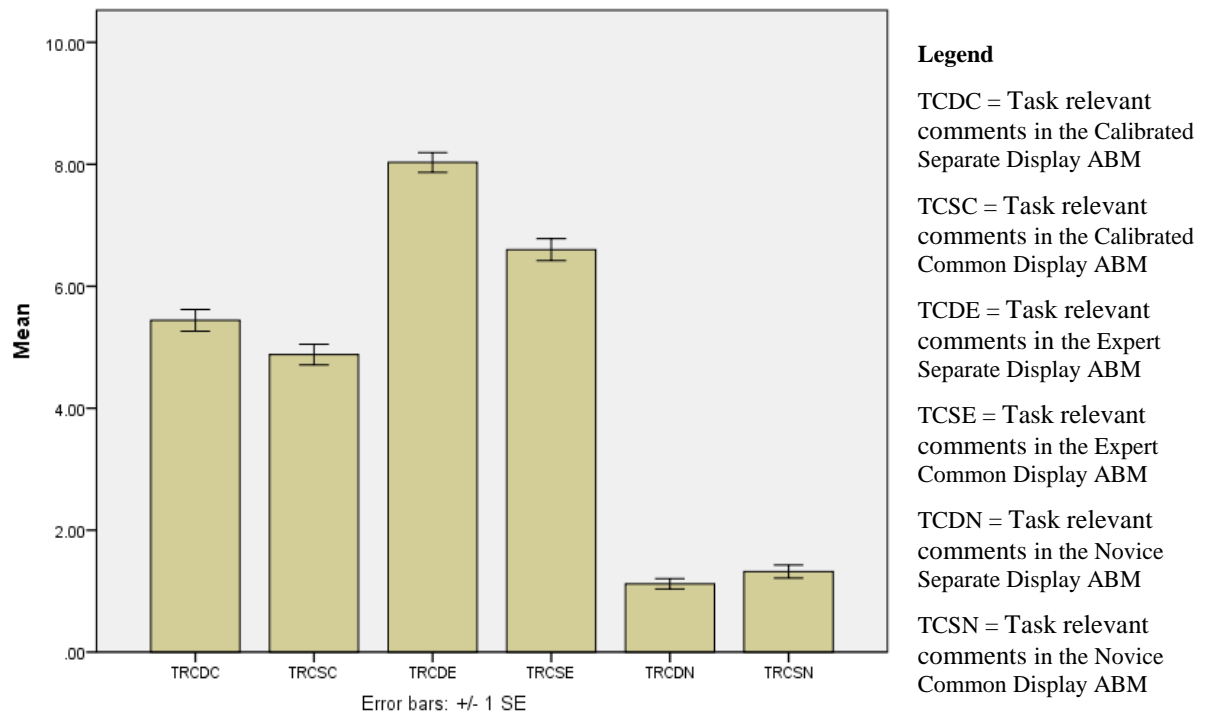
The post-hoc Independent Samples T-Test showed there was also a significant difference in the number of task relevant comments made between all of the model results: the calibrated model ( $M=4.88$ ,  $SD=7.63$ ) and expert model ( $M=6.60$ ,  $SD=1.80$ );  $t(198)=-6.96$ ,  $p < 0.001$ , the calibrated model ( $M=4.88$ ,  $SD=7.63$ ) and novice model ( $M=1.32$ ,  $SD=1.07$ );  $t(198)=17.75$ ,  $p$

< 0.001 and the expert model (M=6.60, SD=1.80) and novice model (M=1.32, SD=1.07);  $t(198)=25.23, p < 0.001$ .

### 5.3.2.2.3 Model Comparisons

A Paired Samples t-test was conducted to compare each of the model results over the two conditions and can be seen in Figure 91. The statistical results can be found in Appendix UU. There was a significant difference in the total comments results between condition 2 (M = 8.03, SD = 1.63) and condition 3 (M = 6.60, SD = 1.80) for the expert model;  $t(99)=6.00, p < 0.001$ , however there was no significant difference between condition 2 (M = 5.44, SD = 1.79) and condition 3 (M = 4.88, SD = 1.70) for the calibrated model;  $t(99)=2.18, p = 0.031$  or condition 2 (M = 1.12, SD = 0.844) and condition 3 (M = 1.32, SD = 1.07) for the novice model;  $t(99)=-164, p = 0.105$ .

*Comparison of Mean Task-Related Communication Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model*



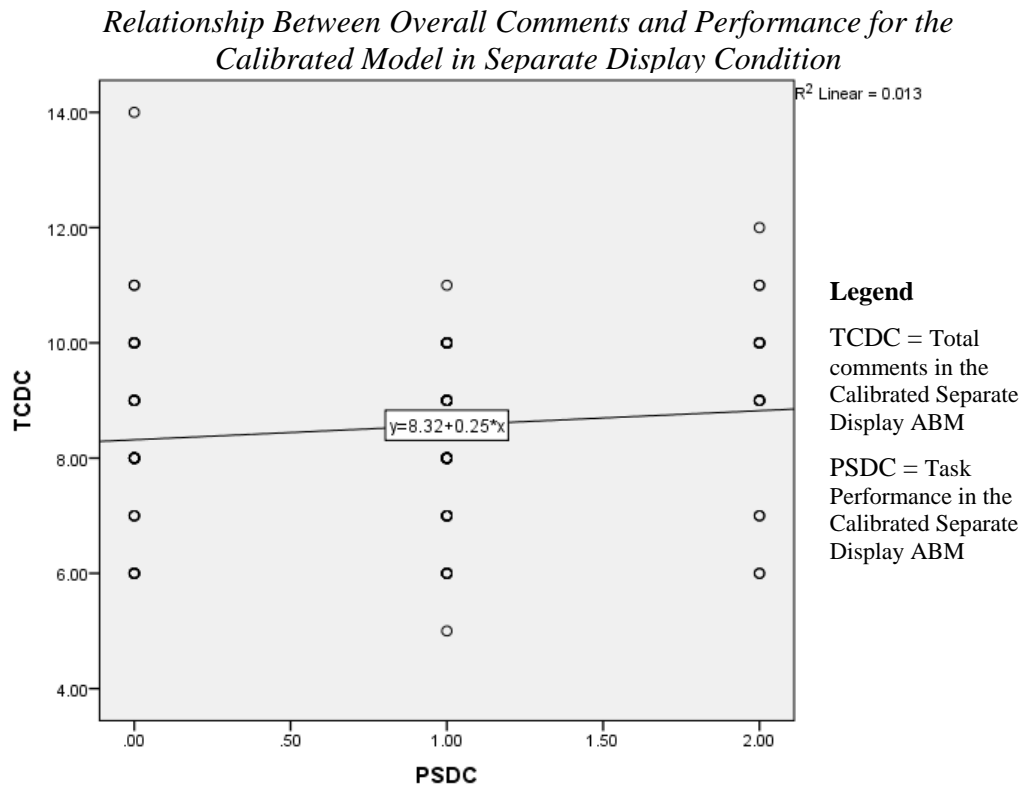
**Figure 91 - Comparison of Mean Task-Related Communication Results Between the Separate and Common Display for the Calibrated Model, Expert Model and Novice Model**

### 5.3.3 Comments against performance

#### 5.3.3.1 Total comments against performance

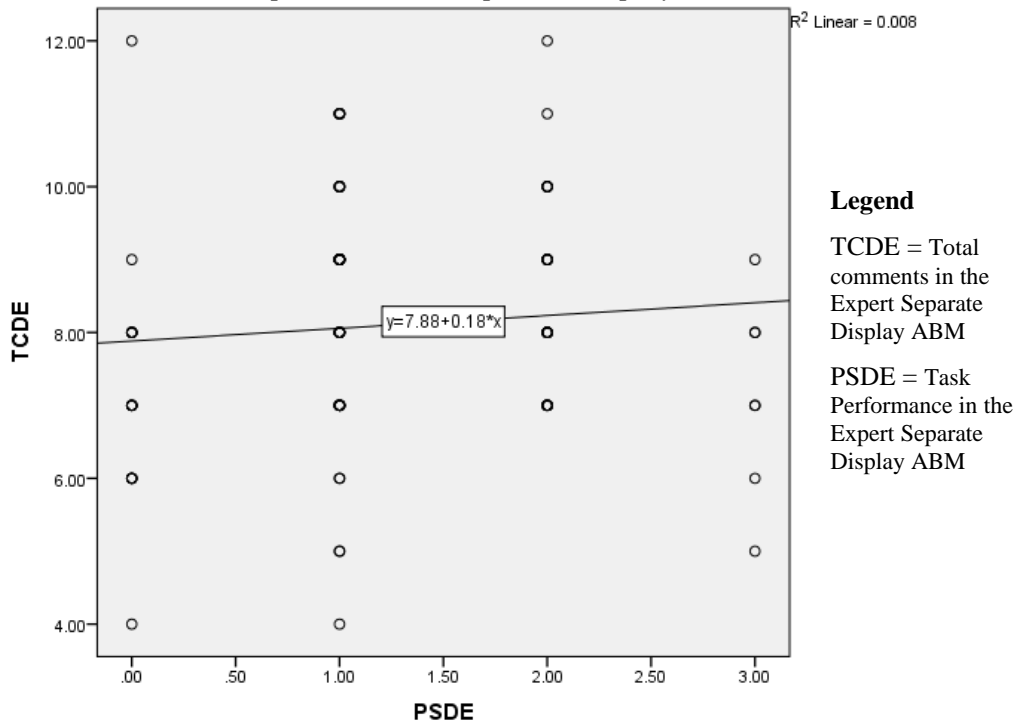
##### 5.3.3.1.1 Condition 2

A Pearson product-moment correlation coefficient was computed to assess the relationship between the team performance scores and the total comments made in condition 2 for each of the three models. The results of which can be seen in Figure 92, Figure 94 & Figure 93 and the statistical results can be found in Appendix VV. The analysis showed that there was a low positive correlation between the team performance scores and the number of total comments made in two of the three models; calibrated model:  $r = 0.392$ ,  $n = 100$ ,  $p = 0.000$  and novice model:  $r = 0.378$ ,  $n = 100$ ,  $p = 0.000$ . There was no correlation between the team performance scores and the number of task relevant comments made in the expert model:  $r = 0.101$ ,  $n = 100$ ,  $p = 0.319$ .



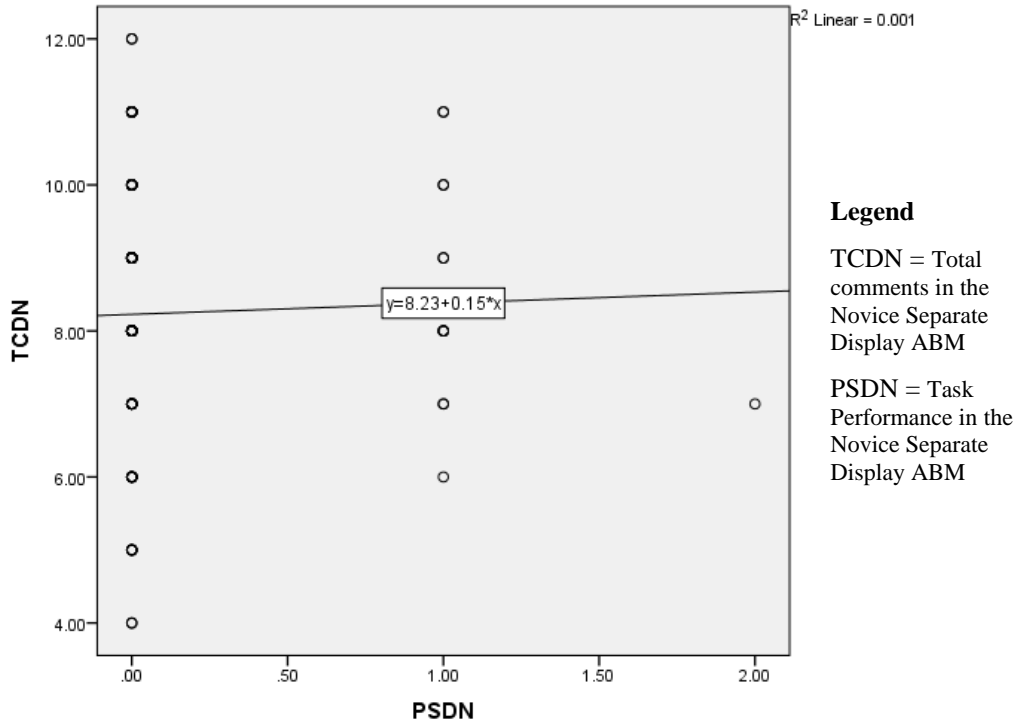
**Figure 92 - Relationship Between Overall Comments and Performance for the Calibrated Model in Separate Display Condition**

*Relationship Between Overall Comments and Performance for the Expert Model in Separate Display Condition*



**Figure 94 - Relationship Between Overall Comments and Performance for the Expert Model in Separate Display Condition**

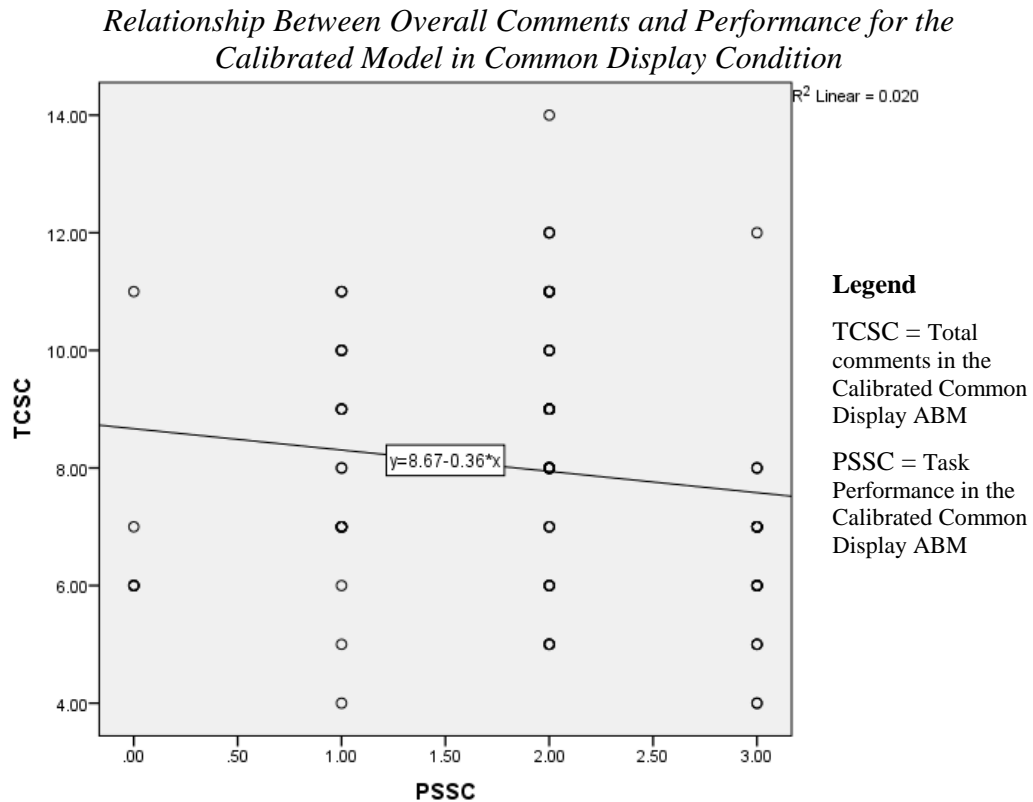
*Relationship Between Overall Comments and Performance for the Novice Model in Separate Display Condition*



**Figure 93 - Relationship Between Overall Comments and Performance for the Novice Model in Separate Display Condition**

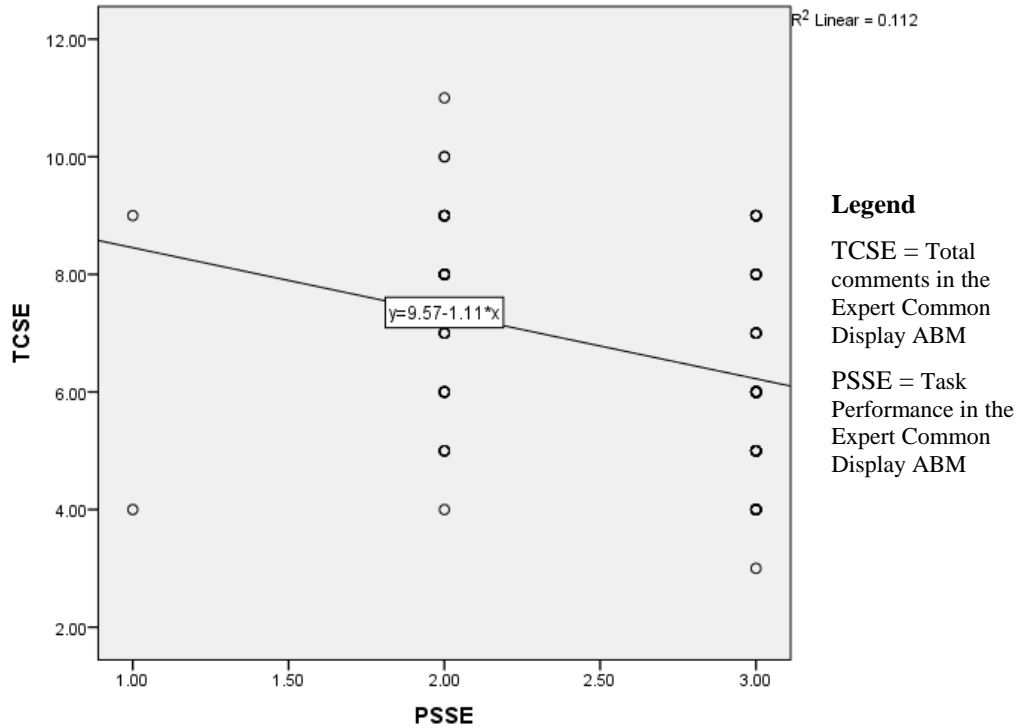
5.3.3.1.2 Condition 3

A Pearson product-moment correlation coefficient was computed to assess the relationship between the team performance scores and the total comments made in condition 3 for each of the models. The results of which can be seen in Figure 95, Figure 97 & Figure 96 and the statistical results can be found in Appendix WW. The analysis showed that there was no correlation between the team performance scores and the total number of comments made in two of the models; calibrated model:  $r = -0.143$ ,  $n = 100$ ,  $p = 0.156$  and novice model:  $r = 0.126$ ,  $n = 100$ ,  $p = 0.213$ . However, there was a low negative correlation between the team performance scores and the total number of comments made in the expert model:  $r = -0.335$ ,  $n = 100$ ,  $p = 0.001$ .



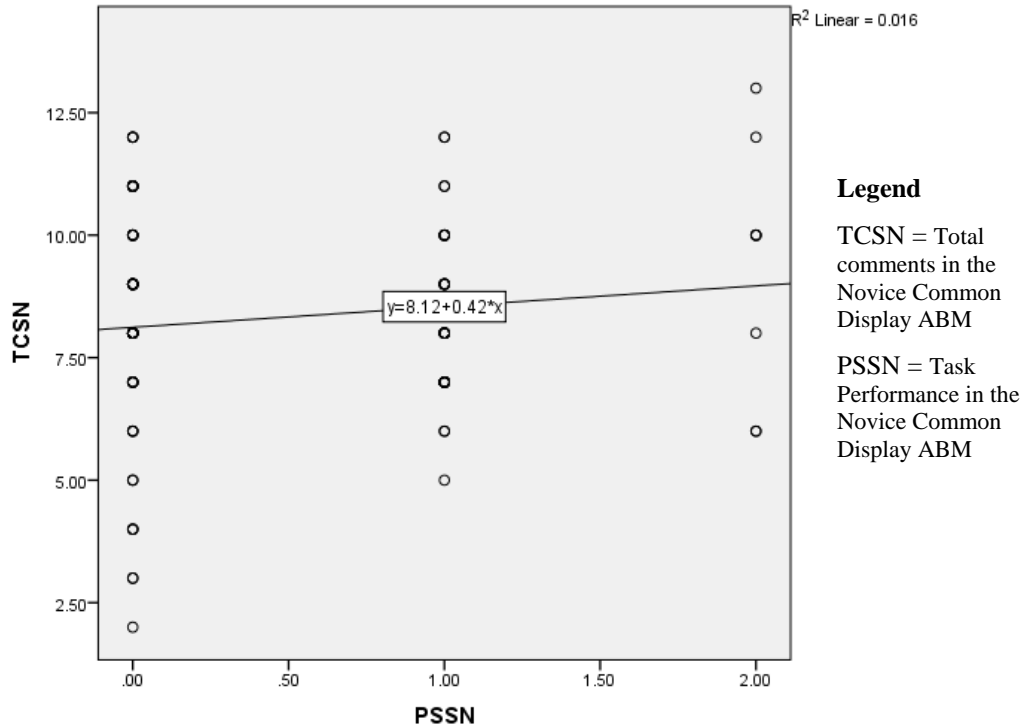
**Figure 95 - Relationship Between Overall Comments and Performance for the Calibrated Model in Common Display Condition**

*Relationship Between Overall Comments and Performance for the Expert Model in Common Display Condition*



**Figure 97 - Relationship Between Overall Comments and Performance for the Expert Model in Common Display Condition**

*Relationship Between Overall Comments and Performance for the Novice Model in Common Display Condition*

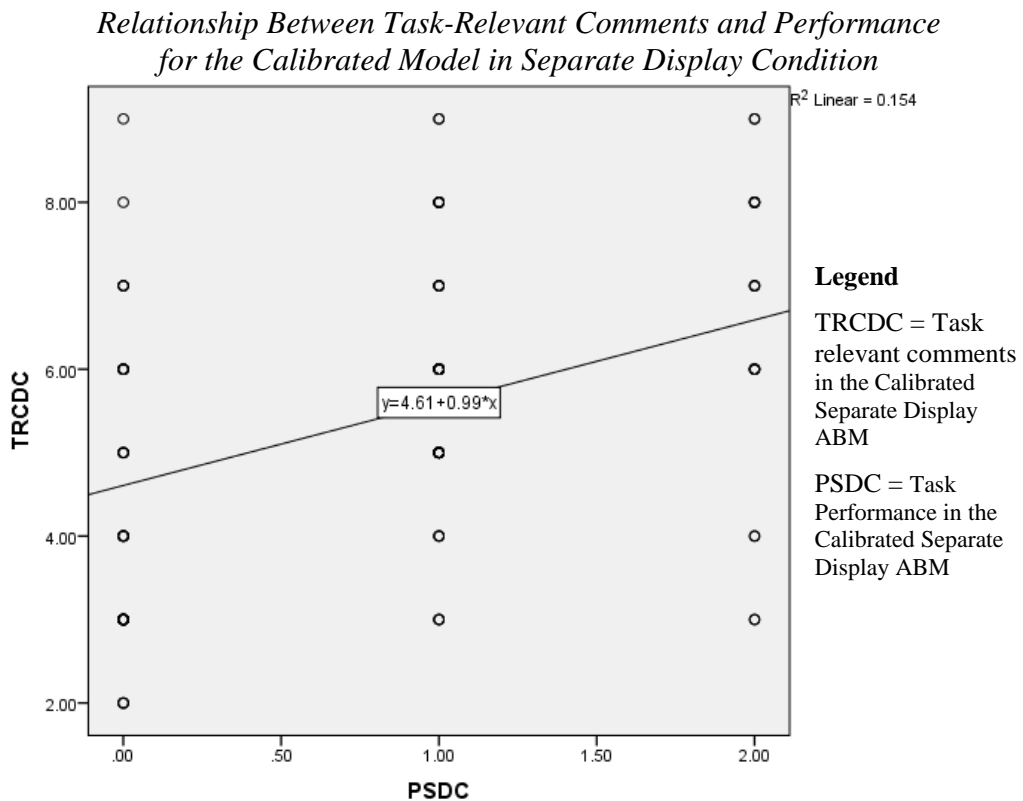


**Figure 96 - Relationship Between Overall Comments and Performance for the Novice Model in Common Display Condition**

### 5.3.3.2 Number of task relevant comments against performance

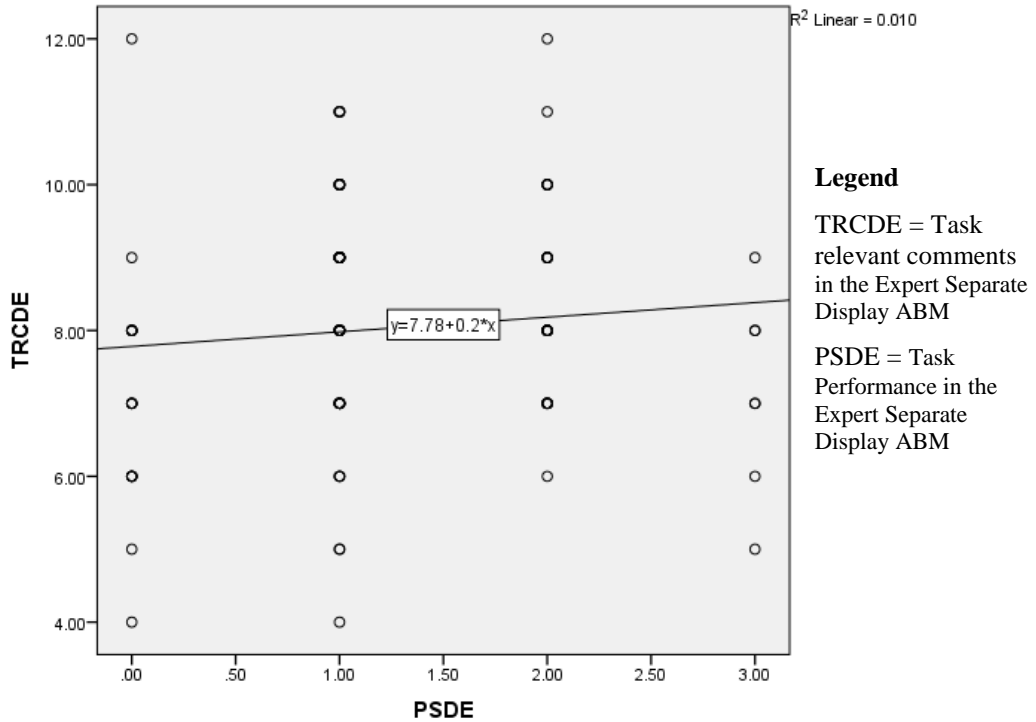
#### 5.3.3.2.1 Condition 2

A Pearson product-moment correlation coefficient was computed to assess the relationship between the team performance scores and the total comments made in condition 2 for each of the models. The results of which can be seen in Figure 98, Figure 99 & Figure 100 and the statistical results can be found in Appendix XX. The analysis showed that there was a low positive correlation between the team performance scores and the number of task relevant comments made in two of the models; calibrated model:  $r = 0.392$ ,  $n = 100$ ,  $p = 0.000$  and novice model:  $r = 0.378$ ,  $n = 100$ ,  $p = 0.000$ . However, there was no correlation between the team performance scores and the total number of comments made in the expert model:  $r = 0.101$ ,  $n = 100$ ,  $p = 0.319$ .



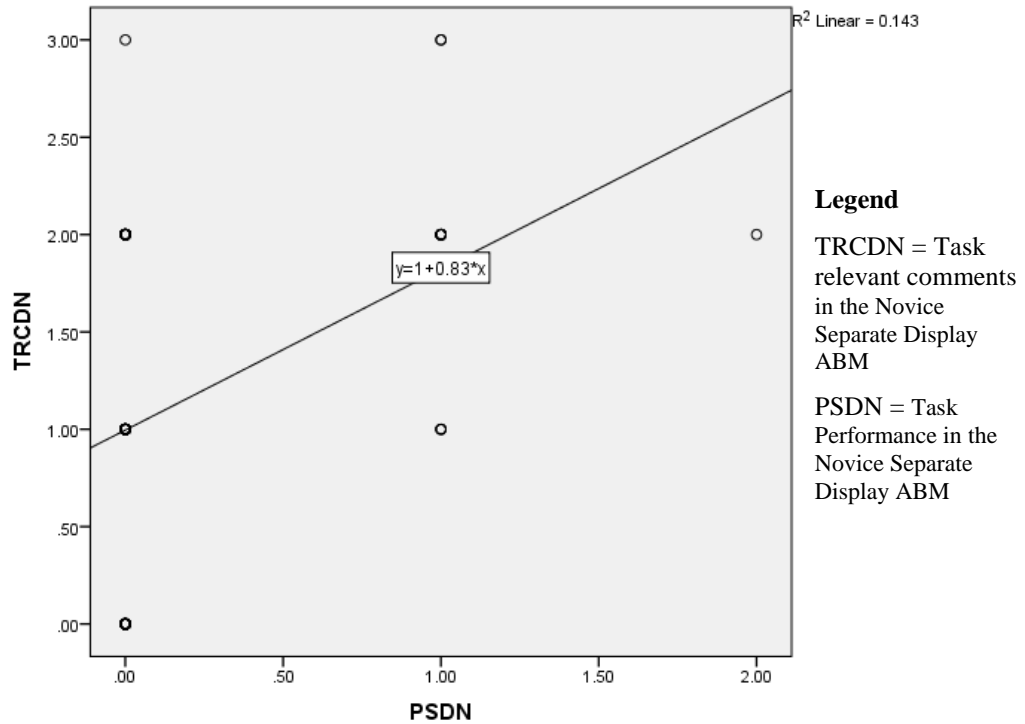
**Figure 98 - Relationship Between Task-Relevant Comments and Performance for the Calibrated Model in Separate Display Condition**

*Relationship Between Task-Relevant Comments and Performance for the Expert Model in Separate Display Condition*



**Figure 100 - Relationship Between Task-Relevant Comments and Performance for the Expert Model in Separate Display Condition**

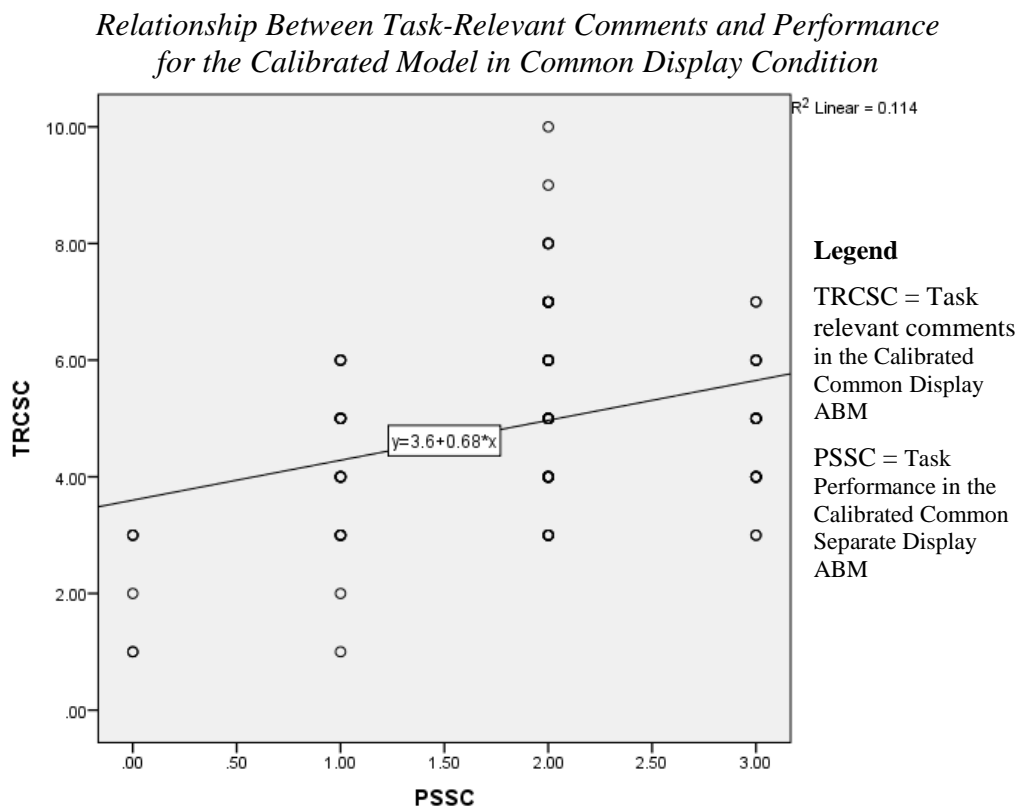
*Relationship Between Task-Relevant Comments and Performance for the Novice Model in Separate Display Condition*



**Figure 99 - Relationship Between Task-Relevant Comments and Performance for the Novice Model in Separate Display Condition**

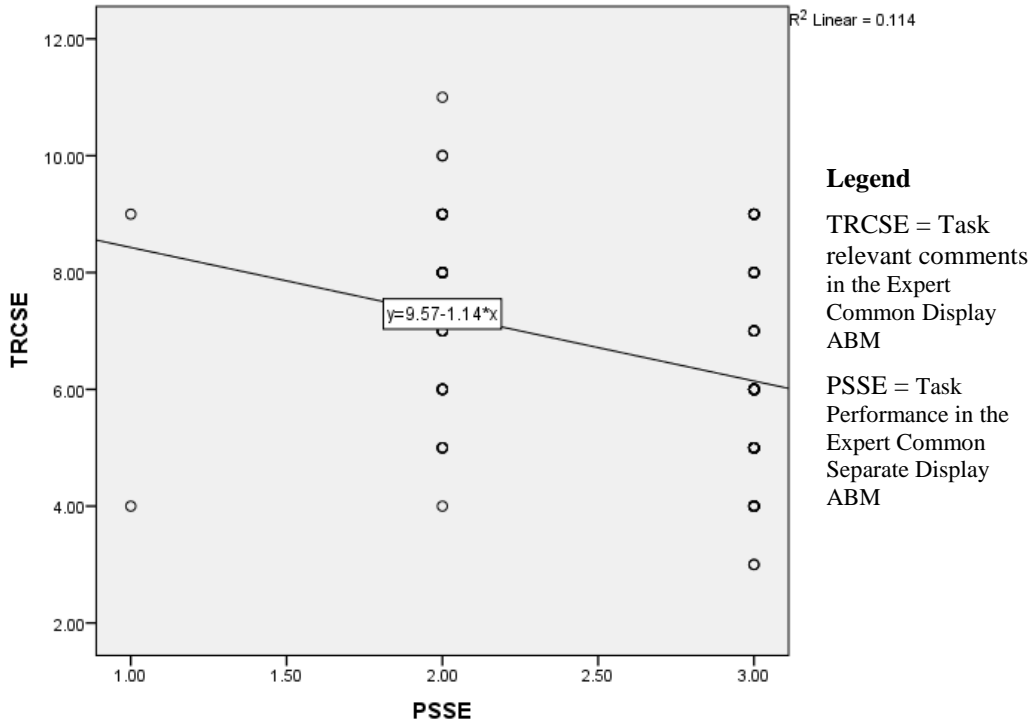
5.3.3.2.2 Condition 3

A Pearson product-moment correlation coefficient was computed to assess the relationship between the team performance scores and the total comments made in condition 3 for each of the models. The results of which can be seen in Figure 101, Figure 103 & Figure 102 and the statistical results can be found in Appendix YY. The analysis showed that there was a correlation between the team performance scores and the number of task relevant comments made in all three of the models; low positive correlation for the calibrated model:  $r = 0.338$ ,  $n = 100$ ,  $p = 0.001$ , low negative correlation for the expert model:  $r = -0.388$ ,  $n = 100$ ,  $p = 0.001$  and high positive correlation for the novice model:  $r = 0.708$ ,  $n = 100$ ,  $p = 0.000$ .



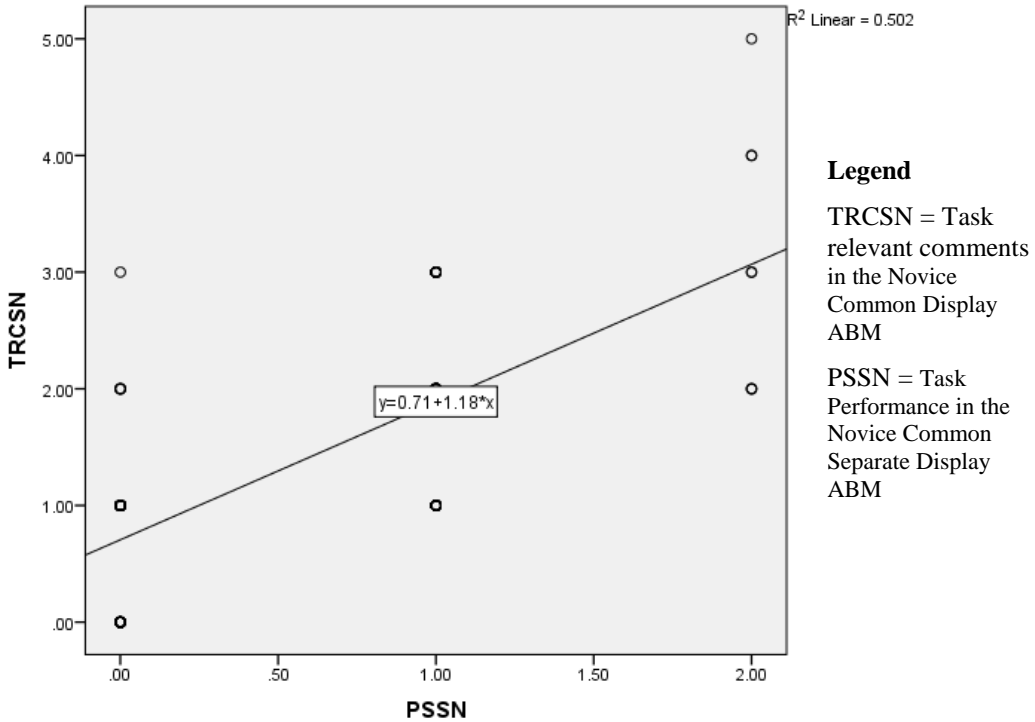
**Figure 101 - Relationship Between Task-Relevant Comments and Performance for the Calibrated Model in Common Display Condition**

*Relationship Between Task-Relevant Comments and Performance for the Expert Model in Common Display Condition*



**Figure 103 - Relationship Between Task-Relevant Comments and Performance for the Expert Model in Common Display Condition**

*Relationship Between Task-Relevant Comments and Performance for the Novice Model in Common Display Condition*



**Figure 102 - Relationship Between Task-Relevant Comments and Performance for the Novice Model in Common Display Condition**

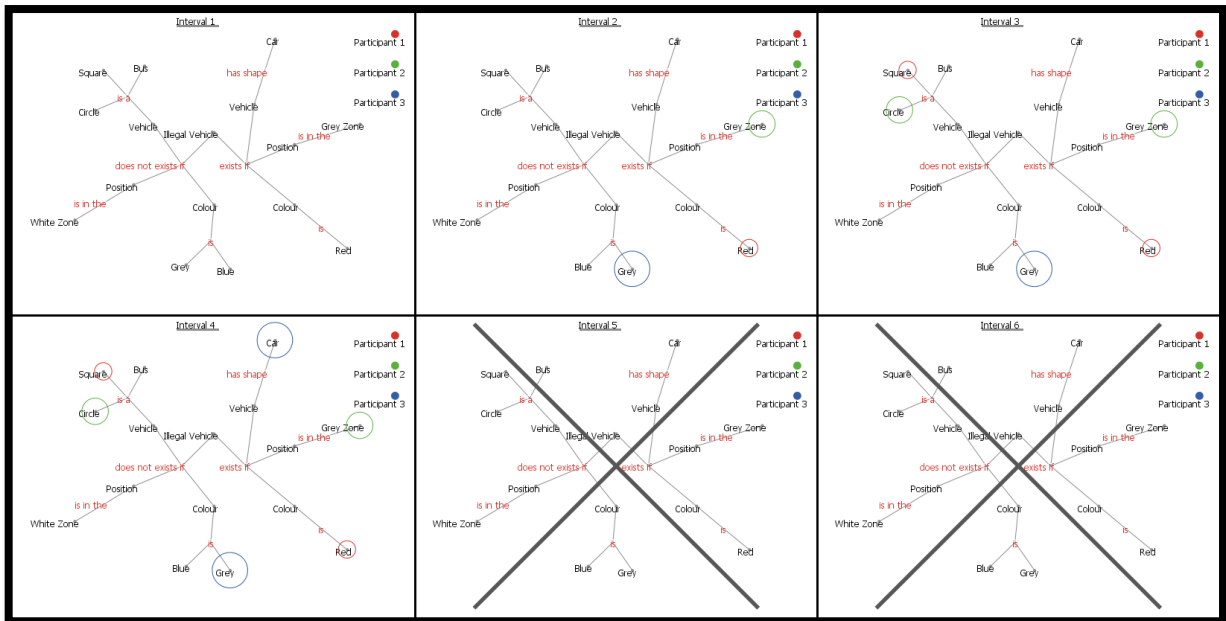
### 5.3.4 Information Held within the Network

Each model exported the data required to create a concept map at equal intervals throughout the task. An example of the concept map created can be seen in Figure 104 for the expert group. When the characteristics are identified before the end of the simulation, no data is provided for the following intervals. For concept maps with no data, a cross is overlaid.

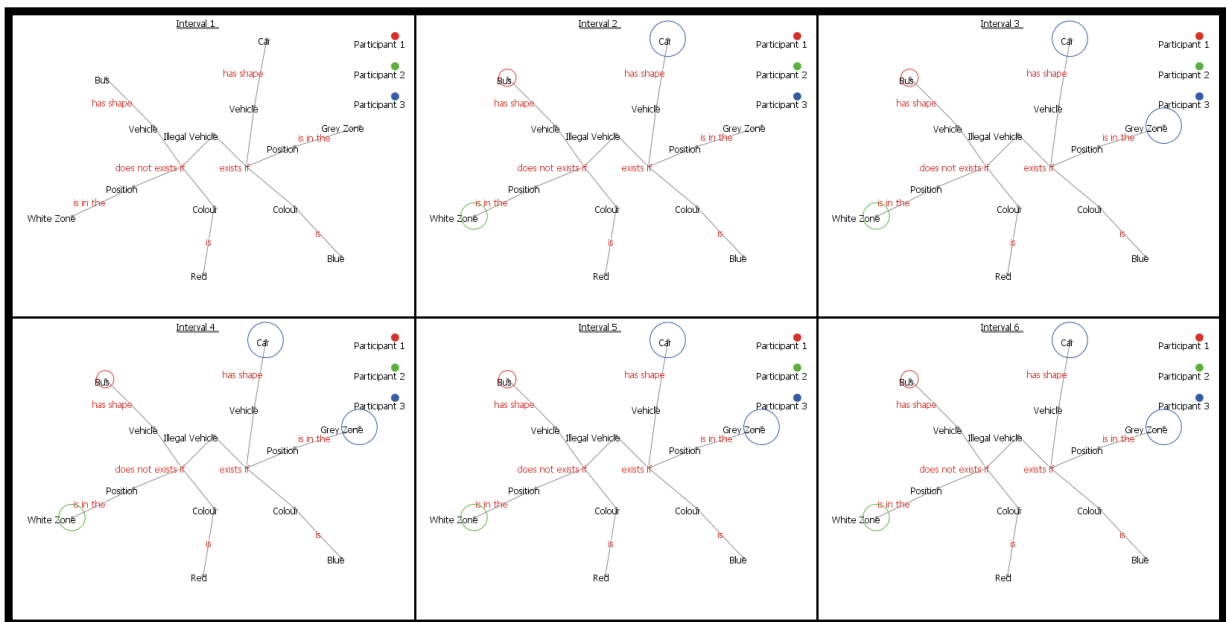
The separate display model, concept maps show that there is knowledge spread around the team without duplication. The same can be seen in the model with the same videos. With this particular group more information about the task was spread around the team when they had separate videos compared to when they had common videos. What can also be seen is that not all agents hold the same information and what information is known and missing at different points over the task. It also depicts how the information for certain agents is developed over time. Unfortunately, a goal standard for how the task should be carried out was not recorded during the experiment, however if this was available the concept maps from the model could be compared to this gold standard and show differences in how the teams in the model performed. This is an interesting piece of work that could be carried out in future ABM studies.

Visually representing system knowledge through this use of concept maps, as seen in the current and previous chapters, has allowed for a qualitative analysis of a system during the given task. By taking data at set intervals it has been possible to see when knowledge is gained and how that knowledge is distributed throughout the team. By viewing all the intervals together, it also allows for a more temporal analysis of the system, it enables the viewer to explore the dynamics of the changing system as it progresses through a task. Although definitions of SA can at times conflict, it is agreed that a key component into understanding this phenomenon is how it changes over time.

## Separate Display



## Common Display



**Figure 104 – Concept map results for the model for sperate and same videos, calibrated for expert agents**

## 5.4 DISCUSSION

In terms of performance it can be concluded that it was possible to calibrate the model to represent similar results observed in both conditions in the experiment in chapter 4. The total number of comments made however were considerably more in the experiment compared to all three of the model settings. This could be a side effect of the model simplification or the design on the agent rules. The results imply that the agents within the model were much more efficient than the humans when it comes to communication to complete a task. The results also suggest that the calibrated and expert model, in terms of performance, were no different than the teams in the experiment in Chapter 4. That is teams in Chapter 4 were performing closer to the expert agents in the model, than the novice agents. This could mean that either the groups were, in general, skilled at the task or that the difficulty of the task itself may have been set too low. The models did show that it was possible to create different levels of expertise based on communication and the results of which supported this, with the novice model performing significantly lower than either the calibrated or expert teams, regardless of the condition. The performance of the calibrated model was also higher in the 3<sup>rd</sup> condition compared to the 2<sup>nd</sup> condition, a result also seen in the experiment. This increase in performance was also seen in each of the other two models across the conditions.

Therefore, based on the performance results of the calibrated model compared to the experiment, one can conclude that the models can replicate similar behaviour and actions to humans, which can in turn be simply manipulated in a realistic way (i.e. changing the content of communication).

When exploring the communications made within the models, there were no differences in total comments made in condition 2. However, in condition 3 experts made fewer total comments than either of the other two models and comparing this to the task relevant

comments, experts made significantly more than the other two models in both conditions. This suggests that the experts were more efficient with both the number of comments made and the types of comments made. When comparing the two conditions, it was only the expert model which showed a reduction in total comments made in the 3<sup>rd</sup> condition, although when it comes to task relevant comments both the expert and calibrated model showed this decrease. One would expect, with the expert models performing higher with less comments that there would be a relationship between the two. However, just like in the human experiment there was no relationship seen between the performance and total comments for any of the model results in condition 2. In condition 3 there was a slight negative correlation between performance and total comments for the expert model, suggesting that more comments actually hinder performance.

Relationships between task-relevant communications and performance tells a different story. For condition 2, the calibrated and novice models showed low positive correlations, suggesting that in these models during this condition the more task relevant comments made, the higher the performance. Interestingly, the expert model did not share this relationship. When looking at the results in condition 3 on the other hand, all three models showed some positive correlation between task-relevant communications and performance, with the novice model showing the highest correlation of all models in all conditions. This suggests, that when the novice models were able to make task-relevant comments it had a significant impact on the performance of the team.

In this chapter the models allowed the exploration of the use of Common or Separate Displays used by teams of agents to complete a task. It appears that the differences are only apparent in conditions where agents are most likely to ask task-relevant questions. Thus, it is important that the content of what is shared, i.e. task-relevant material. This supports the assertion of

team cognition, regarding task relevance and communication quality. However, it is also apparent that working separately seems to be beneficial to the ‘expert’ groups in this model. Presumably communication interrupts task activity and leads to redundancy of information held in the ‘system’ (as illustrated by the concept maps). When expert agents communicate more, time is “wasted”. The results previously discussed supports this premise.

The modelling explores the way in which ‘information’ is used and shared. In the model, it is not assumed how the actions are performed cognitively but only that it takes a specific time. Thus, the act of sharing could be a verbal exchange, but it could equally be an updating of a common information log. Further refinements of the model could manipulate times for communication so that, for instance, verbal exchange would take longer than updating a common log (because of the need to send a message and receive acknowledgement).

However, the point to note from this chapter is that even a small time spent communicating has an impact on overall performance (both in terms of time, as one would expect, but also in terms of likelihood of success). In the other manner in which information is shared, all agents have access to the same view of the situation.

In this chapter the manner in which three-person teams perform tasks in which they have access to the same information or to individual information sources was explored. The exploration involved an experiment and agent-based modelling. In the experiment, teams found the condition in which different information was presented to each individual more difficult than the condition in which information was common. This suggests that when the situation is challenging or ambiguous, simply communicating might not be the most effective response. At first glance, this feels counter-intuitive: surely, in an ambiguous situation, it would be sensible to spend time communicating in order to reach consensus as to the key issues. From the experiment and the model, it appears that this need not improve performance.

It was initially hypothesised that communication carries with it an overhead that could disrupt task performance. From the experiment and the models, it seems that this overhead could be not simply related to time or to task disruption but also to the focus of team activity via the use of task-related communication.

In terms of SA, this and the previous chapter makes three claims. The first is that concept maps, as Hoffman et al. (Hoffman et al., 2002) propose, provide a useful means of representing knowledge and that such mapping illustrates how SA is held in a 'system' (Stanton et al., 2006). Comparison between low and high performance teams in the experiment, and between novice and expert teams of agents in the modelling, show how the distribution information relates to overall performance. In some teams, relevant information was utilised and in other teams such information was duplicated. In either case, overall performance could be comprised: in terms of lack of information, in terms of time 'wasted' in duplication or unnecessary communications. In this task, the situation was designed in such a way as to create a direct mapping between having a piece of information that defines a characteristic of a vehicle and the SA for the task, i.e., defining a vehicle as illegal. The task is constrained but it is proposed that the levels of uncertainty and ambiguity in the Separate Displays condition created real problems for participants in the experiment.

One might expect teams to deal with uncertainty through increasing their communication. In this way, common ground could be established through information sharing and the team could provide Shared SA. This behaviour was only seen in the poor performance teams in the experiment and novice teams in the model. Clearly team performance was affected by more than the type of display and the factors such as familiarity influenced behaviour (Salas et al., 2008, 1995). However, it was also noted that the high performance teams appeared to maintain a style of performance irrespective of display and irrespective of number of

comments made, in which tasks were performed independently and then the results shared and it could be argued that this is analogous to Distributed SA (Baber et al., 2006; Salmon et al., 2008; Stanton et al., 2006). The results of the models suggest that this is an optimal strategy and that unnecessary non-task related communicating can impair performance (Salmon et al., 2010), results that are consistent with the previous two chapters.

#### **5.4.1 Concept Map Critique**

The method of using concept maps can provide a rich set of results to view, however it fails in its ease for interpretation, a failure shared with the SNA in chapter 4 and proposition networks currently used for analysing DSA (Stanton et al., 2006). Even with a small number of intervals, it becomes difficult to interpret what is happening. With increasing intervals, this interpretation would become even more difficult. As with most qualitative methods, not only is the time taken to complete the outputs significant but so is the analysis of those outputs. Using ABM and automated concept map generators does indeed reduce the creation time, however the interpretation of the concept maps remains time consuming and cumbersome. Imagine giving a system analysis within a time-critical task environment numerous concept maps to interpret, how long would it take to complete to the analysis and how much would they be able to remember about the system after many intervals have passed. As previously discussed, tasks which consume time in these environments are likely to delay critical decisions required by the system and in turn result in low performance. Clearly, using a time series of system data is beneficial to understanding the changing nature of a system and the generated results based on intervals in these chapters is a step towards providing a useful analysis of that data, however providing a constant stream of figures to an individual to analyse is not ideal or practical.

Using the example of the system analyst, the question now is: what could be provided that would make the task of analysing system SA less time consuming and more intuitive? It has already been shown that data obtained via transcriptions of communication is a non-intrusive and, from the view point of the agents within the system, objective method of data collection. There is no need for an agent to interpret or suggest what it is they may or may not know, or how they are working within the system. Provided that the communications are analysed in a consistent way from system to system and agent to agent, even the analyst need not interpret what the communications imply. Additionally, communication within a system is temporal and therefore can provide a high resolution of data over the full length of the task being monitored. However, simply providing the analyst a stream of high resolution and low-level data would incur the same problems as would providing numerous figures and images. The problem here is that the focus has been on individuals, the micro world of the system, individual concepts and actions, trying to provide all of this and expecting to witness the emergence of system behaviour. It is like a bee trying to understand the behaviour of the swarm by observing its neighbour's actions, rather than the behaviour of the swarm as a whole. It is the system that is the focus and how it evolves over time, it is from the ground where insight into the emergence of the swarm behaviour can be observed, or in other words, the emergence of DSA within a system.

The following chapter takes on this notion of system observation, it steps back from the individuals and explores how communications can be used to provide a higher-level analysis of system performance, focussing on the dynamics of systems and how situation awareness changes over time.

## **5.5 MODEL CRITIQUE**

This chapter has shown that the use of agent-based modelling can be used to gain insight into how basic communication and knowledge acquisition can represent certain human attributes. Modifications to the model could provide an avenue to exploring other human attributes, for example, change the rate and speed of communication to increase the workload of the agents. The ability, capability or effort of the agents could be increased or decreased as well as the amount an agent could “know” both in the short-term or long-term could also be modified.

These additions would make the model more complex and allow the addition of more humanlike reactions to a situation/condition. Due to the nature of agent-based modelling, the attributes can be changed and manipulated independently, and the effects of those changes can be reliably explored.

## **5.6 SUMMARY**

The work in this chapter presents the development of a model which simulates the actions of the teams involved in the experiment in Chapter 4. The simulations carried out aimed to explore the information flow and knowledge acquisition of the agents within the system. The results presented used concept maps to display the temporal nature of the organisation of knowledge throughout the team structure. To further explore how communication can be used to analysed team structures the communication transcripts obtained from the experiment in Chapter 4 are again used in the next chapter. The content of these transcripts is used to extract participant actions, described as team processes, and the entropy those processes. To analyse the data fully, several displays of the team processes are presented.

# CHAPTER 6 THE DYNAMICS OF DISTRIBUTED SITUATION AWARENESS

*Parts of this chapter have been published in:*

*[1] “The Dynamics of Distributed Situation Awareness” in the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2017, 61(1), p 277-281.*

*The sections: Introduction on Page 277 of [1] has been used to prepare the chapter.*

*The sections: Entropy Method on Page 277 of [1], Application of Entropy Method on Page 278 of [1], Coherence Entropy Time Series and Entropy Peaks on Page 278 of [1], Interaction Entropy Time Series on Page 279 of [1] have been reproduced in this chapter.*

*The work in this chapter is based on the work in [1].*

## **6.1 INTRODUCTION**

As stated in Chapter 2, in many collaborative problem solving situations team situation awareness should be more than just the sum of its parts, i.e. the sum of the individuals situation awareness (Garbis and Artman, 2004; Gorman et al., 2006). In this chapter, the interest is in analytic methods which capture team SA and interactions. One such method of doing this analysis was employed by Wiltshire et al (2017), where communication transcripts are coded based on the actions they represent. Utilizing the concept of order and disorder, also known as entropy, within the system and analysing the data over a sliding window. These results could be plotted as a time series which represents the dynamic nature of the system. To better understand entropy, an explanation of has been provided in the following sections.

Wiltshire et al (2017) used a method which to identify the phase transitions of actions between groups of individuals during a problem-solving task. They found that peaks in entropy corresponded to shifts in collaborative problem-solving communications and therefore identified that teams exhibit phase transitions during collaborative problem solving. They also discovered that lower levels of entropy predicting better performance. In this chapter, the same methodology was used to provide a metric for analysing system SA. Previous methods of analysing system SA has resulted in numerous outputs, for example the concept maps within this thesis and the use of proposition networks (Stanton et al., 2006). It is argued that by characterizing this knowledge in terms of actions this method can provide a way of analysing system SA over time in such a way that only one output is required. This chapter aims to present such an output.

### **6.1.1 Entropy & Thermodynamics**

The term entropy is better known in thermodynamics to describe the configuration of energy within matter, known as energy states, and the likelihood of those energy states occurring. The configuration where energy is most spread out among the matter has the highest entropy, and concentrated energy has low entropy. As the probability of the energy of matter becoming spread out is considerably higher than it becoming more concentrated, natural states of matter will always tend towards high entropy. For example, a hot cup of water contains high energy compared to its surrounding environment and so this system has low entropy and the energy within it is not spread out. The likelihood of the energy states of the hot water and the surrounding environment being spread out is significantly higher than the hot water remaining at the same temperature or getting hotter. As these energy states spread out, the entropy of the system will increase until the point where the surrounding area and the water contained in the cup has the same amount of energy states, which can be described as high entropy. A more

simplistic way of understanding this is by viewing these energy states as either ordered or disordered. When the energy was concentrated to the water, resulting in hot water, the energy in the system was ordered. When this energy was spread out across the system, the energy was disordered. Another example of this transition between an ordered state and a disordered state can be seen in Figure 105 and shows changes of state of matter of water. When the state of water molecules is ordered it is in the form of ice. As there is little energy within the ice, the molecules remain in a rigid structure. In this state the water can be described as having low entropy. As energy is applied to this structure, in the form of heat, the number of energy states increases and the molecules within the ice cube become less rigid and in turn less ordered. As more energy is introduced, the molecules become increasingly disordered, until there is no order, i.e. spread out, and the molecules can move around freely a gas. The water, now steam, can be described as having high entropy.

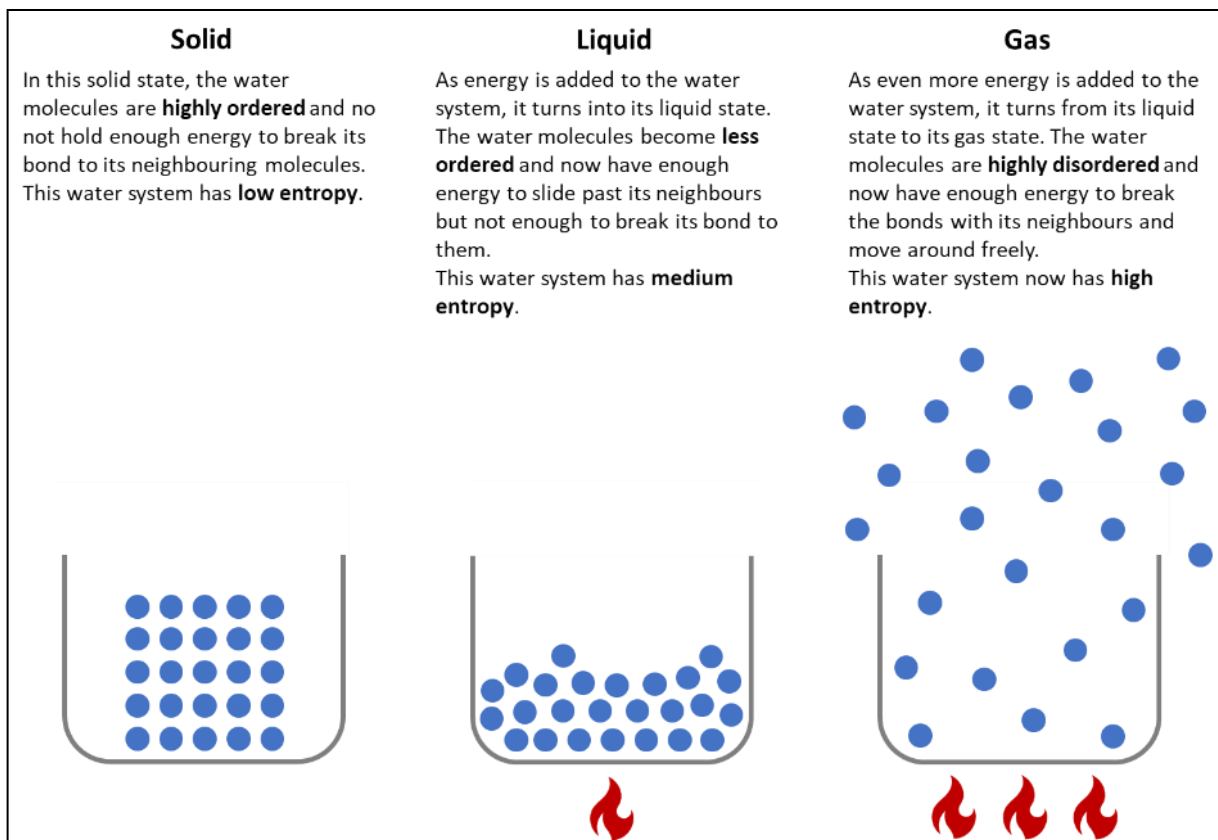


Figure 105 - Changes of states of matter of water

### **6.1.2 Entropy & Team Cognition**

The work in this chapter relies on Shannon & Weavers (1959) theory of entropy in terms of information data rather than thermodynamics. The definition of entropy in information entropy is no different to the definition in thermodynamics, however what is being observed is. As previously stated, in thermodynamics entropy is a description of the likelihood of energy states within a system. In information entropy, entropy is a description of the likelihood of a bit of information being produced by a stochastic source of data. Here it is the probability of these information bits that is of interest. Shannon & Weavers (1959) produced an equation of entropy, which was used to determine the smallest possible size for encoding information. In this sense Shannon defined entropy as the smallest possible average size of encoding a message, while retaining all information required and reducing uncertainty within the message. In this sense, high entropy relates to more specific information within the code, that is more disorder in the information provided. When the entropy is low, less specific information is provided and therefore there is more order.

The work by Stevens and colleagues (Likens et al., 2014; Stevens, 2012; Stevens et al., 2012) have taken this approach and applied it to the theory of team cognition. They estimate a value of entropy from the distribution of team neurodynamic states using EEG data to explore expertise and performance in relation to the degree of cognitive flexibility exhibited by the team. In this sense, higher entropy relates to more cognitive flexibility, and teams exhibiting this higher cognitive flexibility are utilizing more potential cognitive states. Wiltshire et al (2017) noted that the work by Stevens and colleagues tends to focus on the relationship between the calculated entropy and team performance and not the patterns of entropy exhibited by the teams. This lead to the work by Wiltshire et al (2017) where the entropy measures are used to detect transitions between problem solving processes, i.e. ways of

working, by coding communication transcriptions in relation to these team problem solving processes. They focus on the content of communication and how it can be quantified in terms of entropy. Figure 106 - Ordered (low entropy) communication content and disordered (high entropy) communication content simply shows the difference between ordered (low entropy) communication content and disordered (high entropy) communication content.

Wiltshire et al. (2017) do not delve further into the content of the values created nor the patterns of problem-solving processes occurring. The work in this chapter has aimed to provide this by initially using the same method used by Wiltshire et al (2017), but then providing a way in which the processes taking place can be visually presented and analysed.

### Ordered Communication

In this team communication all members of the team are exhibiting the same team process (e.g. transferring information). As this is highly ordered communication, it can also be described as having low entropy.



### Disordered Communication

In this team communication the members of the team are exhibiting the different team process (e.g. transferring information, problem solving, requesting knowledge). As this is highly disordered communication, it can also be described as having high entropy.



**Figure 106 - Ordered (low entropy) communication content and disordered (high entropy) communication content**

## **6.2 HYPOTHESIS**

The hypothesis of this chapter is that using entropy to measure and analyse situation awareness will provide evidences to support the notion of distributed situation awareness as an emergent property of a system, provide a way of analysing teams in a non-intrusive way which does not require operators to self-report or observers to rate individuals and provide a analysis method which can identify patterns in behaviour based on the content of communication.

## **6.3 METHOD**

The method used by Wiltshire et al (2017) integrates theory on collaborative problem-solving with dynamical systems theory, providing a way of identifying problem-solving phase transitions in team communication. They use a coding scheme derived from Rosens's (2010) Macro Cognition in Teams model, which represents 6 semantic categories of CPS processes; team information exchange, team knowledge sharing, team solution option generation, team evaluation and negotiation of alternatives, team process and plan regulation and other (e.g. tangent/off-task or simple agree/disagree). These 6 categories were divided into 15 detailed sub-categories and thus provide 15 codes (Wiltshire et al., 2017) which were assigned to the communication transcripts. Figure 107 and Figure 108 show an excerpt from Wiltshire et al.'s (2017) paper showing these codes and categories.

Wiltshire et al (2017) used communication transcript data obtained from a collaborative problem-solving task and assigned each comment one of the 15 codes. Figure 109 shows an excerpt from Wiltshire et al (2017) showing how the category codes were assigned to the transcripts.

Table 1  
Codes for team communication collaborative problem-solving processes (adapted from Rosen, 2010)

Process	Code	Brief Description
Team information exchange	1. Information provision (IP)	Utterances containing facts about the task environment or situation—simple information that can be accessed from one source in the display and “one bit” statements
	2. Information request (IR)	Question utterances asking for a response of simple information about the task environment or situation, or questions asking for repetition of immediately preceding information
Team knowledge sharing	3. Knowledge provision (KP)	Statements about the task environment or situation that provide either (a) an integration of more than one piece of simple information, or (b) an evaluation or interpretation of the meaning, value, or significance of information with regard to the current subtask
	4. Knowledge request (KR)	Question utterances that request a complex information response about the task environment or situation: to answer the question, the response should provide either (a) an integration of more than one piece of simple information, or (b) an evaluation or interpretation of the meaning, value, or significance of information within the current subtask
Team solution option generation	5. Option generation—Part (OG-P)	Statements that provide an incomplete solution—a sequence of actions (i.e., getting a certain tool) intended to contribute to a given subtask—or ask for further refinement and clarification of a solution. These are propositional and suggestive in nature
	6. Option generation—Full (OG-F)	Statements explicitly proposing a complete or near-complete solution—a sequence of actions intended to accomplish part of the task. A complete solution includes reference to specific actions, tools, system components, and actors
Team evaluation and negotiation of alternatives	7. Solution evaluation (SEval)	Utterances that (a) compare different potential solutions, (b) provide support, criticism, or indifference to a potential solution, or (c) ask for evaluation of a solution

(continued)

Figure 107 - Excerpt from Wiltshire et al (2017) showing the collaborative problem-solving process codes and categories

Table 1 (continued)		
Process	Code	Brief Description
Team process and plan regulation	8. Goal/task orientation (GTO)	Utterances directing the team's process or helping it do its work by proposing questioning, or commenting on goals for the team or specific actions team members need to take to address a goal. These statements direct what the team should do next or later in the future. This includes self-references for an individual and are generally more assertive and focused on individual tasks
	9. Situation update (SU)	Statements that provide information regarding what the team is currently doing or what is currently happening with the simulation
	10. Situation request (SR)	Statements that ask about what the team is currently doing or what is currently happening with the simulation
	11. Reflection (R)	Utterances that provide or ask for a critique or evaluation of the performance of the team as a whole or of individual members
Other	12. Simple agree/disagree/acknowledge (S)	Simple agreement/disagreement utterances are expressions of agreement or disagreement with no rationale provided. Acknowledgements are utterances providing recognition of receipt of communication
	13. Incomplete/filler/exclamation (INC/F/EX)	Fillers are sounds or words that are spoken to fill gaps between utterances. An exclamation is an utterance that has no grammatical connection to surrounding utterances and emphatically expresses emotion such as laughter. Incomplete utterances are statements that have no explicit meaning because they are missing one or more critical components of grammar: subjects, verbs, or objects
	14. Tangent/off-task (T/OT)	Non-task-related statements, including jokes, sarcastic comments, comments on the nature of the experiment, and statements that have nothing to do with the task at hand
	15. Uncertainty (UNC)	Uncertainty statements explicitly express either general or specific uncertainty about the roles, tasks, situations, or anything else task-related

Figure 108 – Continued excerpt from Wiltshire et al (2017) showing the collaborative problem-solving process codes and categories

<b>Time- Min/Sec</b>	<b>Utterance/Action</b>	<b>T12 Code</b>	<b>Code Description</b>
2:57	Okay.	13	Uncertainty
2:58	Alright.	13	Uncertainty
2:59	How do you want to start this off?	8	Goal/Task Orientation
3:01	Uh, I say one of us repairs the, uh, solar panel and the other person repairs the the cable lines.	6	Option Generation - Full
3:07	Alright- let's see where we can we-	13	Uncertainty
3:09	What do you want- What do you want to do?	8	Goal/Task Orientation
3:12	I can repair the, uh, solar panels.	6	Option Generation - Full
3:14	Alrighty, I'll go get a holder and a wrench since I'm here.	8	Goal/Task Orientation
3:17	Yeah.	12	Simple Agree/Disagree Acknowledgement
3:36	Lovely weather we're having.	14	Tangent/Off Task
3:42	Alright, come on...need a wrench.	3	Knowledge Provision
4:00	Hey, are there any black ones?	2	Information Request
4:01	Not that I can see.	1	Information Provision
4:03	Which I guess is a good thing.	3	Knowledge Provision
4:06	Yeah, those we would have to replace.	3	Knowledge Provision
4:11	Wait, what do you mean I can't- what?	13	Uncertainty

**Figure 109 – Excerpt from Wiltshire et al (2017) showing how the category codes were assigned to the communication transcripts in their study**

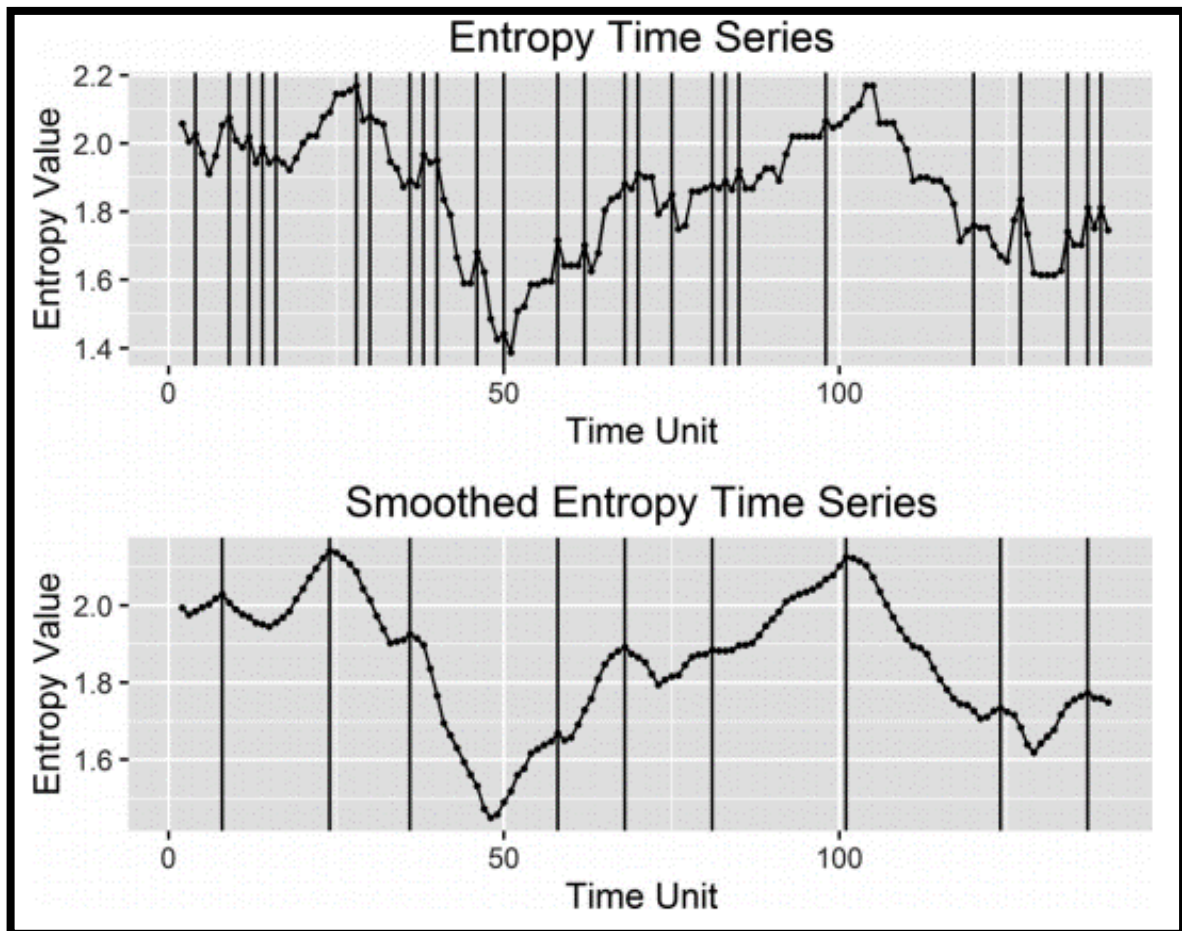
Applied over a moving time window, this provides a series of entropy values, represented as an entropy time series, which show fluctuations of communication states over time. In order to obtain an entropy time series of the coded transcript data and therefore show the changing states in communication over the duration of the task, Wiltshire et al (2017) used a sliding window of 25 (i.e. 25 occurrences of transcript data) and calculated the entropy of each of those windows using the Shannon information entropy equation (Shannon & Weaver, 1959) (Equation 1).

**Equation 1 - The Shannon information entropy equation with 15 process codes**

$$entropy = - \sum_{i=1}^{15} p_i \times \log_e p_i$$

In Equation 1, “ $p_i$  corresponds to the relative probability that a given communication code  $i$  occurred.” In their paper,  $i$  is one of the 15 communication codes (Wiltshire et al., 2017).

To increase the robustness of this process Wiltshire et al (2017) applied a moving average smoothing algorithm, with a period of 5, to the entropy time series. Figure 110 shows an excerpt from Wiltshire et al (2017) showing the results of applying the entropy analysis and smoothing algorithm.



**Figure 110 – Excerpt from Wiltshire et al (2017) showing the results of applying the entropy analysis and smoothing algorithm to the communication transcripts in their study**

Knowing which data points were peaks in the smoothed entropy time series and their respective window of transcript data, Wiltshire et al (2017) identified whether phases of the problem solving process (i.e. individual sub-tasks) fall within the peaks identified. This part of the entropy method was not used in this chapter and therefore a detailed description of how this was achieved has been omitted.

This method was adapted to explore whether the communication during the collaborative problem-solving activity in Chapter 4 can be identified by encoding communication transcripts and calculating a coherence and interaction entropy time series of that data. The method for doing this will now follow.

### **6.3.1 Application of Entropy Method**

The data used in this chapter was taken from the experiment in chapter 4 and for a recap of the experiment please refer to that chapter.

The entropy method was applied to create two time series: a coherence entropy time series (which reflects points of common ground, in terms of the type of information that is being shared) and an interaction entropy time series (which reflects the level of engagement between team members). In the coherence time-series, low entropy values correspond to a high coherence as there is a focus on one particular subtask, i.e. there is high order in the problem solving system. In the interaction time-series, low entropy values correspond to low interaction, as the team member engagement tends to one, that is only one particular team member may be talking resulting in low interaction. As different team members get involved in the task, the disorder will increase, resulting in higher entropy.

### **6.3.1.1 Calculating the Coherence Entropy Time Series**

As the total number of communications during the experiment were considerably less than that obtained by Wiltshire et al (2017), the coding scheme employed only the 6 semantic categories (and not the 15 low-level codes), with the process of coding the communication transcripts following that of the entropy time series of the coded communication transcripts, with  $i$  now being one of the 6 problem solving subtask codes, rather than the 15 as used by Wiltshire et al (2017). Table 6 – Team process codes adapted from Wiltshire et al’s (2017) chosen process codes shows these 6 process codes and how they relate to the 15 subtask codes and Equation 2 reflects the change. For an example of how these codes are assigned to the transcripts, see Table 7 & Table 8.

#### **Equation 2 - The Shannon information entropy equation with 6 process codes**

$$entropy = - \sum_{i=1}^6 p_i \times \log_e p_i$$

For an example of how the codes correspond to the communication transcripts, an excerpt from Group 6’s communication transcript from condition 2 can be seen in Figure 111 - Excerpt from Group 6’s communication transcript from condition 1, with the first 5 calculated coherence entropy values. For this section, this data will be used to explain how the data values were created and presented.

**Table 6 – Team process codes adapted from Wiltshire et al’s (2017) chosen process codes**

<i>Codes Used in This Chapter</i>		<i>Codes Used by Wiltshire et al (2017)</i>	
<b>Process</b>	<b>Process Code</b>	<b>Subprocess</b>	<b>Subprocess Code</b>
Information Exchange	1	Information Provision	1
		Information Request	2
Knowledge Sharing	2	Knowledge Provision	3
		Knowledge Request	4
Solution Option Generation	3	Option Generation - Part	5
		Option Generation - Full	6
Evaluation and Negotiation of Alternatives	4	Solution Evaluation	7
Process and Plan Regulation	5	Goal/Task Orientation	8
		Situation Update	9
		Situation Request	10
		Reflection	11
Miscellaneous/ Not Task Relevant	6	Simple Agree/ Disagree Acknowledgement	12
		Incomplete/Filler/ Exclamation	13
		Tangent/Off Task	14
		Uncertainty	15

**Table 7 - Transcripts of Group 5 in Condition 1 with accompanying process codes**

**Transcript  
Group 5 - Condition 1**

<b>Participant</b>	<b>Comment</b>	<b>Code Process</b>	<b>Code Description</b>
operator3	hi	6	Miscellaneous/ Not Task Relevant
OBSERVER	Reminder: Feedback will be provided after the phrase "The illegal vehicle is: " has been submitted	-	-
operator2	i see two red cars on the bottom lane	1	Information Exchange
operator3	the red vehicle at the top lane might be illegal	3	Solution Option Generation
operator2	why?	4	Evaluation and Negotiation of Alternatives
operator3	i see two red cars at the top	1	Information Exchange
operator1	i see blue cars speeding	1	Information Exchange
operator1	middle lane	1	Information Exchange
operator1	blue	1	Information Exchange
operator3	because so far blue cars have been at the top lane other than the last 2 and all of a sudden the red car came into the top	4	Evaluation and Negotiation of Alternatives
operator2	I have one red car at the top and the bottom has not changed to two blue cars instead of red	2	Knowledge Sharing
operator3	i see a red bus at the top lane	1	Information Exchange
operator1	is there a speeding blue car in the middle lane	2	Evaluation and Negotiation of Alternatives
operator2	now I have a red car and a red bus on the bottom lane followed by a blue car	1	Information Exchange
operator2	now its back to 2 blue cars	1	Information Exchange
operator1	is illegal car blue?	3	Solution Option Generation
operator3	why?	4	Evaluation and Negotiation of Alternatives
OBSERVER	No - the colour of the illegal car is not blue	-	-
operator3	i have only seen one red bus and the rest of them are blue	1	Information Exchange
operator3	and it was going fast	1	Information Exchange
operator3	is the illegal vehicle a red bus?	3	Solution Option Generation

**Table 8 - Transcripts of Group 6 in Condition 1 with accompanying process codes**

**Transcript  
Group 6 - Condition 1**

<b>Participant</b>	<b>Comment</b>	<b>Code Process</b>	<b>Code Description</b>
operator2	hi	6	Miscellaneous/ Not Task Relevant
operator3	hello	6	Miscellaneous/ Not Task Relevant
operator1	hey	6	Miscellaneous/ Not Task Relevant
operator2	busy road lol	6	Miscellaneous/ Not Task Relevant
operator3	road is clear	1	Information Exchange
operator2	where the traffic	1	Information Exchange
operator3	blue buses look dodgy	6	Miscellaneous/ Not Task Relevant
operator2	i think blue in genral is a very suspicious colour	6	Miscellaneous/ Not Task Relevant
operator1	ok guuys	6	Miscellaneous/ Not Task Relevant
operator2	the illegal vechile is a blue bus	3	Solution Option Generation
OBSERVER	The illegal vehicle is not a blue bus	-	-
operator1	damn	6	Miscellaneous/ Not Task Relevant
operator1	though we had her	6	Miscellaneous/ Not Task Relevant
operator3	then it's either the red or the blue car	3	Solution Option Generation
operator1	the illegal vehicle is a red car	3	Solution Option Generation
operator2	so far i have just seen red and blue cars and blue bus..what about you guys?	1	Information Exchange
operator1	same here	1	Information Exchange
operator3	same	1	Information Exchange
operator3	the illegal vehicle is a blue car?	3	Solution Option Generation

Table 9 shows the calculation process for the first window of the coded data in Figure 111. As Code 1 (Information Exchange) appeared twice in the window, the count is therefore 2. Similarly, as the Code 6 (Miscellaneous/ Not Task Relevant) appeared four times in the window, the count for this code is 4. The next row shows the probability of that code appearing in the window, as there are 6 opportunities for a code to appear, the code count was divided by 6, resulting in 0.333 for Code 1 and 0.667 for Code 6. The entropy of each code appearing was then calculated by multiplying the probability by the natural log of the probability. For example, for Code 1, the probability value 0.333 was multiplied by the natural log of 0.333 resulting in the value -0.366. Each of the entropy values were then summed and multiplied by -1 to provide an overall entropy value for the window, in this case that value is 0.637. By iterating the window through the code data by 1 a series of entropy values were created, from now on this data is referred to as the raw entropy team process values. A plot of these values can be seen in Figure 112.

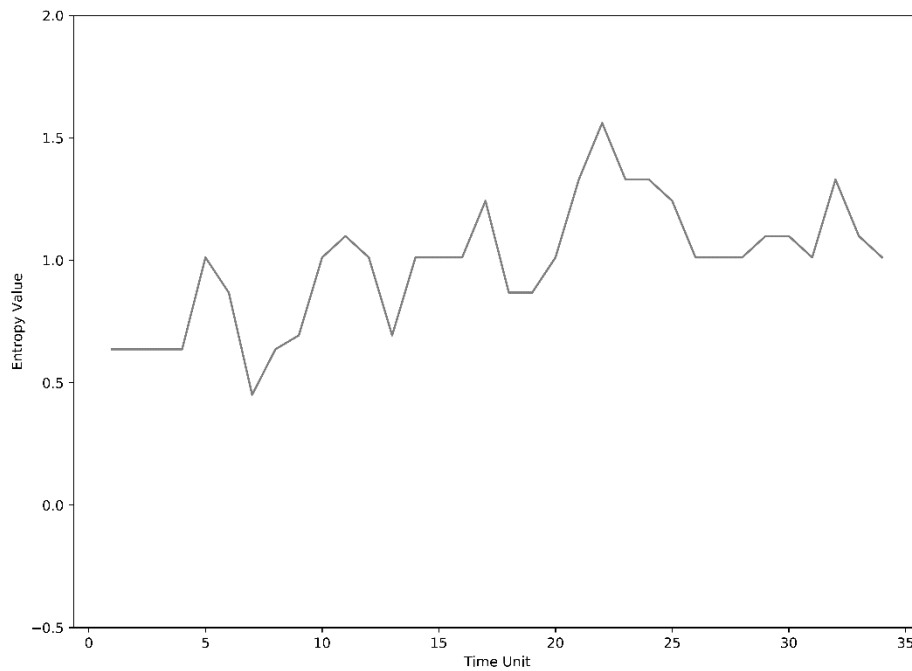
	Window 1 (Size = 6)						
	1	2	3	4	5	6	
<b>Code Count</b>	2	0	0	0	0	4	<b>-Σ entropy<sub>i</sub></b>
<b>p<sub>i</sub></b>	0.333	0	0	0	0	0.667	
<b>entropy<sub>i</sub></b>	-0.366	0	0	0	0	-0.270	
						<u>0.637</u>	

**Table 9 – Entropy process for window 1 with a window size of 6 and the 6 team process codes for group 6 in condition 2**

Participant	Utterance/Action	Time	Coherence	Coherence	Coherence	Coherence	Coherence	Calculated Entropy Value
			Codes Window 1	Codes Window 2	Codes Window 3	Codes Window 4	Codes Window 5	
operator2	hi	10:51:13	6	6	6	6	6	0.637
operator3	hello	10:51:20	6	6	6	6	6	0.637
operator1	hey	10:51:21	6	6	6	6	6	0.637
operator2	busy road	10:51:36	6	6	6	6	6	0.637
operator3	road is clear	10:51:39	1	1	1	1	1	1.011
operator2	where the traffic	10:51:55	1	1	1	1	1	...
operator3	blue buses look dodgy	10:52:42	6	6	6	6	6	
operator2	i think blue in genral is a very suspicious colour	10:52:58	6	6	6	6	6	
operator1	ok guuys	10:53:16	6	6	6	6	6	
operator2	the illegal vechile is a blue bus	10:53:28	3	3	3	3	3	
OBSERVER	The illegal vehicle is not a blue bus	10:53:44	X	X	X	X	X	
operator1	damn	10:53:49	6	6	6	6	6	
operator1	though we had her	10:53:52	6	6	6	6	6	
operator3	then it's either the red or the blue car	10:54:12	3	3	3	3	3	
operator1	the illegal vehicle is a red car	10:54:17	3	3	3	3	3	
operator2	so far i have just seen red and blue cars and blue bus..what about you guys?	10:54:22	1	1	1	1	1	
operator1	same here	10:54:28	1	1	1	1	1	
operator3	same	10:54:28	1	1	1	1	1	
operator3	the illegal vehicle is a blue car?	10:54:44	3	3	3	3	3	
OBSERVER	The illegal vehicle is red	10:54:46	X	X	X	X	X	

Figure 111 - Excerpt from Group 6's communication transcript from condition 1, with the first 5 calculated coherence entropy values

Raw Entropy Team Process Values for Group 6 in Condition 1



**Figure 112 – Raw entropy team process values. Group 6, condition 2**

For each of the raw entropy team process values, the code count values from the original analysis were used to display which of the codes, made up the raw entropy team process values. As there was a maximum of 6 available codes, six common code data series were created using this information and were as follows:

- First most common code
- Second most common code
- Third most common code
- Fourth most common code
- Fifth most common code
- Sixth most common code

For an example of how these data series were populated let's look at Table 9 again. The table shows that in the first window of the data Code 6 (Miscellaneous/ Not Task Relevant) appeared 4 times and Code 1 (Information Exchange) appeared 2 times, therefore the "First most common code" was Code 6 and the "Second most common code" was Code 1. As no other codes appeared, the other common code data series were populated with 0. This process was carried out for each of the raw entropy team process values using the code count values from the original analysis. These common code data series were then overlaid onto the raw entropy team process values graph. Figure 113 shows only the "First most common code" common code data series where Figure 114 shows all present processes. Group 6, condition 2 shows all of the common code data series. The size of each marker represents the frequency of a particular code appearing in the original window data. For example, as Code 6 appeared more times in Window 1 than Code 1 appeared (this marker was displayed first and is larger than the other marker (Code 1)). If two markers are displayed as the same size, that means that both of those codes appeared the same amount of times in the original window. For example, if Code 6 and Code 1 had both appeared three times in Window 1, both of the markers would be the same size on the graph.

Raw Entropy Team Process Values for Group 6 in Condition 1

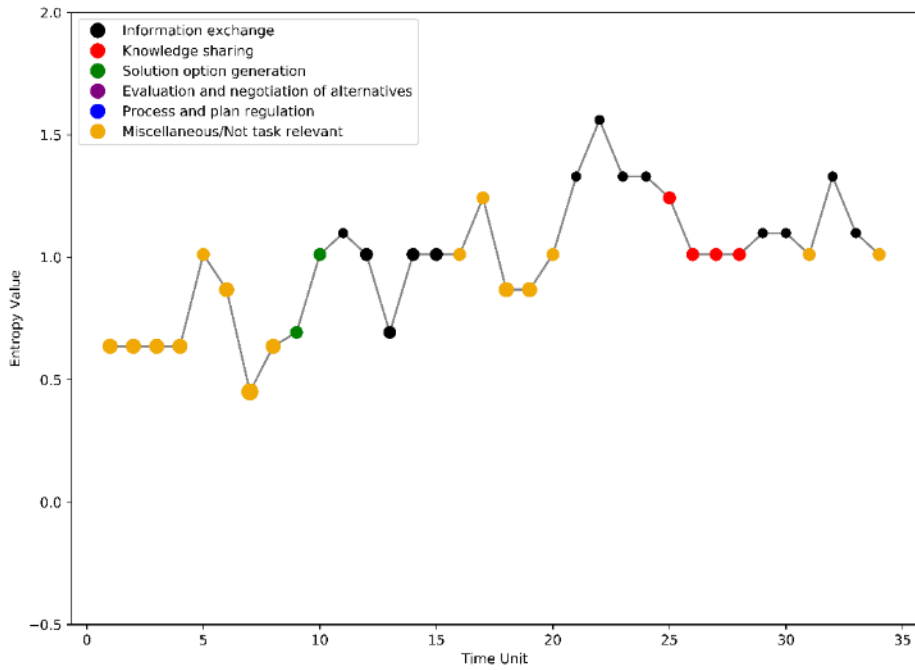


Figure 113 – Raw entropy team process values with overlaid most common processes. Group 6, condition 2

Raw Entropy Team Process Values for Group 6 in Condition 1

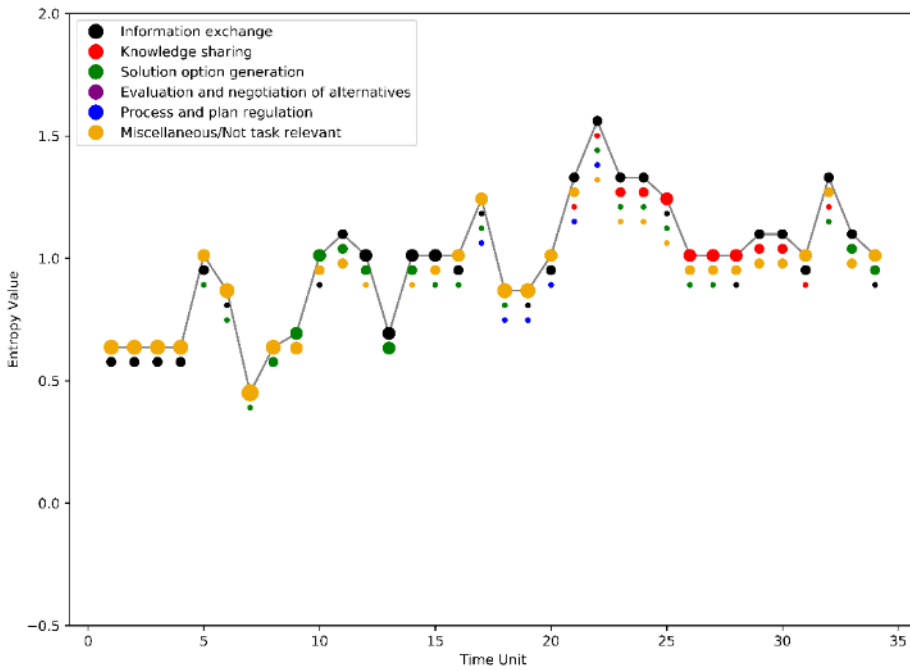


Figure 114 - Raw entropy team process values with overlaid will all present processes. Group 6, condition 2

### 6.3.1.2 Calculating the Interaction Entropy Time Series

The method used to calculate the coherence entropy time series above was also used to calculate an entropy time series of interaction between participants. In this case, each participant was assigned a number; 1, 2 or 3, therefore creating a new coding scheme. The communication transcript data was coded using this new coding scheme, resulting in a new set of coded transcript data which directly identified who provided an input into the communication transcript and at any point in the communication. For an example of how the codes correspond to the communication transcripts, an excerpt from Group 6's communication transcript from condition 2 can be seen in Figure 115 and, for consistency, in this section the data here will be used to explain how the data values were created and presented.

Keeping both the sliding window at size 6, the interaction time series was calculated using the new coded transcript data with a total number of codes now being 3 (rather than 6 for the coherence entropy time series) and the new Equation 3.

**Equation 3 - The Shannon information entropy equation with 3 participant codes**

$$entropy = - \sum_{i=1}^3 p_i \times \log_e p_i$$

Participant	Utterance/Action	Time	Interaction	Interaction	Interaction	Interaction	Interaction	Calculated Entropy Value
			Codes	Codes	Codes	Codes	Codes	
			Wndow 1	Wndow 2	Wndow 3	Wndow 4	Wndow 5	
operator2	hi	10:51:13	2	← 2	2	2	2	1.011
operator3	hello	10:51:20	3	3	← 3	3	3	1.011
operator1	hey	10:51:21	1	1	1	← 1	1	1.011
operator2	busy road	10:51:36	2	2	2	2	← 2	1.011
operator3	road is clear	10:51:39	3	3	3	3	3	← 1.011
operator2	where the traffic	10:51:55	2	2	2	2	2	...
operator3	blue buses look dodgy	10:52:42	3	3	3	3	3	
operator2	i think blue in genral is a very suspicious colour	10:52:58	2	2	2	2	2	
operator1	ok guuys	10:53:16	1	1	1	1	1	
operator2	the illegal vechile is a blue bus	10:53:28	2	2	2	2	2	
OBSERVER	The illegal vehicle is not a blue bus	10:53:44	X	X	X	X	X	
operator1	damn	10:53:49	1	1	1	1	1	
operator1	though we had her	10:53:52	1	1	1	1	1	
operator3	then it's either the red or the blue car	10:54:12	3	3	3	3	3	
operator1	the illegal vehicle is a red car	10:54:17	1	1	1	1	1	
operator2	so far i have just seen red and blue cars and blue bus..what about you guys?	10:54:22	2	2	2	2	2	
operator1	same here	10:54:28	1	1	1	1	1	
operator3	same	10:54:28	3	3	3	3	3	
operator3	the illegal vehicle is a blue car?	10:54:44	3	3	3	3	3	
OBSERVER	The illegal vehicle is red	10:54:46	X	X	X	X	X	

Figure 115 – Excerpt from Group 6’s communication transcript from condition 2, with the first 5 calculated interaction entropy values

**Table 10 – Entropy process for window 1 with a window size of 6 and the 6 interaction codes for group 6 in condition 2**

	Window 1 (Size = 6)			
	1	2	3	
Code Count	1	3	2	
$p_i$	0.166	0.5	0.333	$-\sum$ entropy <sub>i</sub>
entropy <sub>i</sub>	-0.298	-0.346	-0.366	<u>1.011</u>

Table 10 shows the interaction calculation process for the first window of the coded data. As Code 1 (participant 1) appeared once in the window, the count is 1, as the Code 2 (participant 2) appeared three times in the window, the count for this code is 3 and as Code 3 (participant 3) appeared twice the count for this code is 2. The next row shows the probability of that code appearing in the window, as there are 6 opportunities for a code to appear (due to the window size = 6), the code count was divided by 6, resulting in 0.166 for Code 1, 0.5 for Code 2 and 0.333 for Code 3. The entropy of each code appearing was then calculated by multiplying the probability by the natural log of the probability. For example, for Code 1, the probability value 0.166 was multiplied by the natural log of 0.166 resulting in the value -0.298. Each of the entropy values were then summed and multiplied by -1 to provide an overall entropy value for the window, in this case that value is 1.011. Just as before, by iterating the window through the code data by 1 a series of entropy values were created, from now on this data is referred to as the raw entropy interaction values. A plot of these values can be seen in Figure 116.



the raw entropy interaction values using the code count values from the original analysis.

These common code data series were then overlaid onto the raw entropy interaction values graph. Figure 117 shows only the “First most common code” common code data series where Figure 118 shows all of the common code data series.

As with the team process data, the size of each marker represents the frequency of a particular code appearing in the original window data. For example, as Code 2 appeared more times in Window 1, compared to Code 1 and Code 3, this marker was displayed first and is larger than the other markers (see Figure 118). Again, if two or more markers are displayed as the same size, that means that those codes appeared the same amount of times in the original window. For example, if Code 1, Code 2 and Code 3 had each appeared twice in Window 1, all three of these markers would be the same size on the graph.

Raw Entropy Interaction Values for Group 6 in Condition 1

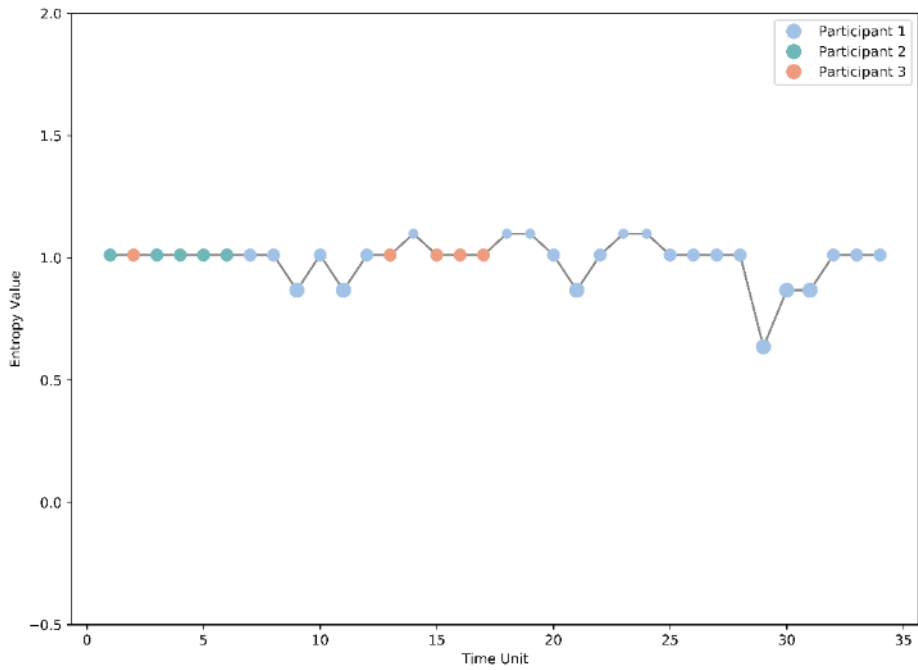


Figure 117 – Raw entropy interaction values with overlaid most common processes. Group 6, condition 2

Raw Entropy Interaction Values for Group 6 in Condition 1

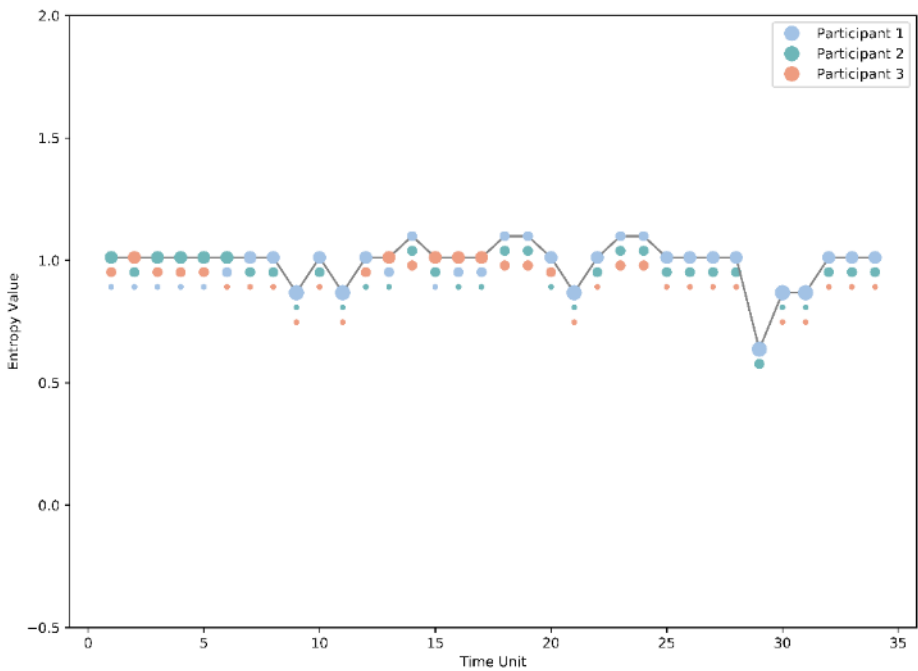


Figure 118 - Raw entropy interaction values with overlaid will all present processes. Group 6, condition 2

## 6.4 RESULTS

When discussing the team process results, it is important to remember that a low entropy value (which indicates low disorder) represents high coherence and high entropy represents low coherence. Depending on the process, a high coherence could represent a group focusing on teamwork, where all members of that team are working together. A low coherence could indicate a group focusing on task work, where they are working independently from the rest of the group. Using entropy to show the order and disorder of team process and team interaction, the overlaid common code data series makes the distinction between order and disorder easier to see. When more markers are present it shows that there is disorder within that data, i.e. multiple actions are taking place or more people are interacting.

In this chapter the communications of two groups were analysed, with Group 4 being a low-performance team and Group 6 being a high-performance team. The results of this analysis can be seen in the following figures. Although the method outlined above produces quantitative data in the form of entropy values, the results will be analysed qualitatively; highlighting regions of high and low entropy, patterns in the entropy process data, and patterns in the entropy interaction data.

### 6.4.1 Coherence

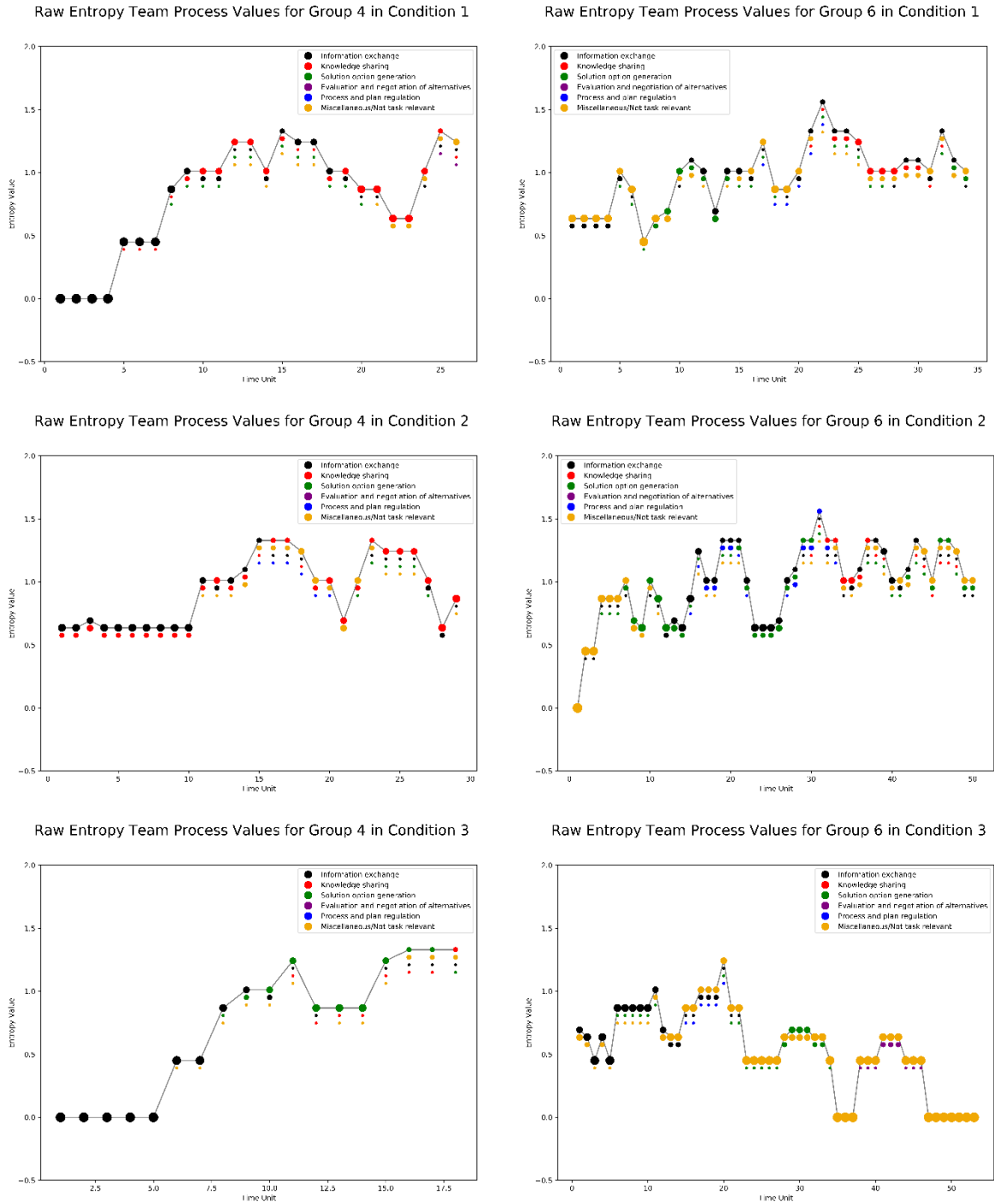
By removing the smoothing algorithm from the data and overlaying the common code data onto the raw entropy team process graphs, the results in Figure 119 provide a more detailed analysis. This figure shows the raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series. Group 4 results can be seen in the first column and Group 6 can be seen in the second column. Each row refers to the condition, i.e. row 1 is the raw entropy team process values for groups 4 and 6 in condition 2.

First, it is clear to see that the processes and raw values are almost identical in the first 8 windows for group 4 in both condition 2 and condition 3, where only the information exchange process was taking place. condition 3 shows a similar pattern, but with the focus primarily on information exchange and then knowledge sharing. After the first 8 windows, the focus shifts to information exchange and knowledge sharing in condition 2, where in condition 3 after the 8<sup>th</sup> window the focus is on solution generation. There is one trough in condition 2 which is due to a shift in process focus to knowledge sharing. In condition 3 there are two troughs in the graph, the first is due to a focus on non-task relevant and knowledge sharing where the second is due to a focus on knowledge sharing and information exchange.

For Group 6 there are many more peaks and troughs throughout the conditions showing more variance in the processes taking place. However, due to the common code data we can see what those process are. In condition 2, the process focus shifts from non-task relevant communications to information exchange and solution option generation, back to non-task relevant communications and ends with information exchange and knowledge sharing. Yet, due to the high entropy a number of other processes were also taking place during this time such as solution option generation and process and plan regulation. condition 3 also starts and ends with non-task relevant communications however, focuses on solution option generation, information exchange and process and plan regulation for the majority of the task with sharing knowledge taking over near the end of the task. Condition 3 shows a stark difference in focus of processes compared to condition 2 and 3. In the first 10 windows, the main focus is on information sharing, after this point the most prevalent process is non-task relevant communications, with this being the only process taking place in the last 7 windows.

However, the secondary processes in the latter half of the graph go from solution option

generation and then to evaluation and negotiation of alternatives. The secondary processes in the beginning of the task focused on solution option generation.



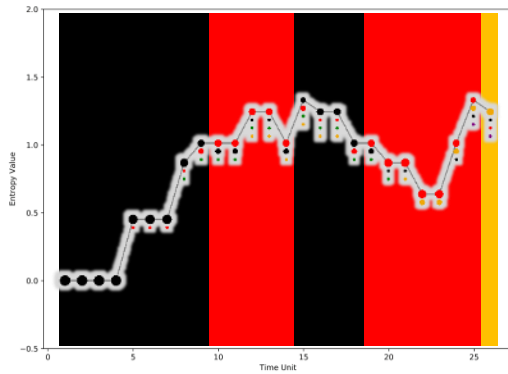
**Figure 119 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series**

Figure 120 shows the same results as above with coloured regions representing the most common process taking place at that time. This figure shows the raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and coloured regions representing the most common process code. The moment a characteristic was identified by the group is also presented. Group 4 results can be seen in the first column and Group 6 can be seen in the second column. Each row refers to the condition, i.e. row 1 is the raw entropy team process values for groups 4 and 6 in condition 2.

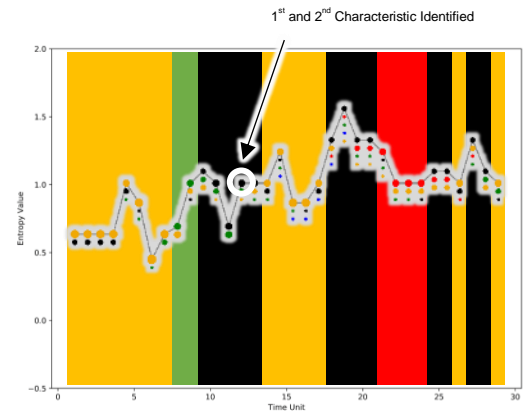
These graphs show that in conditions 1 and 2 group 4 focus first on exchanging information and then share knowledge. Apart from some non-task relevant communications at the end of condition 3, the group primarily sticks to these two processes. In comparison, group 6 focuses on different processes throughout condition 2 and 3, but the pattern is similar in both. Group 6 starts with some non-task relevant communications, moves onto solution option generation and then exchanges information. Group 6 only share knowledge after the first two characteristics were identified in both condition 2 and condition 3. After they share knowledge, information is exchanged and some non-task relevant communication takes place. However, looking at the secondary process, the second most common, the graph shows that after knowledge sharing and the second phase of information exchange, the group starts to generate solutions again.

Condition 3 for both groups showed a different pattern of processes. Group 4 still starts with information exchange, however skips the knowledge sharing process as seen in condition 2 and 2 and begins to generate solutions and in this time identifying one of the characteristics. Group 6 start with a focus on information exchange, different to condition 2 and 3, and then becomes more and more focused on non-task relevant communication. However, as the graphs show, in condition 3 group 6 were able to identify all three characteristics.

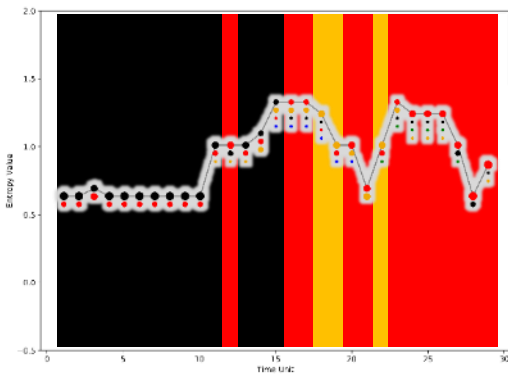
Raw Entropy Team Process Values for Group 4 in condition 1



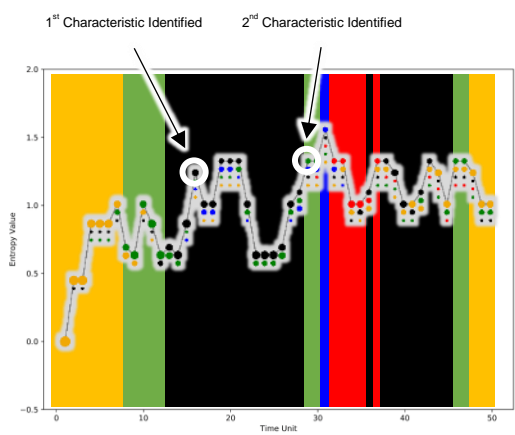
Raw Entropy Team Process Values for Group 6 in condition 1



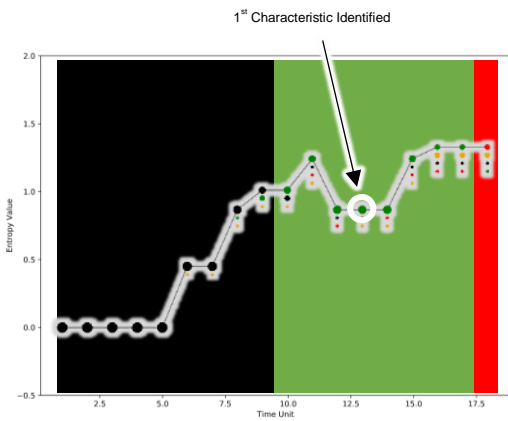
Raw Entropy Team Process Values for Group 4 in condition 2



Raw Entropy Team Process Values for Group 6 in condition 2



Raw Entropy Team Process Values for Group 4 in Condition 3



Raw Entropy Team Process Values for Group 6 in Condition 3

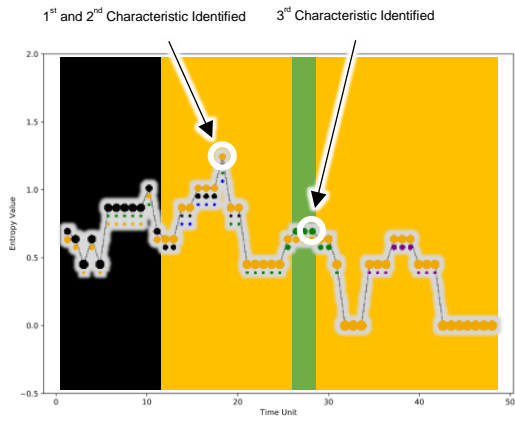
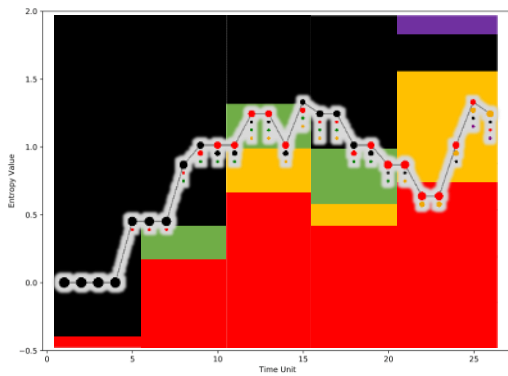


Figure 120 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and coloured regions representing the most common process code. The moment a characteristic was identified is also shown.

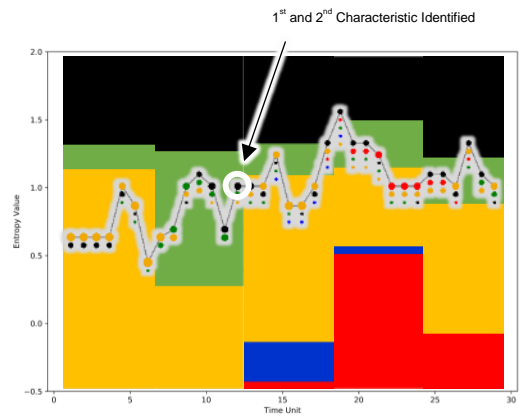
The graphs in Figure 121 show each of the results split into 5 sections, the percentage of each of the processes which occur during that section is represented by a stacked bar. This figure shows the raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and stacked bars showing the distribution of processes. The moment a characteristic was identified is also shown.

In the first section of the Group 4 in condition 2 graph (top left) there are 5 results, equating to a possible 30 code occurrences (6 possible codes over 5 windows). As the red “knowledge sharing” code occurred once and black “information exchange” code occurred 29 times, the stacked bar shows 3.3% red and 96.7% black. This representation of the code occurrences gives a more comprehensive account of the processes taking place during the task. For example, in Figure 120 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and coloured regions representing the most common process code. The moment a characteristic was identified is also shown., the Group 6 in Condition 3 graph (bottom right) the results imply that the group was off task for the majority of the condition, however they were still able to identify all 3 characteristics. The same graph Figure 121 shows that although there was a large amount of non-task relevant communication, there was also solution option generation and information exchange occurring. The stacked bars also show that Group 4 did in fact take part in solution option generation in both condition 2 and condition 3, however comparing the two groups shows that the amount of knowledge sharing was still much higher in group 4 in all three conditions.

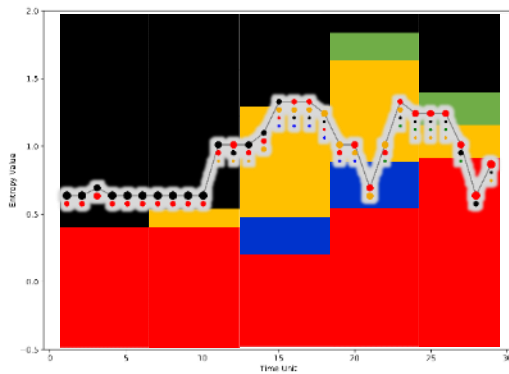
**Raw Entropy Team Process Values for Group 4 in condition 1**



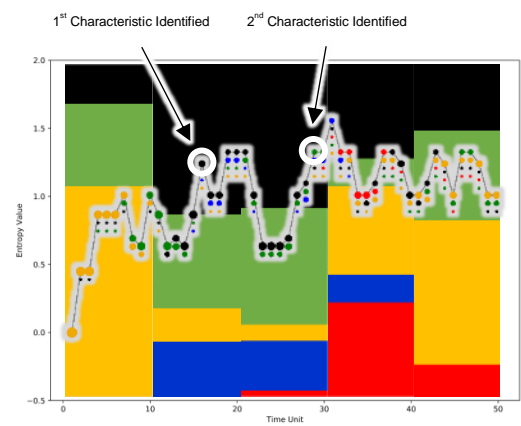
**Raw Entropy Team Process Values for Group 6 in condition 1**



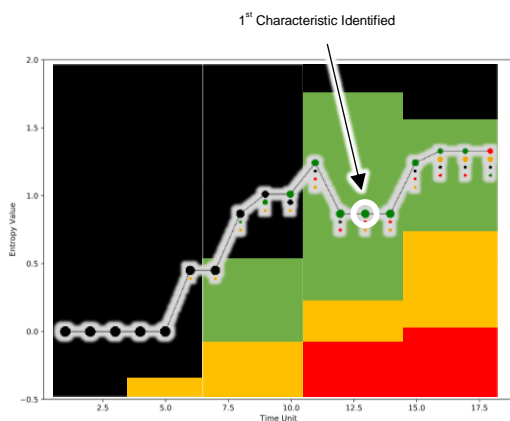
**Raw Entropy Team Process Values for Group 4 in condition 2**



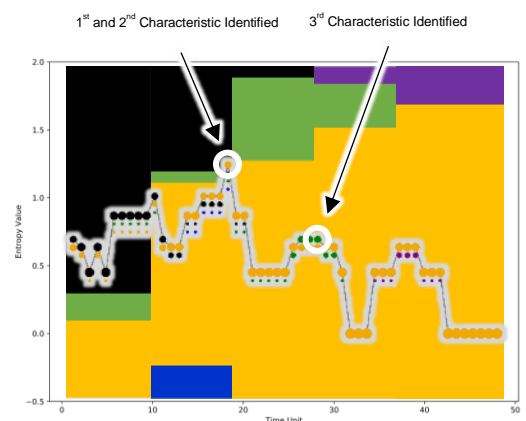
**Raw Entropy Team Process Values for Group 6 in condition 2**



**Raw Entropy Team Process Values for Group 4 in Condition 3**

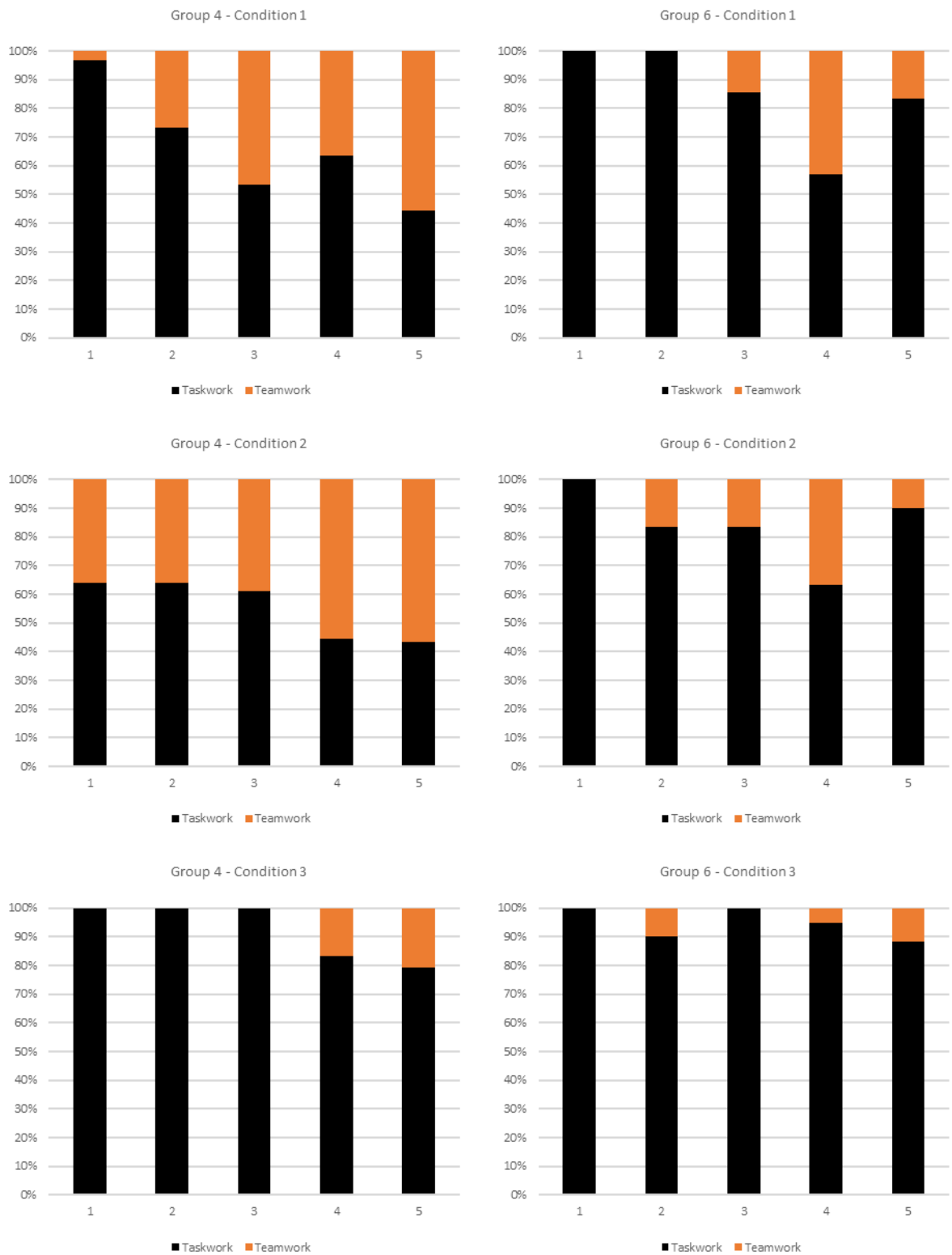


**Raw Entropy Team Process Values for Group 6 in Condition 3**



**Figure 121 - Raw entropy team process values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series and stacked bars showing the distribution of processes. The moment a characteristic was identified is also shown.**

Taking the same section data used in Figure 121, the processes were split between taskwork and teamwork. Task work processes were characterised by processes that did not require a response from another team member where team work required a response. Non-task relevant communication, solution option generation and information exchange were classed as taskwork where sharing knowledge, process plan and regulation and evaluation and negotiation of alternatives were classed as teamwork. The number of times these codes occurred are presented as a percentage for each of the sections in Figure 122, with the orange bar representing taskwork and the black bar representing teamwork. The results show that in condition 2 and 3 group 4 carried out more teamwork processes compared to group 6 and carried out more teamwork in condition 3 compared to condition 2. The distribution of teamwork and taskwork was similar for both groups in condition 3.

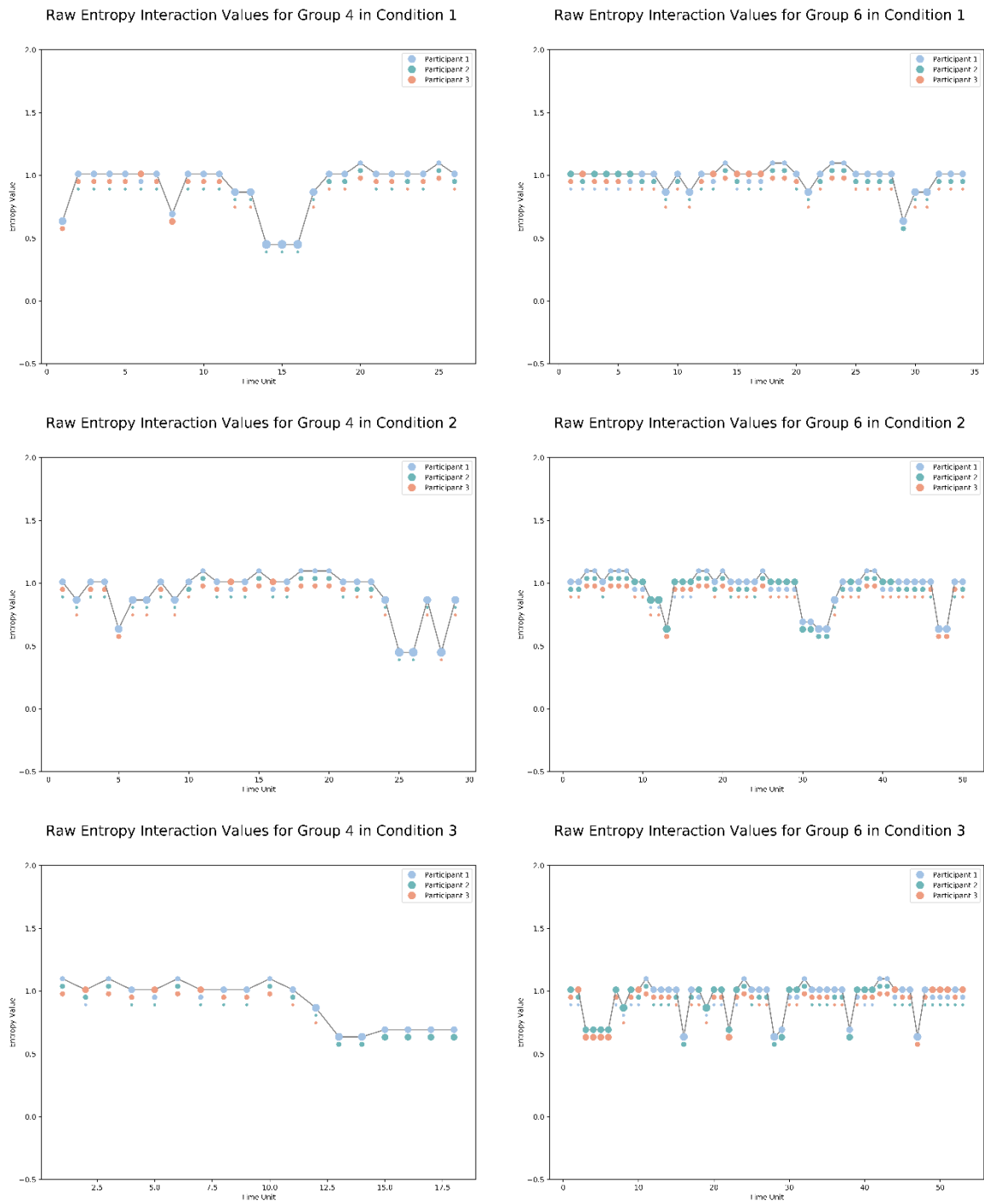


**Figure 122 – Amount of teamwork processes compared to taskwork processes per region for groups 4 and 6 in conditions 1, 2 and 3**

## 6.4.2 Interaction

To provide a more detailed analysis of the entropy interaction data, the smoothing algorithm is again removed, and the common code data is overlaid onto the raw entropy team process graphs. These results can be seen in Figure 123. This figure shows the raw entropy interaction values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series. Group 4 results can be seen in the first column and Group 6 can be seen in the second column. Each row refers to the condition, i.e. row 1 is the raw entropy interaction values for groups 4 and 6 in condition 2.

For group 4 it can be seen in all conditions that participant 1 and participant 2 interacted the most, with participant 1 being the main communicator. Participant 1 is involved in each of the troughs in the data, with participant 3 being the least involved in each of the tasks. Group 6 however had more variance in the communication and no main communicator can be identified. Troughs show different team members taking the role of main communicator in each of the conditions, and when there is high entropy all team members are taking part.



**Figure 123 - Raw entropy interaction values for groups 4 and 6 for each of the three conditions, with the overlaid common code data series**

## 6.5 DISCUSSION

This chapter has shown that by analysing transcript data of team communications it is possible to identify patterns of team behaviour, both in terms of the processes that take place and the interactions between team members. The results suggest that high performing teams focus on task work while they have the confidence to generate solutions on their own, however once the task becomes difficult the team shifts to teamwork to solve the problem together. The first two conditions of the task were new to the teams and so one can assume that they were perceived as difficult, an assumption backed up by the performance results and process behaviour in condition 3. The high-performance team was able to identify all three characteristics well within the task time limit even though the main focus of the team was on non-task relevant communication. This suggests that the team was off topic and therefore should not have been able to generate solutions, however the less common processes indicate that in the background solution option generation was taking place. In conditions 1 and 2 the high-performance team only shared knowledge after the first two characteristics were identified and didn't exchange information until after they had first provided solution options, an independent process. As the results in Chapter 4 show, groups found it difficult to identify the third characteristic in the task in all conditions, and once the first two were identified the high-performance team switched to teamworking. The results in Chapter 4 also identified a learning effect between the first and third condition which was interrupted by condition 3, suggesting that teams found condition 3 easier than the other two. As the high performing team found condition 3 easier, identifying all three characteristics, there was no evidence of teamworking as the group worked independently to complete the task. As the task was complete the focus towards non-task relevant communication after the third characteristic was identified is understandable.

The theory here is that when teams find a task difficult, they will focus on teamwork and when it is easier the focus is on taskwork. As the other group analysed in this chapter was a low-performing team, the process behaviour exhibited by this team provides evidence for this theory. The team clearly found the task difficult (otherwise they would have performed better) and the process behaviour shows a focus on teamworking; sharing knowledge and information exchange for both condition 2 and condition 3. However, due to the learning effect and the third condition being perceived as easier, they exhibited less teamwork behaviour and during this time was able to identify a characteristic.

The interaction results can also provide some insight into how the teams worked and how this may have affected the performance of the teams. For example, the high-performing team had consistently high interaction throughout the tasks with all team members contributing to the task at hand. However, in the low-performing team there was once participant in particular that communicated a lot and another that communicated very little in each of the three conditions. This could explain the low performance in condition 2 and the increase in performance in condition 3. As the information needed was distributed in condition 2, the teams needed to either share what they knew so that other team members could use the knowledge or provide solution options based on what they knew. With only one participant doing so, it would have been difficult for the team to complete the task. In condition 3 however, all participants had this information and so there was no requirement for teamworking. As the condition was perceived as easier, this explains why the team was able to provide solution options and identify a characteristic.

Theories of team SA suggest that through the process of sharing, team SA will increase and therefore so will the performance of the team. However, the results of this chapter show that simply sharing does not equate to high performance and it is important how that team is

contributing to the team effort. High performance in this chapter was associated with taskwork, where participants worked independently until they found the task difficult. When the task was perceived to be difficult the team switched to a focus on teamwork. Sharing here only occurred when participants had exhausted their own capabilities in the task, however the sharing did not always result in an increase in performance. The results of this chapter suggest that high performing individuals will focus on task work while low performing teams will focus on teamworking, with team working consisting of sharing information and knowledge. If this behaviour is translated into the definitions of team SA, one can posit that low performing teams exhibit Endsleys team SA and high-performance teams exhibit DSA. But there is more, teams are dynamic, they switch between teamwork and taskwork depending on the difficulty of the situation. Therefore, a better translation would be, when teams find a task difficult they exhibit Endsleys team SA and when they find it easier they exhibit DSA.

## **6.6 METHOD CRITIQUE**

Three different ways of presenting the order and disorder within a team have been provided. Using the original transcript codes, it was possible to display which of the team processes were taking place and their prevalence throughout the task. This display of team processes made it possible to identify patterns of team behaviour and when a team was focussing on teamwork or taskwork. However, it can be easy to glance at the graphs and make assumptions of performance, for example, in condition 3 it appears that group 6 is not working on the task as the colour of the markers are mainly yellow, representing non-task relevant communication, yet the team did identify all three characteristics and was once of the highest performing teams in the experiment. This case shows that it is not just the most common team

process that is important, and that the other less common processes can provide information into how a team is operating.

## **6.7 SUMMARY**

The work in this chapter used the communication transcripts from the experiment in Chapter 4. The content of the transcripts was used to extract the occurrence of team processes, and the level of order and disorder of these processes was calculated. Several displays of the team processes were presented and the relationship between team processes, taskwork and teamwork and situation awareness were discussed. The next chapter ties together the findings from Chapters 3 to 6 and discusses their relation to the theories of situation awareness. The benefits and limitations of the methods employed in this thesis are also discussed along with examples of how the methods and their resulting outputs could be integrated into real word user interfaces.

# CHAPTER 7 DISCUSSION

## 7.1 INTRODUCTION

This thesis has focussed on two main topics; the use of agent-based modelling to simulate and analyse situation awareness in teams, and evaluating situation awareness in teams based on team processes. The former was first done by creating a model of the operations room on HMS Dryad in Chapter 3 and the results of this were presented in such a way that the knowledge of the agents at the time critical decisions were made in the model was made visible using concept maps. To understand team behaviours in the real world, an experiment which explored the team behaviours during a collaborative problem-solving task was carried out in Chapter 4. The content of the communication transcripts was analysed to extract the knowledge of the participants in order to create concept maps at regular intervals over the task. Another agent based model was then created based on the experimental task and results in Chapter 5 and the results of which were also used to create concept maps at regular intervals over the simulated task in Chapter 5. The second main topic was addressed in Chapter 6 where the communication transcripts were used and analysed in terms of team processes. The results of which were presented as entropy values over a sliding window, team processes variety and the percentage of teamwork and taskwork processes were also presented.

A discussion of how the results of this work relates to the research questions outlined in Chapter 1 and the literature in Chapter 2 will now be presented. The use of agent-based modelling in research, the method of using entropy to analyse team situation awareness and future directions of the research will be discussed after.

## 7.2 RESEARCH QUESTIONS

### 7.2.1 Question 1: How can the use of agent-based modelling help explore humanlike behaviours and the distribution of knowledge throughout a system?

The work in Chapter 3 and Chapter 5 provide the approaches to developing agent-based models, the first based on a case study from the literature and the second from the experiment carried out in Chapter 4. The results generated from the model in Chapter 3 were presented using concept maps, showing the knowledge held by each of the team members within the task. By visually presenting knowledge of the agents via the use of concept maps, it was easier to understand how the information was stored and transferred throughout the system during the task. Information received, used and shared by the agents which was relevant to their own task could also be identified through the use of the concept maps. An interesting result from this chapter was that the concepts maps were able to show that at the time of decision making it was not important for all agents to have the same information and that when information is not shared the team performed better and with greater accuracy than when there was a focus on information sharing.

The concept maps produced in Chapter 5, from the agent-based model of the experiment conducted in Chapter 4, were able to show how information was spread around the team when certain ways of working were employed. When agents were expected to share, and therefore focus on teamwork, information was duplicated throughout the system, that is information was 'known' by more than one agent. When agents were encouraged to focus on task work, with a limit on information sharing, the amount of information was distributed throughout the team, that is there was very little duplication in information. This results from this chapter

were comparable to the results from chapter 5, where performance was higher when the teams did not share as often.

The agent-based modelling in this thesis has allowed for human-like behaviours to be modelled, including communication, interactions and information storing. The agent-based modelling has also allowed the flow of information to be manipulated and the results of that to be presented. Due to the direct access to the model code it is possible to record what the agents know and present this knowledge in the form of concept maps. These concept maps visually represent how the knowledge of the system is organised at any point during the task. The concept maps produced in Chapter 3 show how the information was distributed throughout the system at the time of a decision being made by the key decision maker in that task, where the concept maps produced in Chapter 4 and Chapter 5 show concept maps created at regular intervals throughout the task. Each version of this information organisation provides different avenues for data analysis and interpretation and the use of agent-based modelling allows for many more versions to be created depending on the task, situation and system composition.

### **7.2.2 Question 2: How can the analysis of communication give insight into team situation awareness and team behaviour?**

The organisation of team actions, described as processes in this thesis, were identified by coding the transcripts from the experiment in Chapter 4. To provide a measure of the temporal aspects of team situation awareness, the coded data was analysed by taking a sliding window of the coded results and calculating the entropy of that data, i.e. the level of order within that window in Chapter 6. The results showed that teams exhibited different types of situation awareness depending on the situation and task difficulty. This was done by visually showing the levels of process disorder within the team, along with which processes are being focused

on and the proportion of teamwork against taskwork. An analysis of these results in terms of situation awareness were consistent with the results from Chapters 3, 4 and 5. Analysing situation awareness in terms of processes also showed that teams who perform well did not focus on teamwork as much as teams who performed poorly and it was during task work when performance was highest (in the case of the task in Chapter 4, when characteristics were identified).

Analysing communications in this way revealed that the type of situation awareness can be identified, and each type has different behaviours associated with them. When teams are undertaking teamwork, they exhibit shared situation awareness and when they focus on task work they exhibit distributed situation awareness. Patterns in the team processes showed that teams tend have distributed situation awareness up until they find the task difficult to complete independently.

### **7.2.3 Understanding SA in teams**

Current theories and approaches to understanding situation awareness in teams tend to focus on either the distributed nature of cognition (Stanton et al., 2006) or the summation of individual levels of situation awareness (Endsley, 1995a). What the results in this thesis have shown is that teams switch between these two approaches depending on the situation, the shared goal and perceived task difficulty. When individuals are confident enough to complete a task individually they will exhibit distributed situation awareness, when a task becomes difficult or the team members are not able to complete the task independently they shift to over to exhibiting shared situation awareness, where the focus is on sharing knowledge about the situation and reaching a common ground. Through the communication analysis used in the thesis it is possible to see when these shifts occur (Chapter 6 presenting team process entropy and the levels of teamwork compared to taskwork) and it is also possible to see what

knowledge is known, or more importantly what knowledge is missing (through concept maps). The analysis therefore is not so much a measure of the level SA within the team, but more which type of SA the team is exhibiting and what that means in the context of the current task. This team behaviour was seen during the task in Chapter 4, notably between conditions 2 and 3 with the high-performance team 6. The team first focussed on taskwork in the beginning and when the task became difficult and they realised they required more information than what the displays were providing them they shifted to teamwork and exhibited shared situation awareness. As the information required to complete the task was split between the three team members it was very difficult for the team to have completed the task independently without interacting with each other and sharing information about their current tasks. However, in the third task each participant had all the information needed supplied to them through the displays and it is possible for the task to be completed independently by any of the participants. The results showed that in this 3<sup>rd</sup> condition when it was easier to complete the task independently, very little teamwork took place and the team mostly exhibited distributed situation awareness. Therefore, it is important to understand the roles within a team and expected level of interaction and ‘common ground’ required to complete a task. Once this is known, differences between the exhibited behaviour and expected behaviour can be identified using the analysis methods presented in this thesis.

## **7.3 USING AGENT BASED MODELLING IN RESEARCH**

### **7.3.1 Benefits of using Agent Based Modelling**

Agent Based Modelling has a number of benefits in terms of experimental design and process. First of all the number of trials that can be run and the number of ‘participants’ used is essentially infinite, however you still have to wait for the models to complete their

simulations. For example, in Chapter 4 there were initially 21 participants used in the experiment, of those 21 each were put into groups of 3. This meant that 9 sets of data were produced and due to the poor quality of one of those sets of data, only 8 sets of results were viable. Using the grouped participants, each trial took approximately 1 hour, including the explanation of the experiment and any questions. Therefore, it took 9 hours, to get 8 useable data sets. This time does not include the experimental set up within the laboratory, nor the time taken to develop participant information documentation another ‘behind the scenes’ actions required to carry out an experiment. In comparison, the time taken run 100 trials and therefore obtain 100 usable datasets from the agent-based model created in Chapter 5, was 20 minutes. Clearly, once the model has been created the number of results generated and the time taken to do so is significantly less than in the real world. Another benefit is that not only were 100 datasets obtained, 300 individual simulated participants were also ‘recruited’ in the model. To obtain the same amount of data, and even if it were possible to recruit 300 participants in the real world, it would have taken 300 hours to conduct the world experiment. Even working not stop over a 40 hour week, with no breaks, this would have taken 7 and a half weeks to complete. It is not uncommon for research trials to take weeks, months or even years to complete but with the use of agent based modelling this time can be reduced dramatically allowing for other research to be carried out. With many research projects having strict deadlines, the use of agent based modelling can provide more data faster.

Another benefit of using agent based modelling is when the experimental design needs to be modified. Due to time not being a major factor in running the trials of an agent based model, many iterations of the experiment can be conducted without the need to call participants back or recruit more to redo the experiment. Extensions to projects are not required and a much richer data set can be obtained.

Agent based models also allow for ethically immoral situation or conditions to take place and agents within the model can be pushed to breaking point. For example, agent workload can be much higher than would be used with human participants and there is no such thing as fatigue or participant mortality, although it is possible to code this into the models. Agents can be put through an excessive number of trials with no negative consequences and can be expected to ‘work’ for much longer than would be perceivable with human participants, with zero participant mortality. Agents are also coded to follow the rules and stick to the processes outlined in the model and will not deviate from these rules, unless the model was coded in such a way which allowed for this to happen.

In relation to the work in this thesis, the main benefit of using agent-based modelling is that the knowledge of agents and information within the system is directly accessible. There is no need to interrupt the agents and there is no risk of subjective self-reporting. The results of the models also allow for data to be recorded throughout the task and therefore the temporal aspects of the system can be analysed. With “knowledge objects” within the system being an important aspect of DSA (Stanton et al., 2006), the use of agent-based modelling allows for these knowledge objects to be captured.

### **7.3.2 Limitations using Agent Based Modelling**

Although there are many benefits to using agent based modelling, as outlined above, it would be remiss to exclude the limitations of the approach. First of all it has been argued that it does not represent the real world and humans are more complex than the simplified agent based model. It is important to design models in such a way that it is clear what is being modelled and what is being observed.

Another limitation is the time taken to develop the model. Complexity of the model itself and the skill level of the modeller are both factors in how long it will take to develop the model.

However, once the individual is capable of coding, the time taken reduces dramatically.

As previously mentioned one of the benefits of using agent-based modelling is that agents will follow the rules and processes outlined by the model designer. This does have some drawbacks, too many constraints on the agents restricts the amount of emergent properties to emerge and the risk of developing more of an animation rather than a simulation is increased.

## **7.4 ENTROPY AS A MEASURE OF TEAM ACTIVITY**

### **7.4.1 Benefits of using entropy as a measure of team activity**

Analysing a team in terms of the entropy of team processes using communication transcripts provides a method that is not intrusive to the task being analysed. Many of the current SA measurement techniques are criticised for intruding on the task and disrupting or biasing the results. The method used in this thesis allows for a team to be assessed over time without the need to stop the task to gather data or question the team members themselves. This also eliminates the reliance of self or observer rating, which has also received much criticism.

As the method focuses on the actions and processes taking place during the task, it provides a visual representation of the dynamic nature of team behaviour and how this behaviour changing over time during a collaborative problem-solving task. This visual representation can be analysed to identify trends and patterns of team behaviour.

The outputs and data analysed in Chapter 6 are from a post hoc analysis of transcript communication data obtained during the experiment in Chapter 4. However, current technologies could allow for this analysis to be automated. Simple speech recognition and

machine learning algorithms in conjunction with natural language processing could provide a real-time and automated analysis. Unfortunately, due to the time limitations of the project this avenue of research was not explored in detail.

#### **7.4.2 Limitations of using entropy as a measure of team activity**

Although the method of using entropy outlined in this thesis had been able to produce an analysis which solves some of the problems highlighted with current methodologies, there are a number of limitations which need to be discussed. First of all, an understanding of the colours and codes is required to effectively analyse the results. In Chapter 6 only 6 codes were used and remembering what those codes were and the colours associated to them did not take a long time to do. However, increasing the number of codes, and therefore increasing the number of colours, could make it difficult for the analyst. If the codes were modified or several different sets were employed, this again could make the processes of analysing more difficult. The suggestion here would be to keep the codes to a minimum, and when the codes have been chosen not to change them once the displays are being used in situ.

Another limitation of the method is that it is only the comments which are coded, and therefore does not necessarily show the passage complete of time or show lulls in communication when nothing is being said. Although in the task analysed in Chapter 4 it was necessary to communicate to other team members (in condition 3) to share knowledge about the distributed information and the observer (for feedback on performance) and the lulls in communication was not so critical. What was being said when it was being said was of interest, rather than how often team members were communicating over the task. A substitute for this missing element in this case could be the number of comments made, as each task had the same time limit. It is suggested that when using this method in the future, an additional

code should be used to identify when nothing is being said, which would further help to identify when team members are focusing on individual task work.

## **7.5 INTEGRATING THE ENTROPY OUTPUTS INTO A DISPLAY**

To show how the results from Chapter 6 can be integrated into a display which could be used in an industry control or operations room. Examples of how the outputs could be integrated into a display are shown in Figure 124, Figure 125 & Figure 126. Each of the displays have a set of checkboxes which would allow the user to select which teams to be viewed, if analysis is for the current or previous task and what version of the analysis is displayed. Figure 124 shows the output for Team 4 and Team 6 during the “Current Task”, which was condition 3 in the experiment in Chapter 4. The outputs show the raw entropy output, each of the processes taking place for each entropy value, the stacked percentage of processes and the comparison of teamwork and task work processes. Figure 125 – An example interface for Team 6 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4

shows the output for Team 6 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4. The outputs again show the raw entropy output, each of the processes taking place for each entropy value, the stacked percentage of processes and the comparison of teamwork and task work processes. Figure 126 shows the output for Team 4 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4. The outputs show the raw entropy output, the most common process taking place for each entropy value, the stacked percentage of processes and the comparison of teamwork and task work processes.

Even with these simple examples, it is clear to see how these outputs could be used to track, compare and analyse team behaviour. Figure 124 and Figure 126 all the user to compare one team over two different tasks, where Figure 125 – An example interface for Team 6 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4

allows the user to compare two teams during the same task. All displays allow for the customisation of how the information is displayed to the user by simply deselecting or selecting a checkbox on the screen.

The purpose of these outputs are so that key decision makers can make changes to team dynamics or processes based on their expertise of how the team should be behaving. The outputs could be used after training sessions or missions to analyse how the teams responded to situations, as the outputs use communication data it is easy to trace back to what was being discussed at points of interest. Knowing that each situation is different and requires different processes and procedures to be followed a benchmark could be set by producing outputs of how a team “should” act during a given situation, this could be taken from training sessions or simulations. Following missions could then be compared against that benchmark to evaluate changes in team behaviour.

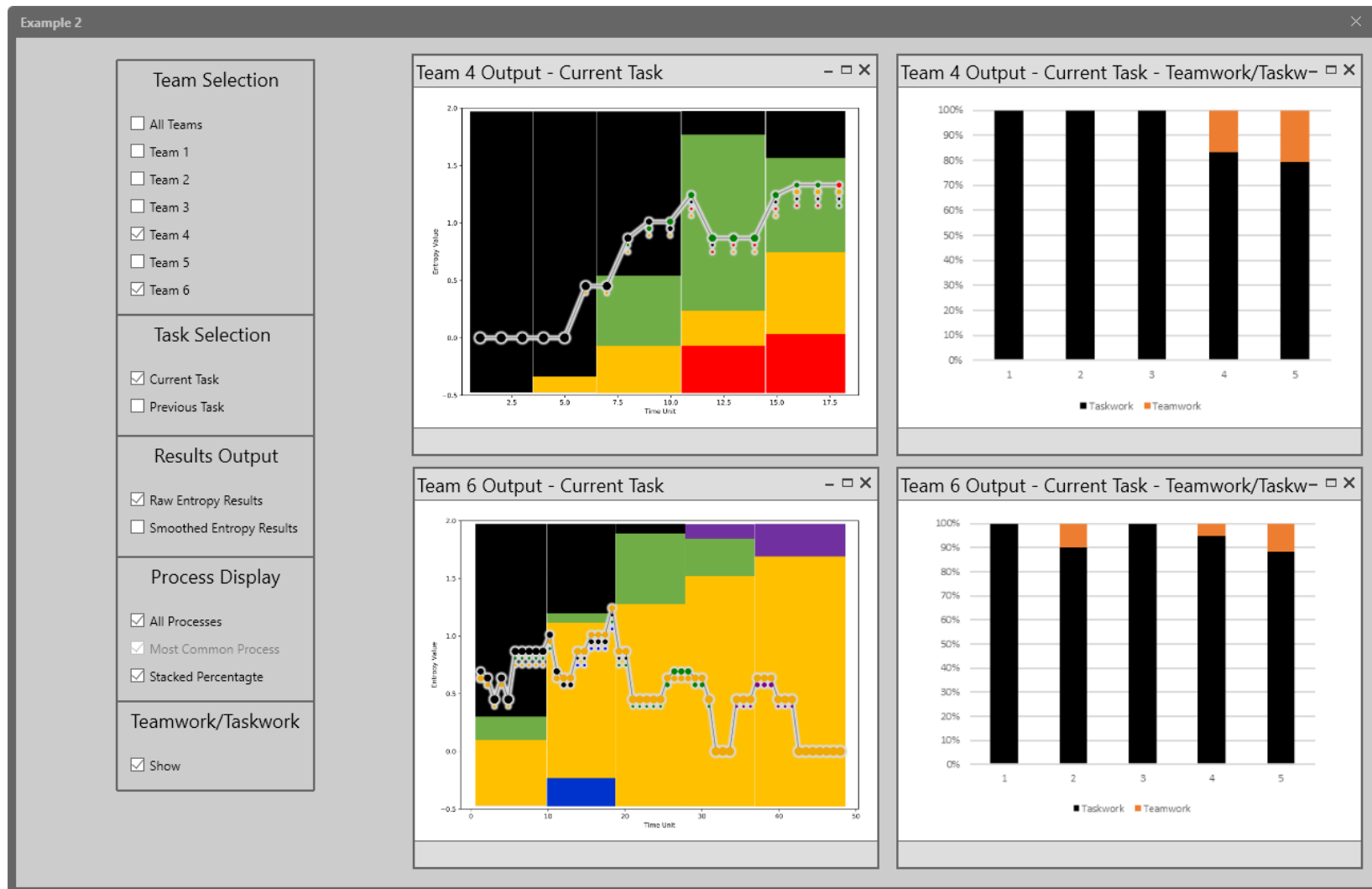
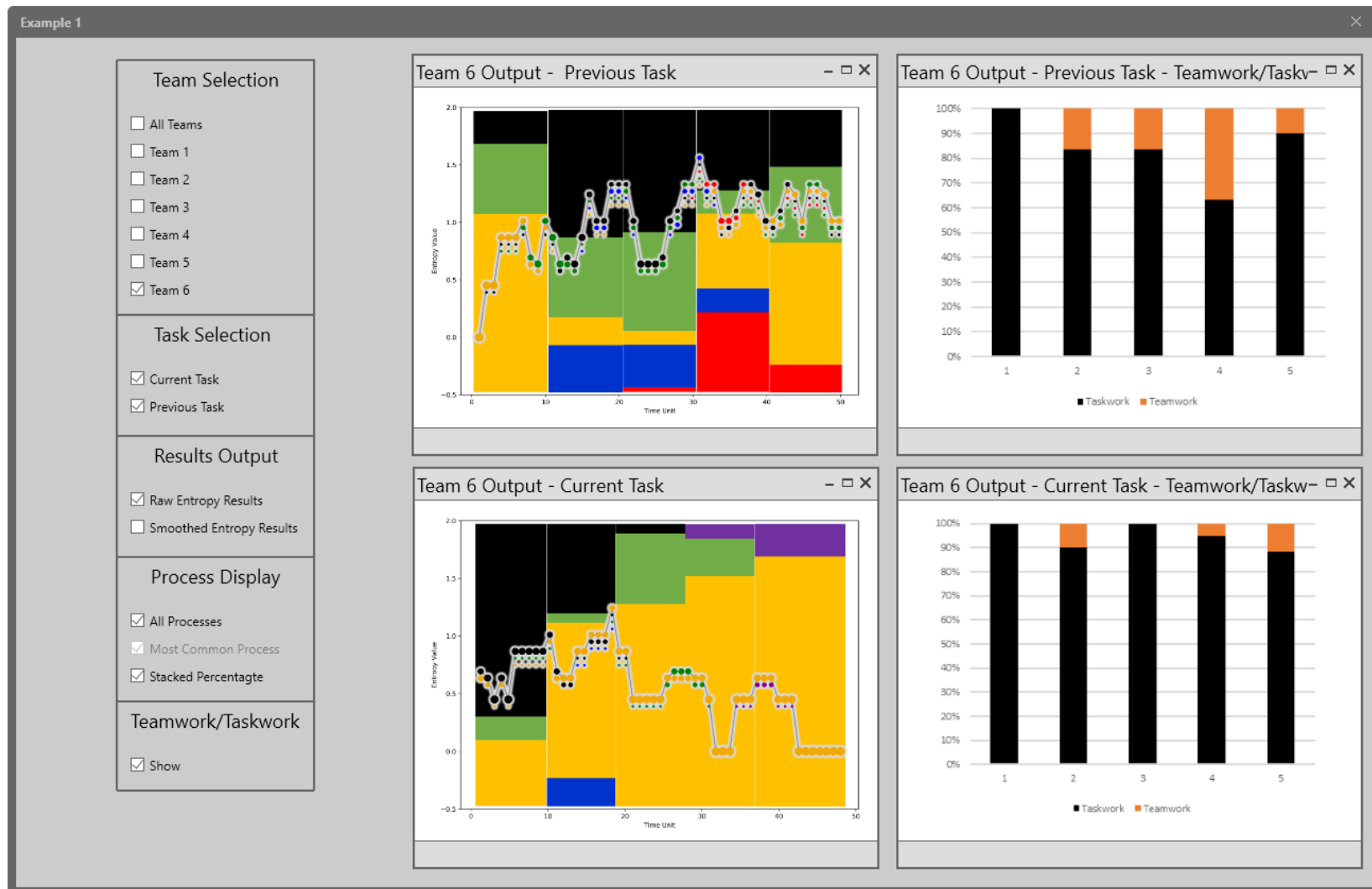
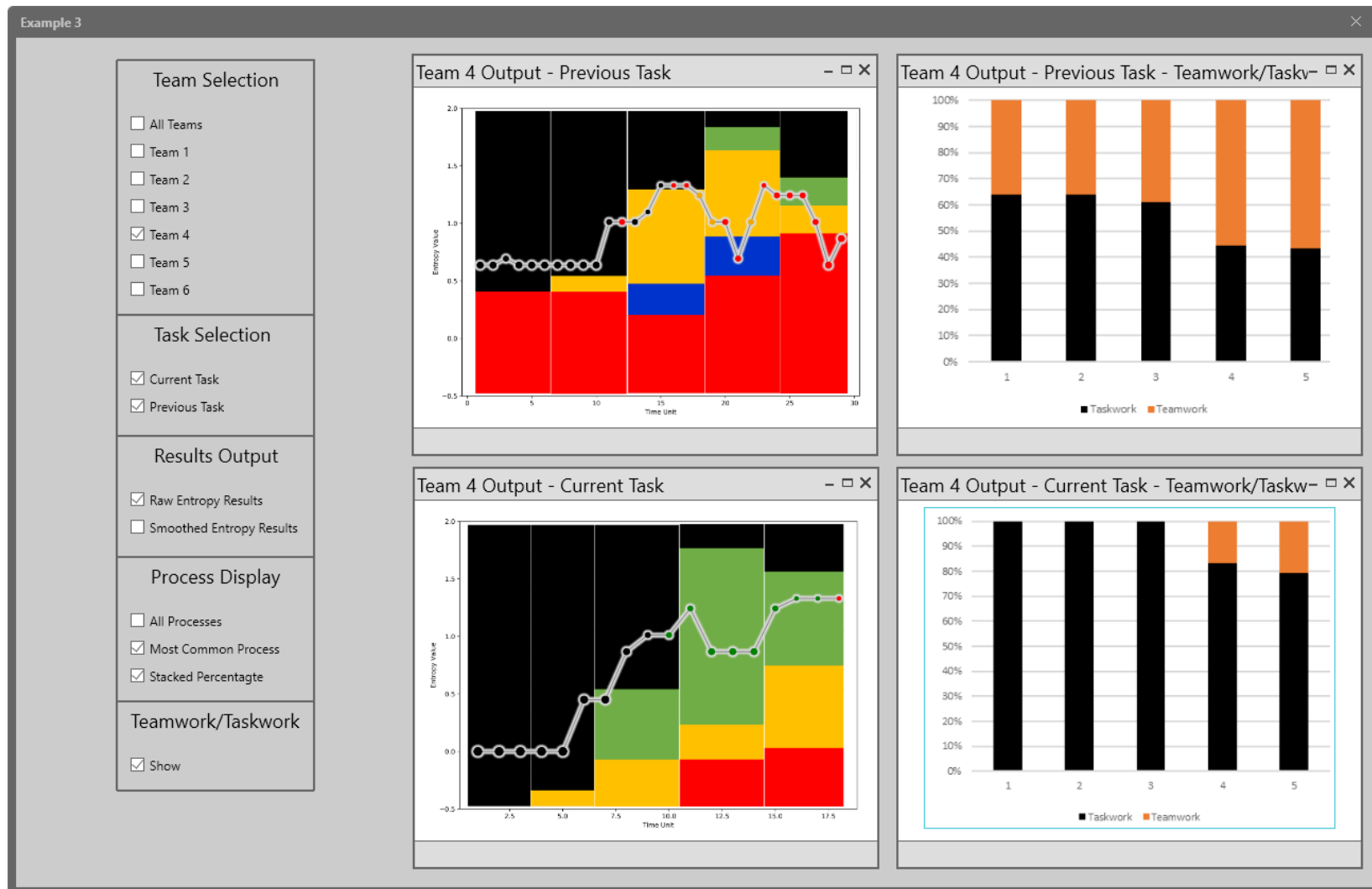


Figure 124 – An example interface for Team 4 and Team 6 during the “Current Task”, which was condition 3 in the experiment in Chapter 4



**Figure 125 – An example interface for Team 6 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4**



**Figure 126 – An example interface for Team 4 only during the “Current Task”, which was condition 3 and “Previous Task”, which was condition 3, from the experiment in Chapter 4**

The display examples discussed above have used the post hoc analysis of the teams during a task. As mentioned earlier, it would be possible to automate the analysis procedure and display the analysis in real-time using speech recognition and machine learning algorithms in conjunction with natural language processing. With a real-time output, an overseer of the group, e.g. captain or PWO within a naval operations room, can use the outputs to track team behaviour against the expected norm and intervene during the task. These interventions from the overseer will inherently change the actions of the team and this will be shown in the following results.

## **7.6 CONTRIBUTIONS OF THE RESEARCH**

The work in this thesis has provided several contributions to the research community. First, a visual output of the changes and development of team SA over time is presented. This output allows for the identification of team behaviour patterns and trends in one self-contained output.

The use of entropy to show the changes in team processes also identifies the type of team SA being exhibited. The results of this thesis has shown that teams exhibit both shared situation awareness and distributed situation, depending on the situation. While teams focus on sharing of knowledge and teamwork, they exhibit shared SA and when they focus on independent working and on taskwork they exhibit distributed SA. The results suggest that when tasks are 'easy' or participants are confident they work independently, their SA is distributed and when tasks are 'difficult' or participants lack confidence in their ability or knowledge of the situation they work as a team, their SA is shared. It is due to the temporal aspects of the entropy outputs, that it was possible to identify this dynamic nature of team SA.

The research in this thesis has also shown that the use of Agent Based Modelling is a useful method for analysing team behaviour and the distribution of knowledge throughout a system. Concept maps which display the results of Agent Based Modelling simulations gives insight into how knowledge is distributed throughout a system and can help identify where knowledge is duplicated or missing.

## **7.7 FUTURE RESEARCH**

The methods used in this thesis are in their infancy, especially the use of entropy to analyse situation awareness in teams. Future research is needed to validate and verify the method and it is suggested that a number of experiments should be carried out with varying team sizes, tasks, situations and team roles.

A future project could implement the suggested automation of the entropy method using speech recognition and machine learning algorithms and research how the automated displays could be used in real-time.

The behaviour and process patterns in this thesis were identified qualitatively. A future project could include a quantitative analysis of the results to determine patterns which could be identified automatically or even predicted based on the communications of the team.

## REFERENCES

- Abar, S., Theodoropoulos, G.K., Lemarinier, P., O'Hare, G.M.P., 2017. Agent Based Modelling and Simulation tools: A review of the state-of-art software. *Comput. Sci. Rev.* 24, 13–33. <https://doi.org/10.1016/J.COSREV.2017.03.001>
- Adams, S., 1998. Practical considerations for measuring Situational Awareness, in: *Proceedings for the Third Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment*. pp. 157–164.
- Adams, S.K., 2007. *Disciplinarily Hetero-and Homogeneous Design Team Convergence: Communication Patterns and Perceptions of Teamwork*.
- Alligood, K.T., Sauer, T., Yorke, J.A., 1997. *Chaos : an introduction to dynamical systems*. Springer.
- Angus, D., Smith, A.E., Wiles, J., 2012. Human Communication as Coupled Time Series: Quantifying Multi-Participant Recurrence. *IEEE Trans. Audio. Speech. Lang. Processing* 20. <https://doi.org/10.1109/TASL.2012.2189566>
- Arksey, H., O'Malley, L., 2005. Scoping studies: Towards a methodological framework. *Int. J. Soc. Res. Methodol. Theory Pract.* 8, 19–32. <https://doi.org/10.1080/1364557032000119616>
- Baber, C., Houghton, R.J., McMaster, R., Stanton, N.A., 2006. Shared situational awareness as a systems-level phenomenon: applying propositional networks to shared awareness in teams. *Hum. Factors Issues Complex Syst. Perform.* 978–990.
- Baber, C., Stanton, N.A., Atkinson, J., McMaster, R., Houghton, R.J., 2013. Using social network analysis and agent-based modelling to explore information flow using common operational pictures for maritime search and rescue operations. *Ergonomics* 56, 889–905.
- Bae, S.-H., Nikolaev, A., Seo, J.Y., Castner, J., 2015. Health care provider social network analysis: A systematic review. *Nurs. Outlook* 63, 566–584. <https://doi.org/10.1016/J.OUTLOOK.2015.05.006>
- Bahrami, B., Olsen, K., Latham, P.E., Roepstorff, A., Rees, G., Frith, C.D., 2010. Optimally Interacting Minds. *Science* (80-. ). 329, 1081–1085. <https://doi.org/10.1126/science.1185718>
- Bales, R.F., 1950. A Set of Categories for the Analysis of Small Group Interaction. *Am. Sociol. Rev.* 15, 257. <https://doi.org/10.2307/2086790>
- Banbury, S., Dudfield, H., Hörmann, H.-J., 2004. Development of Novel Measures to Assess the Effectiveness of Commercial Airline Pilot Situation Awareness Training. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 48, 80–84. <https://doi.org/10.1177/154193120404800118>
- Banbury, S., Howes, A., 2001. Development of generic methodologies for the evaluation of collaborative technologies.
- Barnlund, D.C., 1959. A comparative study of individual, majority, and group judgment. *J. Abnorm. Soc. Psychol.* 58, 55–60. <https://doi.org/10.1037/h0040823>
- Bedny, G., Meister, D., 1999. Theory of activity and situation awareness. *Int. J. Cogn. Ergon.*

3, 63–72.

- Bell, H.H., Waag, W.L., 1997. Using Observer Ratings to Assess Situational Awareness in Tactical Air Environments.
- Bierhals, R., Schuster, I., Kohler, P., Badke-Schaub, P., Kohler, P., Badke-Schaub, P., 2007. Shared mental models-linking team cognition and performance 3, 75–94. <https://doi.org/10.1080/15710880601170891>
- Bolstad, C.A., Cuevas, H., Gonzalez, C., Schneider, M., 2005. Modeling shared situation awareness, in: Proceedings of the 14th Conference on Behavior Representation in Modeling and Simulation (BRIMS), Los Angeles, CA.
- Bolstad, C.A., Foltz, P., Franzke, M., Cuevas, H.M., Rosenstein, M., Costello, A.M., 2007. Predicting Situation Awareness from Team Communications. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 51, 789–793. <https://doi.org/10.1177/154193120705101203>
- Bosse, T., Hoogendoorn, M., Klein, M., Sharpanskykh, A., Treur, J., Van Der Wal, C.N., Van Wissen, A., 2013a. Agent-based modelling of social emotional decision making in emergency situations, in: Co-Evolution of Intelligent Socio-Technical Systems. Springer, pp. 79–117.
- Bosse, T., Majdanik, K., Boersma, K., Ingibergsdottir, K., 2013b. Studying Shared Situation Awareness by Agent-Based Simulation, in: Web Intelligence (WI) and Intelligent Agent Technologies (IAT), 2013 IEEE/WIC/ACM International Joint Conferences On. IEEE, pp. 201–208.
- Bosse, T., Mogles, N., 2014. Spread of Situation Awareness in a Group: Population-Based vs. Agent-Based Modelling, in: Web Intelligence (WI) and Intelligent Agent Technologies (IAT), 2014 IEEE/WIC/ACM International Joint Conferences On. IEEE, pp. 206–213.
- Bourbousson, J., R'Kiouak, M., Eccles, D.W., 2015. The dynamics of team coordination: A social network analysis as a window to shared awareness. Eur. J. Work Organ. Psychol. 24, 742–760. <https://doi.org/10.1080/1359432X.2014.1001977>
- Bowers, C.A., Jentsch, F., Salas, E., Braun, C.C., 1998. Analyzing Communication Sequences for Team Training Needs Assessment. Hum. Factors J. Hum. Factors Ergon. Soc. 40, 672–679. <https://doi.org/10.1518/001872098779649265>
- Brannick, M.T., Prince, A., Prince, C., Salas, E., 1995. The Measurement of Team Process. Hum. Factors J. Hum. Factors Ergon. Soc. 37, 641–651. <https://doi.org/10.1518/001872095779049372>
- Breton, R., Valcartier, D., Tremblay, S., 2007. Measurement of individual and team situation awareness: A critical evaluation of the available metrics and tools and their applicability to command and control environments.
- Browning, J.B., 1993. Jackson Browning Report - Union Carbide Corp. Saf. Heal. 1–15.
- Bundy, G.J., 1994. Not So Friendly Fire: Considerations for Reducing the Risk of Fratricide.
- Campbell, J., 1968. INDIVIDUAL VERSUS GROUP PROBLEM SOLVING IN AN INDUSTRIAL SAMPLE. J. Appl. Psychol. 52, 205–210. <https://doi.org/10.1037/h0025790>
- Carretta, T.R., Perry, D.C., Ree, M.J., 1996. Prediction of Situational Awareness in F-15 Pilots. Int. J. Aviat. Psychol. 6, 21–41. [https://doi.org/10.1207/s15327108ijap0601\\_2](https://doi.org/10.1207/s15327108ijap0601_2)

- Casti, J.L., 1996. Chaos data analyzer. *Complexity* 2, 46–47.
- Cela, K.L., Sicilia, M.Á., Sánchez, S., 2015. Social Network Analysis in E-Learning Environments: A Preliminary Systematic Review. *Educ. Psychol. Rev.* 27, 219–246. <https://doi.org/10.1007/s10648-014-9276-0>
- Chambers, D., Wilson, P., Thompson, C., Harden, M., 2012. Social Network Analysis in Healthcare Settings: A Systematic Scoping Review. *PLoS One* 7, e41911. <https://doi.org/10.1371/journal.pone.0041911>
- Chiappe, D., Strybel, T.Z., Vu, K.-P.L., 2012a. Mechanisms for the acquisition of situation awareness in situated agents. *Theor. Issues Ergon. Sci.* 13, 625–647.
- Chiappe, D., Vu, K.-P.L., Rorie, C., Morgan, C., 2012b. A situated approach to shared situation awareness, in: *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. Sage Publications, pp. 748–752.
- Choi, H.-S., Levine, J.M., 2004. Minority influence in work teams: The impact of newcomers. *J. Exp. Soc. Psychol.* 40, 273–280. [https://doi.org/10.1016/S0022-1031\(03\)00101-X](https://doi.org/10.1016/S0022-1031(03)00101-X)
- Chowdhury, I., 2014. A user-centered approach to road design : blending distributed situation awareness with self-explaining roads. Heriot-Watt University.
- Clemente, F.M., Martins, F.M.L., Kalamaras, D., Wong, P. Del, Mendes, R.S., 2015. General network analysis of national soccer teams in FIFA World Cup 2014. *Int. J. Perform. Anal. Sport* 15, 80–96. <https://doi.org/10.1080/24748668.2015.11868778>
- Coffey, J.W., Hoffman, R., Cañas, A., 2006. Concept map-based knowledge modeling: perspectives from information and knowledge visualization. *Inf. Vis.* 5, 192–201.
- Connelly, S., Lindsay, P., Gallagher, M., 2007. An agent based approach to examining shared situation awareness. *IEEE*, pp. 138–147. <https://doi.org/10.1109/ICECCS.2007.14>
- Cooke, N.J., DeJoode, J.A., Pedersen, H.K., Gorman, J.C., Connor, O.O., 2004. The Role of Individual and Team Cognition in Uninhabited Air Vehicle Command-and-Control.
- Cooke, N.J., Gorman, J.C., Myers, C.W., Duran, J.L., 2013. Interactive team cognition. *Cogn. Sci.* 37, 255–285. <https://doi.org/10.1111/cogs.12009>
- Cooke, N.J., Gorman, J.C., Winner, J.L., 2008. Team Cognition, in: *Handbook of Applied Cognition, Second Edition*. John Wiley & Sons Ltd, Chichester, UK, pp. 239–268. <https://doi.org/10.1002/9780470713181.ch10>
- Cooke, N.J., Salas, E., Kiekel, P., A. Bell, B., 2000. Why Measure Team Cognition? 3.
- Crozier, M.S., Ting, H.Y., Boone, D.C., O'Regan, N.B., Bandrauk, N., Furey, A., Squires, C., Hapgood, J., Hogan, M.P., 2015. Use of Human Patient Simulation and Validation of the Team Situation Awareness Global Assessment Technique (TSAGAT): A Multidisciplinary Team Assessment Tool in Trauma Education. *J. Surg. Educ.* 72, 156–163. <https://doi.org/10.1016/j.jsurg.2014.07.009>
- Dale, R., Fusaroli, R., Duran, N.D., Richardson, D.C., 2014. The Self-Organization of Human Interaction, in: *Psychology of Learning and Motivation*. <https://doi.org/10.1016/B978-0-12-407187-2.00002-2>
- Deighton, C.D.B., 1997. Towards the development of an integrated human factors and engineering evaluation methodology for rotorcraft D/NAW Systems.

- Dekker, A.H., 2002. Applying social network analysis concepts to military C4ISR architectures. *Connections* 24, 93–103.
- Demir, M., Cooke, N.J., Amazeen, P.G., 2018a. A conceptual model of team dynamical behaviors and performance in human-autonomy teaming. *Cogn. Syst. Res.* 52, 497–507. <https://doi.org/10.1016/J.COGSYS.2018.07.029>
- Demir, M., McNeese, N.J., Cooke, N.J., 2018b. The Impact of Perceived Autonomous Agents on Dynamic Team Behaviors. *IEEE Trans. Emerg. Top. Comput. Intell.* 2, 258–267.
- Dennehy, K., 1997. Cranfield situation awareness scale: users manual. Applied Psychology unit, College of Aeronautics, Cranfield University, COA report No. 9702, Bedford.
- Durso, F.T., Hackworth, C.A., Truitt, T.R., Crutchfield, J., Nikolic, D., Manning, C.A., 1999. Situation Awareness As a Predictor of Performance in En Route Air Traffic Controllers, Air Traffic Control Quarterly. DTIC Document.
- Dyke, C., 1990. Expectation and strategy in a nonlinear world. *Syst. Res.* 7, 117–125. <https://doi.org/10.1002/sres.3850070205>
- Edgar, G.K., Edgar, H.E., 2007. Using signal detection theory to measure situation awareness: the technique, the tool (QUASA), the test, the way forward. *Decis. Mak. complex Environ.* 373–385.
- Endsley, M., Jones, W.M., 1997. Situation Awareness Information Dominance & Information Warfare.
- Endsley, M.R., 2015. Situation awareness misconceptions and misunderstandings. *J. Cogn. Eng. Decis. Mak.* 9, 4–32.
- Endsley, M.R., 2000. Direct measurement of situation awareness: Validity and use of SAGAT. *Situat. Aware. Anal. Meas.* 10.
- Endsley, M.R., 1995a. Toward a theory of situation awareness in dynamic systems. *Hum. Factors J. Hum. Factors Ergon. Soc.* 37, 32–64.
- Endsley, M.R., 1995b. Measurement of situation awareness in dynamic systems. *Hum. Factors J. Hum. Factors Ergon. Soc.* 37, 65–84.
- Endsley, M.R., 1993. A Survey of Situation Awareness Requirements in Air-to-Air Combat Fighters. *Int. J. Aviat. Psychol.* 3, 157–168. [https://doi.org/10.1207/s15327108ijap0302\\_5](https://doi.org/10.1207/s15327108ijap0302_5)
- Endsley, M.R., 1988. Situation awareness global assessment technique (SAGAT), in: Aerospace and Electronics Conference, 1988. NAECON 1988., Proceedings of the IEEE 1988 National. IEEE, pp. 789–795.
- Endsley, M.R., Jones, W.M., 2001. A model of inter- and intrateam situation awareness: implications for design, training and measurement., in: In: M. McNeese, E. Salas, M. Endsley (Eds.) *New Trends in Cooperative Activities: Understanding System Dynamics in Complex Environments*. Human Factors and Ergonomics Society, Santa Monica, CA.
- Endsley, M.R., Kiris, E.O., 1995. Situation awareness global assessment technique (SAGAT) TRACON air traffic control version user guide. Lubbock, TX Texas Tech Univ.
- Endsley, M.R., Selcon, S.J., Hardiman, T.D., Croft, D.G., 1998. A comparative analysis of SAGAT and SART for evaluations of situation awareness, in: Proceedings of the Human

- Factors and Ergonomics Society Annual Meeting. SAGE Publications, pp. 82–86.
- ESSAI, 2001. WP2 Identification of Factors affecting Situation Awareness and Crisis Management on the Flight Deck.
- Festinger, L., 1954. A Theory of Social Comparison Processes. *Hum. Relations* 7, 117–140. <https://doi.org/10.1177/001872675400700202>
- Fiore, S.M., Rosen, M., Salas, E., Burke, S., Jentsch, F., 2007. Problem-solving : Parsing and Defining the Theoretical Problem Space. *Knowl. Creat. Diffus. Util.* 143–163.
- Fiore, S.M., Rosen, M.A., Smith-Jentsch, K.A., Salas, E., Letsky, M., Warner, N., 2010a. Toward an understanding of macrocognition in teams: Predicting processes in complex collaborative contexts. *Hum. Factors* 52, 203–224. <https://doi.org/10.1177/0018720810369807>
- Fiore, S.M., Smith-Jentsch, K.A., Salas, E., Warner, N., Letsky, M., 2010b. Towards an understanding of macrocognition in teams: Developing and defining complex collaborative processes and products. *Theor. Issues Ergon. Sci.* 11, 250–271. <https://doi.org/10.1080/14639221003729128>
- Fiore, S.M., Wiltshire, T.J., 2016. Technology as Teammate: Examining the Role of External Cognition in Support of Team Cognitive Processes. *Front. Psychol.* 7, 1531. <https://doi.org/10.3389/fpsyg.2016.01531>
- Fischer, A., Greiff, S., Funke, J., 2013. The Process of Solving Complex Problems. *J. Probl. Solving* 4, 19. <https://doi.org/10.7771/1932-6246.1118>
- Fischer, U., Orasanu, J., 1999. SAY IT AGAIN, SAM! EFFECTIVE COMMUNICATION STRATEGIES TO MITIGATE PILOT ERROR.
- Fisher, B.A., 1970. The Process of Decision Modification in Small Discussion Groups. *J. Commun.* 20, 51–64. <https://doi.org/10.1111/j.1460-2466.1970.tb00863.x>
- Foltz, P.W., 2007. Automated content processing of spoken and written discourse: Text coherence, essays, and team analyses. *Inf. Des. J.* 13, 5–13. <https://doi.org/10.1075/idjdd.13.1.02fol>
- Foltz, P.W., Bolstad, C.A., Cuevas, H.M., Franzke, M., Rosenstein, M., Costello, A.M., 2017. Measuring situation awareness through automated communication analysis, in: *Macrocognition in Teams: Theories and Methodologies*. pp. 259–275. <https://doi.org/10.1201/9781315593166>
- Foushee, H.C., 1984. Dyads and triads at 35,000 feet: Factors affecting group process and aircrew performance. *Am. Psychol.* 39, 885–893. <https://doi.org/10.1037/0003-066X.39.8.885>
- Foushee, H.C., Manos, K.L., 1981. Information transfer within the cockpit: Problems in intracockpit communications., in: *Information Transfer Problems in the Aviation System (NASA TP-1875)*. pp. 63-- 71.
- Fowlkes, J.E., Lane, N.E., Salas, E., Franz, T., Oser, R., 1994. Improving the measurement of team performance: The TARGETs methodology. *Mil. Psychol.* 6, 47–61. [https://doi.org/10.1207/s15327876mp0601\\_3](https://doi.org/10.1207/s15327876mp0601_3)
- Freeman, L.C., 2004. *The development of social network analysis : a study in the sociology of science*. Empirical Press.

- Fusaroli, R., Rączaszek-Leonardi, J., Tylén, K., 2014. Dialog as interpersonal synergy. *New Ideas Psychol.* 32, 147–157. <https://doi.org/10.1016/J.NEWIDEAPSYCH.2013.03.005>
- Garbis, C., Artman, H., 2004. Team situation awareness as communicative practice, in: *A Cognitive Approach to Situation Awareness: Theory and Application*. pp. 275–296.
- Gorman, J.C., Cooke, N.J., Amazeen, P.G., 2010. Training adaptive teams. *Hum. Factors* 52, 295–307. <https://doi.org/10.1177/0018720810371689>
- Gorman, J.C., Cooke, N.J., Pederson, H.K., Olena, O.C., DeJoode, J.A., 2005. Coordinated Awareness of Situation by Teams (CAST): Measuring Team Situation Awareness of a Communication Glitch. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 49, 274–277. <https://doi.org/10.1177/154193120504900313>
- Gorman, J.C., Cooke, N.J., Winner, J.L., 2006. Measuring team situation awareness in decentralized command and control environments. *Ergonomics* 49, 1312–1325. <https://doi.org/10.1080/00140130600612788>
- Gorman, J.C., Dunbar, T.A., Grimm, D., Gipson, C.L., 2017. Understanding and Modeling Teams As Dynamical Systems. *Front. Psychol.* 8, 1053. <https://doi.org/10.3389/fpsyg.2017.01053>
- Gorman, J.C., Foltz, P.W., Kiekel, P.A., Martin, M.J., Cooke, N.J., 2012. Evaluation of Latent Semantic Analysis-Based Measures of Team Communications Content. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 47, 424–428. <https://doi.org/10.1177/154193120304700337>
- Grant, M.J., Booth, A., 2009. A typology of reviews: an analysis of 14 review types and associated methodologies. *Heal. Inf. Libr. J.* 26, 91–108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x>
- Hackman, J.R., 1987. The design of work teams. In *Handbook of Organizational Behavior*, ed. JW Lorsch.
- Hackman, J.R., 1978. The design of work in the 1980s. *Organ. Dyn.* 7, 3–17. [https://doi.org/10.1016/0090-2616\(78\)90031-1](https://doi.org/10.1016/0090-2616(78)90031-1)
- Hackman, J.R., Morris, C.G., 1975. GROUP TASKS , GROUP INTERACFIION PROCESS , AND GROUP PERFORMANCE EFFECTIVENESS : A REVIEW AND PROPOSED INTEGRATION1 I . The Role of Interaction Process in Task-Oriented Groups : Current Thought and Evidence 8, 45–48.
- Harris, T.E., Sherblom, J., 2005. *Small group and team communication*. Pearson/Allyn and Bacon.
- Hart, C., 2018. *Doing a literature review: Releasing the research imagination*. Sage.
- Hassall, S.L., 2009. The Relationship between Communication and Team Performance : Testing Moderators and Identifying Communication Profiles in Established Work Teams. *Relatsh. between Commun. Team Perform. Test. Moderators Identifying Commun. Profiles Establ. Work Teams*.
- Hauss, Y., Eyferth, K., 2003. Securing future ATM-concepts' safety by measuring situation awareness in ATC. *Aerosp. Sci. Technol.* 7, 417–427.
- Hazlehurst, B., McMullen, C.K., Gorman, P.N., 2007. Distributed cognition in the heart room: How situation awareness arises from coordinated communications during cardiac

- surgery. *J. Biomed. Inform.* 40, 539–551. <https://doi.org/10.1016/J.JBI.2007.02.001>
- Heath, C., Luff, P., 1991. Collaborative Activity and Technological Design: Task Coordination in London Underground Control Rooms, in: *Proceedings of the Second European Conference on Computer-Supported Cooperative Work ECSCW '91*. pp. 65–80. [https://doi.org/10.1007/978-94-011-3506-1\\_5](https://doi.org/10.1007/978-94-011-3506-1_5)
- Hirokawa, R.Y., 1990. The Role of Communication in Group Decision-Making Efficacy: A Task-Contingency Perspective. *Small Gr. Res.* 21, 190–204. <https://doi.org/10.1177/1046496490212003>
- Hirokawa, R.Y., 1980. A comparative analysis of communication patterns within effective and ineffective decision-making groups. *Commun. Monogr.* 47, 312–321. <https://doi.org/10.1080/03637758009376040>
- Hoffman, E., Trott, J., Neely, K.P., 2002. Concept mapping: A tool to bridge the disciplinary divide. *Am. J. Obstet. Gynecol.* 187, S41–S43.
- Hogg, D.N., Folleso, K., Strand-Volden, F., Torralba, B., 1995. Development of a situation awareness measure to evaluate advanced alarm systems in nuclear power plant control rooms. *Ergonomics* 38, 2394–2413.
- Holland, J.H., 1992. Complex adaptive systems. *Daedalus* 121, 17–30. <https://doi.org/10.2307/20025416>
- Hollingshead, A.B., Brandon, D.P., 2003. Potential Benefits of Communication in Transactive Memory Systems. *Hum. Commun. Res.* 29, 607–615. <https://doi.org/10.1111/j.1468-2958.2003.tb00859.x>
- Houghton, R.J., Baber, C., McMaster, R., Stanton, N.A., Salmon, P., Stewart, R., Walker, G., 2006. Command and control in emergency services operations: a social network analysis. *Ergonomics* 49, 1204–1225. <https://doi.org/10.1080/00140130600619528>
- Hutchins, E., 1995a. *Cognition in the Wild*.
- Hutchins, E., 1995b. How a cockpit remembers its speeds. *Cogn. Sci.* 19, 265–288. [https://doi.org/http://dx.doi.org/10.1016/0364-0213\(95\)90020-9](https://doi.org/http://dx.doi.org/10.1016/0364-0213(95)90020-9)
- Janis, I.L., 1982. *Groupthink: Psychological studies of policy decisions and fiascoes*. Houghton Mifflin Boston.
- Janssen, M.A., 2005. Agent-based modelling. *Model. Ecol. Econ.* 155–172.
- Jeannot, E., Kelly, C., Thompson, D., 2003. The Development of Situation Awareness Measures in ATM Systems. *System* 1.0, 88. <https://doi.org/HRS/HSP-005-REP-01>
- Jones, D.G., Endsley, M.R., 2004. Use of Real-Time Probes for Measuring Situation Awareness. *Int. J. Aviat. Psychol.* 14, 343–367.
- Jones, D.G., Kaber, D.B., 2004. Situation awareness measurement and the situation awareness global assessment technique, in: *Handbook of Human Factors and Ergonomics Methods*. pp. 42.1-42–7.
- Kahn, K., 2007. Comparing multi-agent models composed from micro-behaviours. *Third Int. Model. Work.*
- Kalloniatis, A., Ali, I., Neville, T., La, P., Macleod, I., Zuparic, M., Kohn, E., 2017. The Situation Awareness Weighted Network (SAWN) model and method: Theory and

- application. *Appl. Ergon.* 61, 178–196. <https://doi.org/10.1016/J.APERGO.2017.02.002>
- Key, C.E.J., 2016. The comparative Situation Awareness performance of older (to younger) drivers. Loughborough University.
- Kiekel, P.A., Cooke, N.J., Foltz, P., Foltz, P.W., Shope, S.M., 2001. Automating Measurement of Team Cognition through Analysis of Communication.
- Kirilkin, V., Potapenkov, V., Tsybova, E., 2013. The Method of Redistributing the Functions of Aircraft Control and the System for its Implementation [WWW Document]. 2014.
- Kitchenham, B.A., Budgen, D., Pearl Brereton, O., 2011. Using mapping studies as the basis for further research – A participant-observer case study. *Inf. Softw. Technol.* 53, 638–651. <https://doi.org/10.1016/J.INFSOF.2010.12.011>
- Kitchin, J., Baber, C., 2018. EXPLORING WORKLOAD AND PERFORMANCE THROUGH THE USE OF VISUAL ANALYTICS, in: *Contemporary Ergonomics and Human Factors*.
- Kitchin, J., Baber, C., 2017. The Dynamics of Distributed Situation Awareness. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 61, 277–281. <https://doi.org/10.1177/1541931213601551>
- Kitchin, J., Baber, C., 2016a. Towards Agent-Based Modelling for Situation Awareness: modeling a ships Operations Room, in: *Contemporary Ergonomics and Human Factors*. Daventry, UK, pp. 284–289.
- Kitchin, J., Baber, C., 2016b. A comparison of shared and distributed situation awareness in teams through the use of agent-based modelling. *Theor. Issues Ergon. Sci.* 17, 8–41. <https://doi.org/10.1080/1463922X.2015.1106616>
- Krippendorff, K., 2006. On the Reliability of Unitizing Continuous Data. *Sociol. Methodol.* 25, 47. <https://doi.org/10.2307/271061>
- Lamm, H., Trommsdorff, G., 1973. Helmut lamm gisela trommsdorff 3, 361–388.
- Lampton, D.R., Riley, J.M., Kaber, D.B., Sheik-Nainar, M.A., Endsley, M.R., 2006. Use of Immersive Virtual Environments for Measuring and Training Situation Awareness.
- Landauer, T.K., Foltz, P.W., Laham, D., 1998. An introduction to latent semantic analysis. *Discourse Process.* 25, 259–284. <https://doi.org/10.1080/01638539809545028>
- Letsky, M.P., Warner, N.W., Fiore, S.M., Smith, C.A., 2008. Macrocognition in team: Theories and methodologies.
- Likens, A.D., Amazeen, P.G., Stevens, R., Galloway, T., Gorman, J.C., 2014. Neural signatures of team coordination are revealed by multifractal analysis. *Soc. Neurosci.* 9, 219–234. <https://doi.org/10.1080/17470919.2014.882861>
- Lingard, L., Espin, S., Whyte, S., Regehr, G., Baker, G.R., Reznick, R., Bohnen, J., Orser, B., Doran, D., Grober, E., 2004. Communication failures in the operating room: an observational classification of recurrent types and effects. *Qual. Saf. Health Care* 13, 330–4. <https://doi.org/10.1136/qhc.13.5.330>
- Mabry, E.A., Attridge, M.D., 1990. Small Group Interaction and Outcome Correlates for Structured and Unstructured Tasks. *Small Gr. Res.* 21, 315–332. <https://doi.org/10.1177/1046496490213002>

- MacMillan, J., Entin, E.E., Serfaty, D., 2005. Communication overhead: The hidden cost of team cognition., in: *Team Cognition: Understanding the Factors That Drive Process and Performance*. American Psychological Association, Washington, pp. 61–82.  
<https://doi.org/10.1037/10690-004>
- Marks, M.A., Mathieu, J.E., Zaccaro, S.J., 2001. A Temporally Based Framework and Taxonomy of Team Processes. *Acad. Manag. Rev.* 26, 356–376.  
<https://doi.org/10.5465/amr.2001.4845785>
- Marks, M.A., Zaccaro, S.J., Mathieu, J.E., 2000. Performance implications of leader briefings and team-interaction training for team adaptation to novel environments. *J. Appl. Psychol.* 85, 971–986. <https://doi.org/10.1037/0021-9010.85.6.971>
- Marlow, S.L., Lacerenza, C.N., Paoletti, J., Burke, C.S., Salas, E., 2018. Does team communication represent a one-size-fits-all approach?: A meta-analysis of team communication and performance. *Organ. Behav. Hum. Decis. Process.* 144, 145–170.  
<https://doi.org/10.1016/j.obhdp.2017.08.001>
- Martin, M.J., Foltz, P.W., 2010. Automated team discourse annotation and performance prediction using LSA. pp. 97–100. <https://doi.org/10.3115/1613984.1614009>
- Mathieu, J.E., Heffner, T.S., Goodwin, G.F., Salas, E., Cannon-Bowers, J.A., 2000. The influence of shared mental models on team process and performance. undefined.
- Matthews, M.D., Beal, S.A., 2002. Assessing situation awareness in field training exercises, *Assessing situation awareness in field training exercises*. DTIC Document.
- McGrath, J., 1984. *GROUPS: INTERACTION AND PERFORMANCE*.
- McGrath, J.E., 1990. Time Matters in Groups, in: *Intellectual Teamwork*. Psychology Press, pp. 23–61. <https://doi.org/10.4324/9781315807645-9>
- McGuinness, B., 1999. Situational awareness and the CREW awareness rating scale (CARS), in: *Proceedings of the 1999 Avionics Conference*. pp. 1815–1999.
- McGuinness, B., Foy, L., 2000. A subjective measure of SA: the Crew Awareness Rating Scale (CARS), in: *Proceedings of the First Human Performance, Situation Awareness, and Automation Conference*, Savannah, Georgia.
- Mead, S.P., 2001. Using Social Network Analysis to Visualize Project Teams. *Proj. Manag. J.* 32, 32–38. <https://doi.org/10.1177/875697280103200405>
- Mesmer-Magnus, J.R., DeChurch, L.A., 2009. Information sharing and team performance: a meta-analysis. *J. Appl. Psychol.* 94, 535. <https://doi.org/10.1037/a0013773>
- Mickan, S., Rodger, S., Mickan, Sharon; Rodger, S., 2000. Characteristics of effective teams. *Aust. Heal. Rev.* 23, 201–208.
- Min, D., Chung, Y.H., Yoon, W.C., 2004. *COMPARATIVE ANALYSIS OF COMMUNICATION AT MAIN CONTROL ROOMS OF NUCLEAR POWER PLANTS*.
- Mishra, A., Catchpole, K., Mcculloch, P., Mishra, M.A., 2009. The Oxford NOTECHS System: reliability and validity of a tool for measuring teamwork behaviour in the operating theatre. *Qual Saf Heal. Care* 18, 104–108.  
<https://doi.org/10.1136/qshc.2007.024760>

- Mohammadfam, I., Bastani, S., Esaghi, M., Golmohamadi, R., Saeed, A., 2015. Evaluation of coordination of emergency response team through the social network analysis. Case study: Oil and gas refinery. *Saf. Health Work* 6, 30–34. <https://doi.org/10.1016/j.shaw.2014.09.004>
- Mohammed, S., Dumville, B.C., 2001. Team mental models in a team knowledge framework: expanding theory and measurement across disciplinary boundaries. *J. Organ. Behav.* 22, 89–106. <https://doi.org/10.1002/job.86>
- Moiser, K., Chidester, T., 1991. Situation assessment and situation awareness in a team setting, *Designing for Everyone*. London, Taylor & Francis.
- Moorman, D.W., 2007. Communication, teams, and medical mistakes. *Ann. Surg.* 245, 173–5. <https://doi.org/10.1097/01.sla.0000254060.41574.a2>
- Mosier, K.L., Chidester, T.R., 1991. Situation assessment and situation awareness in a team setting. *Des. everyone* 798–800.
- Muniz, E., Stout, R., Bowers, C., Salas, E., 1998. A methodology for measuring team situational awareness: situational awareness linked indicators adapted to novel tasks (SALIENT). NATO Hum. factors Med. panel Collab. crew Perform. complex Syst. Edinburgh, North Atl. Treaties Organ. Neuilly-sur-Seine 20–24.
- Newton, O.B., Wiltshire, T.J., Fiore, S.M., 2018. Macro-cognition in Teams and Metacognition: Developing Instructional Strategies for Complex Collaborative Problem Solving. pp. 33–54. <https://doi.org/10.1108/S1534-085620180000019006>
- Nofi, A.A., 2000. Defining and measuring shared situational awareness, Defining and measuring shared situational awareness. DTIC Document.
- Novak, J.D., Cañas, A.J., 2008. The theory underlying concept maps and how to construct and use them.
- Novak, J.D., Cañas, A.J., 2006. The origins of the concept mapping tool and the continuing evolution of the tool. *Inf. Vis.* 5, 175–184.
- Paré, G., Trudel, M.C., Jaana, M., Kitsiou, S., 2015. Synthesizing information systems knowledge: A typology of literature reviews. *Inf. Manag.* 52, 183–199. <https://doi.org/10.1016/j.im.2014.08.008>
- Parker, D., DeCottis, T., 2013. Theories of Team Cognition: Cross-Disciplinary Perspectives. *Theor. team Cogn. Cross-disciplinary Perspect.* 177, 111–134.
- Parush, A., Kramer, C., Foster-Hunt, T., Momtahan, K., Hunter, A., Sohmer, B., 2011. Communication and team situation awareness in the OR: Implications for augmentative information display. *J. Biomed. Inform.* 44, 477–485. <https://doi.org/10.1016/J.JBI.2010.04.002>
- Patton, E., 2011. When groups fall apart: The Donner Party disaster. *J. Manag. Hist.* 17, 435–450. <https://doi.org/10.1108/17511341111164436>
- Payne, J.W., Bettman, J.R., Johnson, E.J., 1993. The adaptive decision maker. Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9781139173933>
- Peterson, J., Pearce, P.F., Ferguson, L.A., Langford, C.A., 2016. Understanding scoping reviews. *J. Am. Assoc. Nurse Pract.* 29, 12–16. <https://doi.org/10.1002/2327-6924.12380>

- Pollock, K., 2013. Review of Persistent Lessons Identified Relating to Interoperability from Emergencies and Major Incidents since 1986. *Emerg. Plan. Coll. Occas. Pap. New Ser.* 6.
- Quesada, J., Kintsch, W., Gomez, E., 2005. Complex problem-solving: A field in search of a definition? *Theor. Issues Ergon. Sci.* 6, 5–33.  
<https://doi.org/10.1080/14639220512331311553>
- Reed, E. (Edward S., 1996. *Encountering the world : toward an ecological psychology.* Oxford University Press.
- Reed, S.K., Vallacher, R.R., 2019. A comparison of information processing and dynamical systems perspectives on problem solving. *Think. Reason.* 1–37.  
<https://doi.org/10.1080/13546783.2019.1605930>
- Resnick, L.B., 2004. Shared cognition: Thinking as social practice., in: *Perspectives on Socially Shared Cognition.* American Psychological Association, Washington, pp. 1–20.  
<https://doi.org/10.1037/10096-018>
- Ribeiro, J., Silva, P., Duarte, R., Davids, K., Garganta, J., 2017. Team Sports Performance Analysed Through the Lens of Social Network Theory: Implications for Research and Practice. *Sport. Med.* 47, 1689–1696. <https://doi.org/10.1007/s40279-017-0695-1>
- Roberts, T.L., Cheney, P.H., Sweeney, P.D., Hightower, R.T., 2004. The effects of information technology project complexity on group interaction. *J. Manag. Inf. Syst.*  
<https://doi.org/10.1080/07421222.2004.11045814>
- Rogers, W.P., Armstrong, N.A., Acheson, D.C., Covert, E.E., Feynman, R.P., Hotz, R.B., Kutyna, D.J., Ride, S.K., Rummel, R.W., Sutter, J.F., Arthur B.C. Walker, J., Wheelon, A.D., Yeager, C.E., NASA, 1986. Report to the President on the Space Shuttle Challenger Accident 18–20, 83–112.
- Roscoe, S.N., 1993. An aid in the selection process—WOMBAT. *Civ. Aviat. Train.* 4, 48–51.
- Roscoe, S.N., Corl, L., Jean, L., 2001. *Predicting Human Performance.*
- Rose, J., Bearman, C., Dorrian, J., 2018. The Low-Event Task Subjective Situation Awareness (LETSSA) technique: Development and evaluation of a new subjective measure of situation awareness. *Appl. Ergon.* 68, 273–282.  
<https://doi.org/10.1016/j.apergo.2017.12.006>
- Rosen, M.A., 2010. *Collaborative problem solving: The role of team knowledge building processes and external representations.* (Doctoral Diss. Univ. Cent. Florida Orlando, Florida).
- Rumrill, P.D., Fitzgerald, S.M., Merchant, W.R., 2010. Using scoping literature reviews as a means of understanding and interpreting existing literature. *Work* 35, 399–404.  
<https://doi.org/10.3233/WOR-2010-0998>
- Salas, E., Burke, C.S., Cannon-Bowers, J.A., 2000. Teamwork: Emerging principles. *Int. J. Manag. Rev.* 2, 339–356. <https://doi.org/10.1111/1468-2370.00046>
- Salas, E., Burke, C.S., Stagl, K.C., 2004. Developing teams and developing team leaders: strategies and principles, in: *Leader Development for Transforming Organizations.* Lawrence Erlbaum Associates. <https://doi.org/10.4324/9781410610102>
- Salas, E., Cannon-Bowers, J.A., Johnston, J.H., 1997. How can you turn a team of experts

- into an expert team?: Emerging training strategies., in: *Naturalistic Decision Making., Expertise: Research and Applications*. Lawrence Erlbaum Associates, Inc, Hillsdale, NJ, US, pp. 359–370.
- Salas, E., Cooke, N.J., Rosen, M.A., 2008. On Teams, Teamwork, and Team Performance: Discoveries and Developments. *Hum. Factors J. Hum. Factors Ergon. Soc.* 50, 540–547. <https://doi.org/10.1518/001872008X288457>
- Salas, E., Dickinson, T.L., Converse, S.A., Tannenbaum, S.I., 1992. Toward an understanding of team performance and training.
- Salas, E., Fiore, S.M. (Eds.), 2004. *Team cognition: Understanding the factors that drive process and performance*. American Psychological Association, Washington. <https://doi.org/10.1037/10690-000>
- Salas, E., Prince, C., Baker, D.P., Shrestha, L., 1995. Situation awareness in team performance: Implications for measurement and training. *Hum. Factors J. Hum. Factors Ergon. Soc.* 37, 123–136.
- Salazar, A.J., Hirokawa, R.Y., Propp, K.M., Julian, K.M., Leatham, G.B., 1994. In Search of True Causes: Examination of the Effect of Group Potential and Group Interaction on Decision Performance. *Hum. Commun. Res.* 20, 529–599. <https://doi.org/10.1111/j.1468-2958.1994.tb00334.x>
- Salmon, 2008. *Distributed Situation Awareness: Advances in theory, Measurement and Application to Team Work*. System. Ashgate.
- Salmon, P., Stanton, N., Walker, G., Green, D., 2006. Situation awareness measurement: A review of applicability for C4i environments. *Appl. Ergon.* 37, 225–238. <https://doi.org/10.1016/j.apergo.2005.02.001>
- Salmon, P.M., Stanton, N.A., Jenkins, D.P., 2017. *Distributed situation awareness: Theory, measurement and application to teamwork*. CRC Press.
- Salmon, P.M., Stanton, N.A., Jenkins, D.P., Walker, G.H., Young, M.S., Aujla, A., 2007. What Really Is Going on? Review, Critique and Extension of Situation Awareness Theory. *Eng. Psychol. Cogn. Ergon.* 9, 407–416. [https://doi.org/10.1007/978-3-540-73331-7\\_45](https://doi.org/10.1007/978-3-540-73331-7_45)
- Salmon, P.M., Stanton, N.A., Walker, G.H., Jenkins, D.P., Rafferty, L., 2010. Is it really better to share? Distributed situation awareness and its implications for collaborative system design. *Theor. Issues Ergon. Sci.* 11, 58–83.
- Salmon, Stanton, Walker, Jenkins, 2008. What really is going on? Review of situation awareness models for individuals and teams. *Theor. Issues Ergon. Sci.* 9, 297–323.
- Sasou, K., Reason, J., 1999. Team errors: definition and taxonomy. *Reliab. Eng. Syst. Saf.* 65, 1–9. [https://doi.org/10.1016/S0951-8320\(98\)00074-X](https://doi.org/10.1016/S0951-8320(98)00074-X)
- Scott, J., 1988. Social Network Analysis. *Sociology* 22, 109–127. <https://doi.org/10.1177/0038038588022001007>
- Scott, J., Tallia, A., Crosson, J.C., Orzano, A.J., Stroebel, C., DiCicco-Bloom, B., O'Malley, D., Shaw, E., Crabtree, B., 2005. Social network analysis as an analytic tool for interaction patterns in primary care practices. *Ann. Fam. Med.* 3, 443–448. <https://doi.org/10.1370/afm.344>

- Shannon, C.E., Weaver, W., 1959. The mathematical theory of communication. Univ. Illinois Press.
- Shrestha, L.B., Prince, C., Baker, D.P., Salas, E., 1995. Understanding Situational Awareness: Concepts, Methods, and Training | American Institutes for Research. Human/Technology Interact. Complex Syst.
- Singleton, W.T. (William T., 1989. The mind at work : psychological ergonomics. Cambridge University Press.
- Smith, K., Hancock, P.A., 1995. Situation awareness is adaptive, externally directed consciousness. Hum. Factors J. Hum. Factors Ergon. Soc. 37, 137–148.
- Sorensen, L.J., Stanton, N.A., 2013. Y is best: How Distributed Situational Awareness is mediated by organisational structure and correlated with task success. Saf. Sci. 56, 72–79.
- Sorenson, J.R., 2006. Task Demands, Group Interaction and Group Performance. Sociometry 34, 483. <https://doi.org/10.2307/2786194>
- Stanton, N., Baber, C., Harris, D., 2008. Case Study at HMS Dryad, in: Modelling Command and Control: Event Analysis of Systemic Teamwork. Ashgate Publishing, Ltd., pp. 119–156.
- Stanton, N., Baber, C., Walker, G., Salmon, P., Green, D., Houghton, R., McMasters, R., Gibson, H., 2005. Distributed situational awareness, in: Contemporary Ergonomics 2005: Proceedings of the International Conference on Contemporary Ergonomics (CE2005), 5-7 April 2005, Hatfield, UK. CRC Press, p. 97.
- Stanton, N.A. (Neville A., Salmon, P., Walker, G.H., 2018. Systems Thinking in Practice : Applications of the Event Analysis of Systemic Teamwork Method. Chapman and Hall/CRC.
- Stanton, N.A., Roberts, A.P.J., 2018. Examining social, information, and task networks in submarine command and control. IEEE Trans. Human-Machine Syst. 48, 252–265. <https://doi.org/10.1109/THMS.2017.2720659>
- Stanton, N.A., Salmon, P.M., Rafferty, L.A., Walker, G.H., Baber, C., Jenkins, D.P., 2013. Human factors methods: A practical guide for engineering and design. Ashgate Pub. Co.
- Stanton, N.A., Salmon, P.M., Walker, G.H., 2014. Let the Reader Decide: A Paradigm Shift for Situation Awareness in Sociotechnical Systems. J. Cogn. Eng. Decis. Mak. 9, 44–50. <https://doi.org/10.1177/1555343414552297>
- Stanton, N.A., Salmon, P.M., Walker, G.H., Jenkins, D.P., 2010. Is situation awareness all in the mind? Theor. Issues Ergon. Sci. 11, 29–40.
- Stanton, N.A., Stewart, R., Harris, D., Houghton, R.J., Baber, C., McMaster, R., Salmon, P., Hoyle, G., Walker, G., Young, M.S., 2006. Distributed situation awareness in dynamic systems: theoretical development and application of an ergonomics methodology. Ergonomics 49, 1288–1311.
- Stanton, N.A., Walker, G.H., 2011. Exploring the psychological factors involved in the Ladbroke Grove rail accident. Accid. Anal. Prev. 43, 1117–1127. <https://doi.org/10.1016/J.AAP.2010.12.020>
- Stevens, R., 2013. The Organizational Neurodynamics of Teams, Nonlinear Dynamics,

Psychology, and Life Sciences.

- Stevens, R., 2012. Charting Neurodynamic Eddies in the Temporal Flows of Teamwork. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 56, 208–212.  
<https://doi.org/10.1177/1071181312561020>
- Stevens, R., Berka, C., ... A.B.-U.P., 2017, U., 2010. Systems and methods for assessing team dynamics and effectiveness. Google Patents.
- Stevens, R., Galloway, T., Lamb, C., 2014. Submarine Navigation team resilience: Linking EEG and behavioral models, in: *Proceedings of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, pp. 245–249.  
<https://doi.org/10.1177/1541931214581051>
- Stevens, R., Galloway, T., Lamb, J., Steed, R., Lamb, C., 2017a. Linking Team Neurodynamic Organizations with Observational Ratings of Team Performance. Springer, Cham, pp. 315–330. [https://doi.org/10.1007/978-3-319-33261-1\\_20](https://doi.org/10.1007/978-3-319-33261-1_20)
- Stevens, R., Galloway, T., Willemsen-Dunlap, A., 2017b. A team's neurodynamic organization is more than the sum of it's members', in: *Proceedings of the Human Factors and Ergonomics Society*. SAGE PublicationsSage CA: Los Angeles, CA, pp. 2010–2014. <https://doi.org/10.1177/1541931213601997>
- Stevens, R., Galloway, T.L., Willemsen-Dunlap, A., Avellino, A.M., 2018a. Toward Rapid and Predictive Neurodynamic Feedback and Scaffolding for Teams. pp. 153–172.  
<https://doi.org/10.1108/s1534-085620180000019011>
- Stevens, R., Willemsen-Dunlap, A., Gorman, J., Galloway, T., Grimm, D., Halpin, D., 2018b. Neurodynamic and Communication Analysis of Healthcare Teams During Simulation Debriefings. *Proc. Int. Symp. Hum. Factors Ergon. Heal. Care* 7, 167–172.  
<https://doi.org/10.1177/2327857918071044>
- Stevens, R.H., Galloway, T., Berka, C., Wang, P., 2011. Developing Systems for the Rapid Modeling of Team Neurodynamics. Springer, Berlin, Heidelberg, pp. 356–365.  
[https://doi.org/10.1007/978-3-642-21852-1\\_42](https://doi.org/10.1007/978-3-642-21852-1_42)
- Stevens, R.H., Galloway, T.L., 2017. Are neurodynamic organizations a fundamental property of teamwork? *Front. Psychol.* 8, 644. <https://doi.org/10.3389/fpsyg.2017.00644>
- Stevens, R.H., Galloway, T.L., 2016. Modeling the neurodynamic organizations and interactions of teams. *Soc. Neurosci.* 11, 123–139.  
<https://doi.org/10.1080/17470919.2015.1056883>
- Stevens, R.H., Galloway, T.L., Wang, P., Berka, C., 2012. Cognitive Neurophysiologic Synchronies. *Hum. Factors J. Hum. Factors Ergon. Soc.* 54, 489–502.  
<https://doi.org/10.1177/0018720811427296>
- Stevens, R.H., Galloway, T.L., Willemsen-Dunlap, A., 2018. Neuroergonomics: Quantitative Modeling of Individual, Shared, and Team Neurodynamic Information. *Hum. Factors J. Hum. Factors Ergon. Soc.* 60, 1022–1034. <https://doi.org/10.1177/0018720818781623>
- Stevens, R.H., Galloway, T.L., Willemsen-Dunlap, A., 2017. Low level predictors of team dynamics: A neurodynamic approach. *Res. Manag. Groups Teams* 18, 71–92.  
<https://doi.org/10.1108/S1534-085620160000018004>
- Stevens, R.H., Gorman, J.C., 2011. Mapping cognitive attractors onto the dynamic landscapes

- of teamwork, in: *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. Springer, Berlin, Heidelberg, pp. 366–375. [https://doi.org/10.1007/978-3-642-21852-1\\_43](https://doi.org/10.1007/978-3-642-21852-1_43)
- Strater, L.D., Endsley, M.R., Pleban, R.J., Matthews, M.D., 2001. Measures of Platoon Leader Situation Awareness in Virtual Decision-Making Exercises. TRW INC FAIRFAX VA Syst. Inf. Technol. Gr.
- Sullivan, C., Blackman, H.S., 1991. Insights into Pilot Situation Awareness Using Verbal Protocol Analysis. *Proc. Hum. Factors Soc. Annu. Meet.* 35, 57–61. <https://doi.org/10.1518/107118191786755986>
- Sundstrom, E., Busby, P.L., Bobrow, W.S., 1997. Group process and performance: Interpersonal behaviors and decision quality in group problem solving by consensus. *Gr. Dyn.* 1, 241–253. <https://doi.org/10.1037/1089-2699.1.3.241>
- Sutcliffe, K.M., Lewton, E., Rosenthal, M.M., 2004. Communication failures: an insidious contributor to medical mishaps. *Acad. Med.* 79, 186–94.
- Taylor, D.W., Faust, W.L., 1952. Twenty questions: efficiency in problem solving as a function of size of group. *J. Exp. Psychol.* 44, 360–368. <https://doi.org/10.1037/h0054376>
- Taylor, R.M., 1995. CC-SArt: The Development of an Experiential Measure of Cognitive Compatibility in System Design, in: Report to TTCP UTP-7 Human Factors in Aircraft Environments, Annual Meeting.
- Taylor, R.M., 1990. Situational Awareness Rating Technique(SART): The development of a tool for aircrew systems design. *AGARD, Situational Aware. Aerosp. Oper.* 17 p(SEE N 90-28972 23-53).
- Treffner, P.J., Kelso, J.A.S., 1999. Dynamic Encounters: Long Memory During Functional Stabilization. *Ecol. Psychol.* 11, 103–137. [https://doi.org/10.1207/s15326969eco1102\\_1](https://doi.org/10.1207/s15326969eco1102_1)
- Tschan, F., 1995. Communication Enhances Small Group Performance if it Conforms to Task Requirements: The Concept of Ideal Communication Cycles. *Basic Appl. Soc. Psych.* 17, 371–393. [https://doi.org/10.1207/s15324834basp1703\\_6](https://doi.org/10.1207/s15324834basp1703_6)
- Tuckman, B.W., 1965. Developmental sequence in small groups. *Psychol. Bull.* 63, 384–399. <https://doi.org/10.1037/h0022100>
- Turner, J.R., Chen, Q., Danks, S., 2014. Team Shared Cognitive Constructs: A Meta-Analysis Exploring the Effects of Shared Cognitive Constructs on Team Performance. *Perform. Improv. Q.* 27, 83–117. <https://doi.org/10.1002/piq.21163>
- U.S. Nuclear Regulatory Commission, 1979. TMI-2 Lessons Learned Task Force.
- United States. National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling., 2011. Deep water : the Gulf oil disaster and the future of offshore drilling : report to the President. National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling.
- Vidulich, M.A., Hughes, E.R., 1991. Testing a subjective metric of situation awareness, in: *Proceedings of the Human Factors Society Annual Meeting*. SAGE Publications Sage CA: Los Angeles, CA, pp. 1307–1311.
- Waag, W.L., Houck, M.R., 1994. Tools for assessing situational awareness in an operational

- fighter environment. *Aviat. Space. Environ. Med.*
- Walker, G., 2005. Verbal protocol analysis. *Handb. Hum. factors Ergon. method* 301–311.
- Walker, G.H., Stanton, N.A., Chowdhury, I., 2013. Self Explaining Roads and situation awareness. *Saf. Sci.* 56, 18–28. <https://doi.org/10.1016/J.SSCI.2012.06.018>
- Walker, G.H., Stanton, N.A., Salmon, P.M., Jenkins, D.P., 2008a. A review of sociotechnical systems theory: A classic concept for new command and control paradigms. *Theor. Issues Ergon. Sci.* 9, 479–499. <https://doi.org/10.1080/14639220701635470>
- Walker, G.H., Stanton, N.A., Young, M.S., 2008b. Feedback and driver situation awareness (SA): A comparison of SA measures and contexts. *Transp. Res. Part F Traffic Psychol. Behav.* 11, 282–299. <https://doi.org/10.1016/j.trf.2008.01.003>
- Wäsche, H., 2015. Interorganizational cooperation in sport tourism: A social network analysis. *Sport Manag. Rev.* 18, 542–554. <https://doi.org/10.1016/J.SMR.2015.01.003>
- Wasserman, S., Faust, K., 1994. *Social network analysis : methods and applications.* Cambridge University Press.
- Wellens, A.R., 1993. Group situation awareness and distributed decision making: From military to civilian applications. *Individ. Gr. Decis. Mak. Curr. issues* 267–287.
- Wenger, E., 1998. Community of Practice: a Brief Introduction. *Learn. doing* 15, 1–7. <https://doi.org/10.2277/0521663636>
- West, E., Barron, D.N., 2005. Social and geographical boundaries around senior nurse and physician leaders: an application of social network analysis. *Can. J. Nurs. Res.* 37, 132–48.
- West, E., Barron, D.N., Dowsett, J., Newton, J.N., 1999. Hierarchies and cliques in the social networks of health care professionals: implications for the design of dissemination strategies. *Soc. Sci. Med.* 48, 633–46.
- Wheelan, S., Verdi, A., McKeage, R., 1994. *The Group Development Observation System: Origins and applications.*
- Wheelan, S.A., Williams, T., 2003. Mapping dynamic interaction patterns in work groups. *Small Gr. Res.* 34, 443–467. <https://doi.org/10.1177/1046496403254043>
- Willems, B., 2002. Decision Support Automation Research in the En Route Air Traffic Control Environment 264.
- Wilson, J.R., Cordiner, L., Nichols, S., Norton, L., Bristol, N., Clarke, T., Roberts, S., 2001. On the Right Track: Systematic Implementation of Ergonomics in Railway Network Control. *Cogn. Technol. Work* 3, 238–253. <https://doi.org/10.1007/s10111-001-8005-x>
- Wiltshire, T.J., Butner, J.E., Fiore, S.M., 2017. Problem-Solving Phase Transitions During Team Collaboration. *Cogn. Sci.* 1–39.
- Wiltshire, T.J., Rosch, K., Fiorella, L., Fiore, S.M., 2014. Training for Collaborative Problem Solving: Improving Team Process and Performance through Metacognitive Prompting. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 58, 1154–1158. <https://doi.org/10.1177/1541931214581241>
- Woods, D.D., Sarter, N.B., 2010. Capturing the dynamics of attention control from individual to distributed systems: the shape of models to come. *Theor. Issues Ergon. Sci.* 11, 7–28.

- Wright, M.C., Taekman, J.M., Endsley, M.R., 2004. Objective measures of situation awareness in a simulated medical environment. *Qual Saf Heal. Care* 13, 65–71. <https://doi.org/10.1136/qshc.2004.009951>
- Wu, Q., Cormican, K., 2016. Shared Leadership and Team Creativity: A Social Network Analysis in Engineering Design Teams. *J. Technol. Manag. Innov.* 11, 2–12. <https://doi.org/10.4067/S0718-27242016000200001>
- Yim, H. Bin, Lee, S.M., Seong, P.H., 2014. A development of a quantitative situation awareness measurement tool: Computational Representation of Situation Awareness with Graphical Expressions (CoRSAGE). *Ann. Nucl. Energy* 65, 144–157. <https://doi.org/10.1016/J.ANUCENE.2013.10.029>
- Yim, H. Bin, Seong, P.H., 2016. A Quantitative Team Situation Awareness Measurement Method Considering Technical and Nontechnical Skills of Teams. *Nucl. Eng. Technol.* 48, 144–152. <https://doi.org/10.1016/J.NET.2015.09.007>
- Zheng, K., Padman, R., Johnson, M.P., 2007. Social contagion and technology adoption: a study in healthcare professionals. *AMIA ... Annu. Symp. proceedings. AMIA Symp.* 1175.
- Zheng, X., Le, Y., Chan, A.P.C., Hu, Y., Li, Y., 2016. Review of the application of social network analysis (SNA) in construction project management research. *Int. J. Proj. Manag.* 34, 1214–1225. <https://doi.org/10.1016/J.IJROMAN.2016.06.005>

## APPENDICES

### Appendix A – Summary of Situation Awareness Measurement Techniques

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
SA Requirements Analysis	Individual	Post-hoc	SA Requirements Analysis	Endsley (1993)	<ul style="list-style-type: none"> <li>• “Provides a structured approach for identifying the situation awareness requirements associated with a particular task or scenario” (Stanton et al., 2013)</li> <li>• Tells us what each of the individuals need to know during the task (Stanton et al., 2013) and how the information is combined to address each decision made (Endsley, 2000)</li> <li>• The technique is generic and can be applied to many domains (Stanton et al., 2013)</li> <li>• The technique strives to be technology free, with Endsley (2000) seeing the potential for obtaining the information through system displays.</li> </ul>	<ul style="list-style-type: none"> <li>• Very time consuming due to the interviews and task analyses required (Stanton et al., 2013)</li> <li>• Requires access to many subject matter experts (Stanton et al., 2013)</li> <li>• Analysts require an in-depth understanding of situation awareness (Stanton et al., 2013)</li> <li>• May suffer issues with subject matter experts self-rating their own situation awareness under a hypothetical task during interviews. Results may be idealistic or biased.</li> </ul>	No	Individual Post-hoc
Freeze-probe	Individual	Concurrent	SAGAT	Endsley (1988)	<ul style="list-style-type: none"> <li>• Provides direct measurement of individual situation awareness (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Removes the need to collect data post-trial (Salmon et al., 2006; Stanton et al., 2013)</li> </ul>	<ul style="list-style-type: none"> <li>• Not applicable to ‘in the field’ measurements – one cannot freeze the real-world (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Intrusion upon the primary task may interfere with performance and SA itself (Salmon et al., 2006; Stanton et al., 2013)</li> </ul>	No	Individual

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
	Individual	Concurrent	SAGAT-TRACON	Endsley & Kiris (1995)	<ul style="list-style-type: none"> <li>• Most used methods – allows for direct comparison to other studies and is recognisable to researchers and practitioners (Salmon et al., 2006)</li> <li>• Freeze-probe techniques are the most successful, SAGAT in particular, and therefore has many validation studies to draw from (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Can be applied in a variety of domains (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Situation awareness is rated using subject matter expertise and so removes the problem with subjective situation awareness found with methods that require self-rating (Salmon et al., 2006)</li> <li>• Evidence suggests that SAGAT is a valid metric of SA (Jones and Kaber, 2004)</li> </ul>	<ul style="list-style-type: none"> <li>• Does not take into account the ability to achieve high SA without first achieving lower levels of SA (e.g. perception) (Salmon, 2008)</li> <li>• The process of SA is not measured, only what the individual has access to within the environment (Salmon, 2008)</li> <li>• The technique assumes that ‘awareness’ of more elements implies higher SA and could dismiss higher levels of situation awareness where elements are used as memory aids, and are not made aware of at all times (Salmon, 2008; Stanton et al., 2013)</li> <li>• Assumes that SA is a sum of parts and does not allow for mapping between SA elements. Ignores the relationships between concepts (Salmon, 2008)</li> <li>• Requires task and system simulation hardware which is costly (Stanton et al., 2013)</li> <li>• Probes direct individuals to SA elements, potentially biasing the results (Stanton et al., 2013)</li> <li>• SA is defined beforehand and then individuals measured against that definition, in the real-world it is not possible to know beforehand what SA should comprise of (Stanton et al., 2013)</li> <li>• Requires significant prep, using situation awareness</li> </ul>	No	Individual
Freeze-probe	Individual	Concurrent	SALSA	Hauss & Eyferth (2003)			No	Individual
	Individual	Concurrent	SACRI	Hogg, Folleso, Strand-Volden & Torralba (1995)			No	Individual
	Team	Concurrent	TSAGAT	Crozier, Ting, Boone, O’Regan, Bandrauk, Furey, Squires, Hapgood & Hogan (2015)			Yes	Team Concurrent

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion		
						requirements analysis, before the measurement can take place (Stanton et al., 2013)				
Real-time probe	Individual	Concurrent	SPAM	Durso, Hackworth, Truitt, Crutchfield, Nikolic & Manning (1999)	<ul style="list-style-type: none"> <li>• Reduced level of intrusiveness compared to the freeze-probe techniques (Salmon et al., 2006)</li> <li>• Can be applied to many domains (Key, 2016)</li> <li>• Allows for situation awareness to be compared across studies and conditions (Key, 2016)</li> <li>• Can be applied “in the field” as the need to freeze the task is not required (Salmon et al., 2006)</li> <li>• Removes the need to collect data post-trial (Salmon et al., 2006; Stanton et al., 2013)</li> </ul>	<ul style="list-style-type: none"> <li>• Intrusion upon the primary task may interfere with performance and SA itself (Salmon et al., 2006)</li> <li>• Probes direct individuals to SA elements, potentially biasing the results (Salmon et al., 2006)</li> <li>• Generation of probes in real time may be too difficult in certain environments and may place pressure on subject matter experts (Salmon et al., 2006) – otherwise SA is defined beforehand and then individuals measured against that definition, in the real-world it is not possible to know beforehand what SA should comprise of (Stanton et al., 2013)</li> <li>• When assessing team situation awareness, numerous subject matter experts would be needed to present the probes (Salmon, 2008)</li> </ul>	No	Individual		
Real-time probe & self-rating	Individual	Concurrent	QUASA	Edgar & Edgar (2007)			No	Individual		
Real-time probe & self-rating	Individual	Concurrent	SASHA	Jeannot, Kelly & Thompson (2003)			No	Individual		
Real-time probe & networks	Individual, Team	Concurrent	IPTE	Banbury & Howes (2001)			Yes	Team Concurrent		
Real-time probes, process indices & observer rating	Team	Concurrent	SAMTC	Lampton, Riley, Kaber, Sheik-Nainar & Endsley (2006)			Yes	Team Concurrent		
Observer rating	Individual	Concurrent	SAVANT	Willems (2002)			<ul style="list-style-type: none"> <li>• Most used for “in-the-field” measurements as it can be used</li> </ul>	<ul style="list-style-type: none"> <li>• Cannot guarantee that observers can accurately rate the internal</li> </ul>	No	Individual

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
	Individual	Concurrent, post-hoc	SABARS	Matthews & Beal (2002)	for real world scenarios (Salmon et al., 2006; Stanton et al., 2013) <ul style="list-style-type: none"> <li>• Non-intrusive (Salmon et al., 2006; Stanton et al., 2013)</li> </ul>	construct of an individuals SA (Endsley, 1995b; Salmon et al., 2006) <ul style="list-style-type: none"> <li>• The act of observation may alter the individuals behaviour, they may operate “by-the-book” behaviours which exhibit high SA where in reality they have low SA (Salmon, 2008). This altered behaviour turn could bias the results (Salmon et al., 2006)</li> <li>• Subject matter experts are required multiple times, which could become problematic especially in the military domain (Salmon et al., 2006)</li> <li>• SA is defined beforehand and then individuals measured against that definition, in the real-world it is not possible to know beforehand what SA should comprise of (Stanton et al., 2013)</li> <li>• It could be very difficult to distinguish between different levels of SA across a team (Salmon, 2008)</li> </ul>	No	Individual
	Individual	Concurrent	SASRF	Carretta, Perry & Ree (1996)			No	Individual
	Individual	Concurrent	Force the user to ask	Payne, Bettman & Johnson (1993)			No	Individual
	Individual, Team	Post-hoc	CSA	Moiser & Chidester (1991)			No	Individual
Observer rating	Team	Concurrent, post-hoc	CAST	Gorman, Cooke & Winner (Gorman et al., 2006)			Yes	Team Concurrent
	Team	Concurrent, post-hoc	TARGETs	Fowlkes, Lane, Salas, Franz & Oser (1994)			Yes	Team Concurrent
	Team	Concurrent, post-hoc	SALIENT	Muniz, Stout, Bowers & Salas (1998)			Yes	Team Concurrent
Self-rating	Individual	Concurrent	RESA	Wilson, Cordiner, Nichols, Norton, Bristol, Clarke & Roberts (2001)	<ul style="list-style-type: none"> <li>• Low cost due to not requiring specialised simulation hardware (Salmon et al., 2006)</li> <li>• Removes the need to collect data post-trial (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Non-intrusive to task performance (Salmon et al., 2006)</li> </ul>	<ul style="list-style-type: none"> <li>• Individuals are more prone to remembering periods when SA is high and may forget periods when SA is low (Salmon et al., 2006)</li> <li>• SA ratings may be correlated with performance (Endsley, 1995b) – individuals who</li> </ul>	No	Individual
	Individual	Concurrent	CLSA	Adams (1998)			No	Individual
	Individual	Concurrent, post-hoc	C-SAS	Dennehy (1997)			No	Individual

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
	Individual	Concurrent, post-hoc	SAPS	Deighton (1997)	<ul style="list-style-type: none"> <li>• Popular due to its simplicity and low amount of training needed (Salmon et al., 2006)</li> <li>• Generic and can be applied in many domains (Salmon et al., 2006)</li> <li>• Ratings can be obtained from many individuals without the need for a large number of subject matter experts or hardware, and so is more applicable to measuring team situation awareness (Salmon et al., 2006)</li> </ul>	<p>perform will automatically rate their SA as high</p> <ul style="list-style-type: none"> <li>• Individuals are prone to forgetting periods of the task when SA is low and vice versa (Salmon et al., 2006)</li> <li>• No method has been developed to measure team situation awareness</li> <li>• As measurement occurs at the end of the task, it is argued that individual SA is captured only then (Endsley, 1995b; Stanton et al., 2013)</li> <li>• Individuals may not be able to rate their own SA accurately (Endsley, 1995b)</li> <li>• The techniques do not give any insight into the process of achieving situation awareness, it only gives a rating on how the individual feels during the task (Salmon, 2008)</li> <li>• It is argued that due to the measurement being taken post-task, that the scores represent working memory rather than situation awareness (Chowdhury, 2014)</li> <li>• Subjective situation awareness measurement techniques have been criticised as a sufficient measure of situation awareness, it is argued that they provide an indication of the level of confidence one has of their own situation awareness (Endsley, 1995a;</li> </ul>	No	Individual
	Individual	Post-hoc	SARS	Waag & Houck (1994) Bell & Wagg (1997)			No	Individual
	Individual	Post-hoc	CC-SART	Taylor (1995)			No	Individual Post-hoc
	Individual	Post-hoc	SA-SWORD	Vidulich & Hughes (1991)			No	Individual Post-hoc
Self-rating	Individual	Post-hoc	MARS	Matthews & Beal (2002)			No	Individual Post-hoc
	Individual	Post-hoc	PSAQ	Strater, Endsley, Pleban & Matthews (2001)			No	Individual Post-hoc
	Individual	Concurrent	LETSSA	Rose, Bearman & Dorrian (2018)			No	Individual
	Individual, Team	Post-hoc	SART	Taylor (1990)			No	Post-hoc
	Individual, Team	Post-hoc	FASA	ESSAI (2001)			No	Post-hoc
	Individual, Team	Post-hoc	SAW-IM	Banbury, Dudfield & Hörmann (2004)			No	Post-hoc
	Team	Concurrent, post-hoc	CARS	McGuinness (1999) McGuinness & Foy (2000)	Yes	Team Concurrent		

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
						Endsley et al., 1998; Jones and Endsley, 2004), rather than the product or process of achieving situation awareness itself.		
Performance	Individual	Concurrent, post-hoc	WOMBAT	Roscoe (1993)	<ul style="list-style-type: none"> <li>• Simplistic to measure (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Non-intrusive (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Can be used as a “back-up” to other SA measures (Salmon et al., 2006; Stanton et al., 2013)</li> <li>• Provides an objective measure of SA</li> </ul>	<ul style="list-style-type: none"> <li>• Assumes that efficient performance is a result of efficient SA and vice versa (Salmon et al., 2006; Stanton et al., 2013)</li> </ul>	No	Individual
	Individual	Post-hoc	Degree of Situation Awareness	Kirilkin, Potapenkov & Tsybova (2013)			No	Individual Post-hoc
	Individual, Team	Concurrent	Performance measures	-			Yes	Team Concurrent
Performance	Team	Concurrent, post-hoc	DuoWOMBAT	Roscoe, Corl & Jean (2001)			Yes	Team Concurrent
Process indices	Individual	Concurrent	Eye-tracker	-	<ul style="list-style-type: none"> <li>• The use of VPA can detect the type of situation awareness within groups (Walker et al., 2008b)</li> <li>• Communication analysis could be used to predict team situation awareness (Foltz et al., 2017)</li> <li>• Other than eye tracking equipment, they are low cost, easy to administer and unobtrusive</li> </ul>	<ul style="list-style-type: none"> <li>• The use of VPA may not be able to detect changes in situation awareness quality (Walker et al., 2008b)</li> <li>• Communication analysis may be less practical and viable in time-pressured, fast-paced operations due to time constraints and technological limitations (Foltz et al., 2017)</li> <li>• It is difficult to use eye tracking cannot be used in the field with current technologies, although emerging technologies may make this more possible (google glasses?)</li> </ul>	No	Individual
	Individual	Concurrent	EEG	-			No	Individual
	Individual, Team	Concurrent, post-hoc	VPA	Sullivan & Blackman (1991) Walker (2005)			Yes	Team Concurrent

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
	Individual, Team	Concurrent, post-hoc	Communications	Endsley & Jones (1997)		<ul style="list-style-type: none"> <li>Eye tracking technology can be temperamental and requires lengthy analysis time (Salmon et al., 2006)</li> <li>Fixation on an element does not necessarily mean that it has been perceived (Salmon et al., 2006)</li> <li>Process indices do not give information about the product of SA (Salmon et al., 2006)</li> </ul>	Yes	Team Concurrent
Networks	Individual, Team, System	Concurrent, post-hoc	Proposition Networks	Stanton, Stewart, Harris, Houghton, Baber, McMaster, Salmon, Hoyle, Walker & Young (2006)	<ul style="list-style-type: none"> <li>Does not require scenario freezes or probes</li> <li>Does not require observer ratings</li> <li>The measures can be analysed statistically and visually (Key, 2016)</li> </ul>	<ul style="list-style-type: none"> <li>May have difficulties identifying knowledge used but not openly expressed (Key, 2016)</li> <li>The data used to construct the network is subjective, it could potentially be prone to error or may lack relevant content (Key, 2016)</li> </ul>	Yes	Team Concurrent
Networks	Team, System	Concurrent, post-hoc	SAWN	Kalloniatis, Ali, Neville, La, Macleod, Zuparic & Kohn (2017)	<ul style="list-style-type: none"> <li>Can be applied to many domains (Key, 2016)</li> <li>Proposition networks have been shown to be applicable to various domains (Salmon et al., 2017; Stanton and Walker, 2011; Walker et al., 2013)</li> <li>Links between knowledge objects are specified within the proposition networks (Stanton et al., 2013)</li> </ul>	<ul style="list-style-type: none"> <li>CDM data is prone to problems with memory degradation as it is carried out post task (Key, 2016)</li> <li>Without accepted and commonly used software support, the network generation can be highly subjective and resource intensive (Key, 2016)</li> </ul>	Yes	Team Concurrent
Modelling	Individual	Concurrent, post-hoc	CoRSAGE	Yim, Bin, Lee & Seong (2014)	<ul style="list-style-type: none"> <li>Does not require the use of subject matter experts – saves time and the problems that occur with subjective</li> </ul>	<ul style="list-style-type: none"> <li>Still a lot of scepticism in using probability to measure human cognition</li> </ul>	No	Individual

Measurement Type	Individual, Team or System	Type	Method	Author/s	Advantages	Disadvantages	Included in Review?	Reason for review inclusion / exclusion
	Team	Concurrent, post-hoc	SAAI	Yim & Seong (2016)	assessments of situation awareness <ul style="list-style-type: none"> <li>• Visual representation of situation awareness flow</li> <li>• Provides a quantitative measure of SA</li> <li>• Non-intrusive</li> <li>• Provides results in real-time</li> </ul>	<ul style="list-style-type: none"> <li>• Currently a prototype and so requires more verification and validation</li> <li>• Bayesian inference cannot reflect rapid changes in mental status which occurs in rapidly changing conditions (Rose et al., 2018)</li> </ul>	Yes	Team Concurrent

## **Appendix B – Comparason of alternative ABM packages**

### **BEHAVIOUR COMPOSER**

Behaviour Composer is a web-based tool developed by Oxford University and is based on the NetLogo (Web) package (Kahn, 2007). The package has a set of prototype agents which have scheduler conditions and actions defined by commands. The package does not require the user to produce text based code, although the background NetLogo code is accessible if need be. The package uses a library of generic micro-behaviours, blocks of NetLogo code, which are designed to be customised and modified and are organised into a range of categories: “initial position and state, movement, appearance, attribute maintenance, reproduction, death, and social networks” (Kahn, 2007). The micro-behaviours are not analogous to functions within programming languages, they are fragments of code which are assigned to agents or the observer and run as independent processes which are not limited to execution order (Kahn, 2007). Figure 127 shows an example of the Behaviour Composer interface with the sample model “Simple Swarming Model” loaded from the inbuilt library. The interface in this view shows which micro-behaviours are assigned to the agents, in this case fish & informed fish, and the observer options. Figure 128 shows how this agent composition is translated into a visual model of fish swimming in a swarm based on the proximity to other fish and the interactions of those fish.

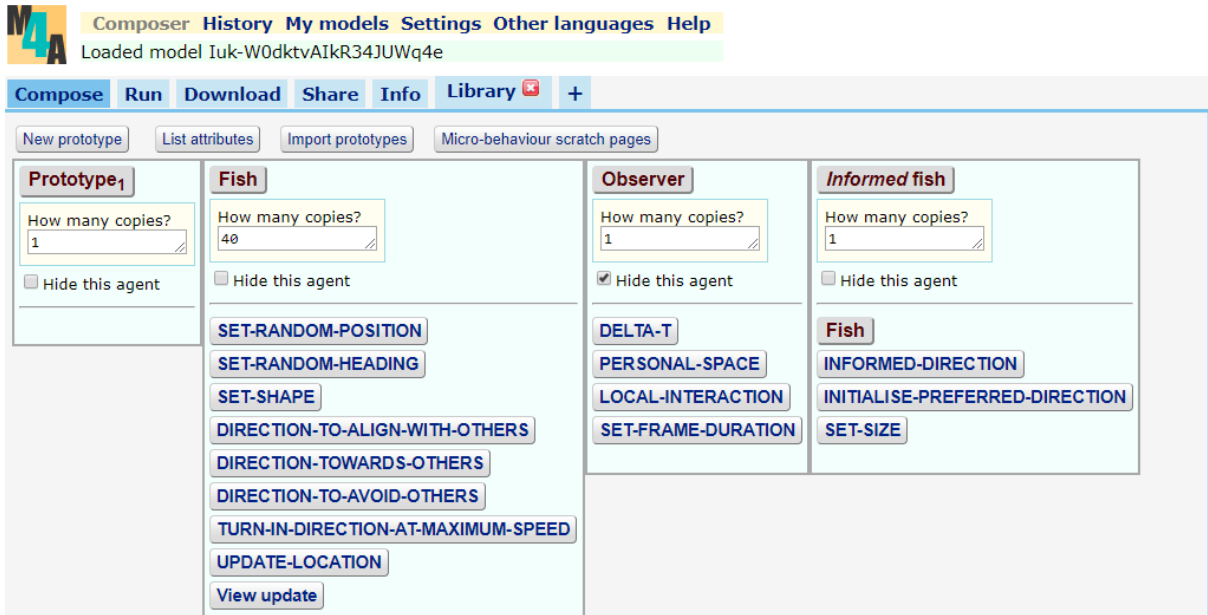


Figure 127 – Behaviour Composer: Compose View

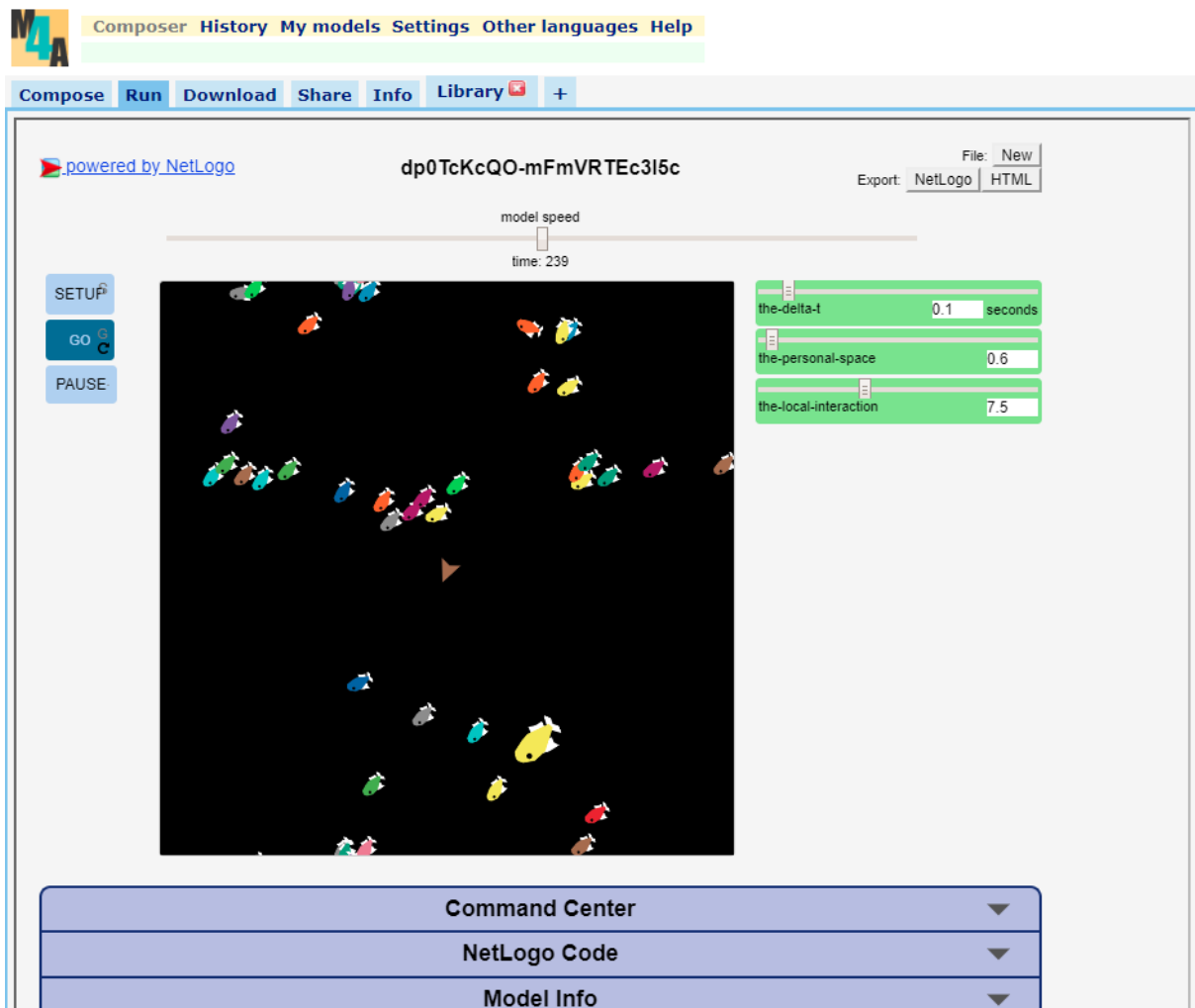


Figure 128 – Behaviour Composer: Run View

The package has a comprehensive library of sample models and tutorials for getting up to speed with creating agent based models, requires no programming experience and has a clean and simple user interface. It is a higher-level version of the NetLogo package, which can be accessed through a browser, negating the need to download any software files. The user does not need to learn what is meant by a prototype and what all the micro-behaviours are, their association to the agents and how to build up a desired model however, for a beginner Behaviour Composer provides a powerful ABM package without compromising time and effort in learning a new coding language.

## **SCRATCH**

Scratch is an online and downloadable visual programming package created by the MIT Media Lab targeted primarily at children. The drag and drop interactive interface allows for a very quick and visual way of coding. In Scratch agents are called sprites, and similar to NetLogo and Behaviour Composer attributes and actions can be assigned to those sprites. Figure 129 shows an example of the Scratch interface and the code sample for a flocking model, similar to the examples shown for NetLogo and Behaviour Composer. This example was created by the author as there were no suitable examples in the Scratch library/community uploads. The language of the code is very straightforward and similar to NetLogo, however instead of typing out the code, blocks are premade which can be dragged into a workspace and snapped together. Only certain blocks snap into other blocks, which allows for fast learning of the package and 'language'.

With first time use of the package, this example model took a couple of hours and required some basic programming knowledge (if statements & while loops). The drag and drop interface is smooth and intuitive, however there is no option to assign rules to all agents which results in duplicated code for each sprite in the model, a tedious and time-consuming

task when modifying the code. There is also no way of storing global or local variables, which reduces the functionality of the package. The block functions are also limited, which requires either some imagination to get the desired result or a compromise on functionality. For beginners to modelling, Scratch could be an option for very small scale simple models however it is clear that it was not intended for this use and due to its limitations was determined unsuitable for this project.

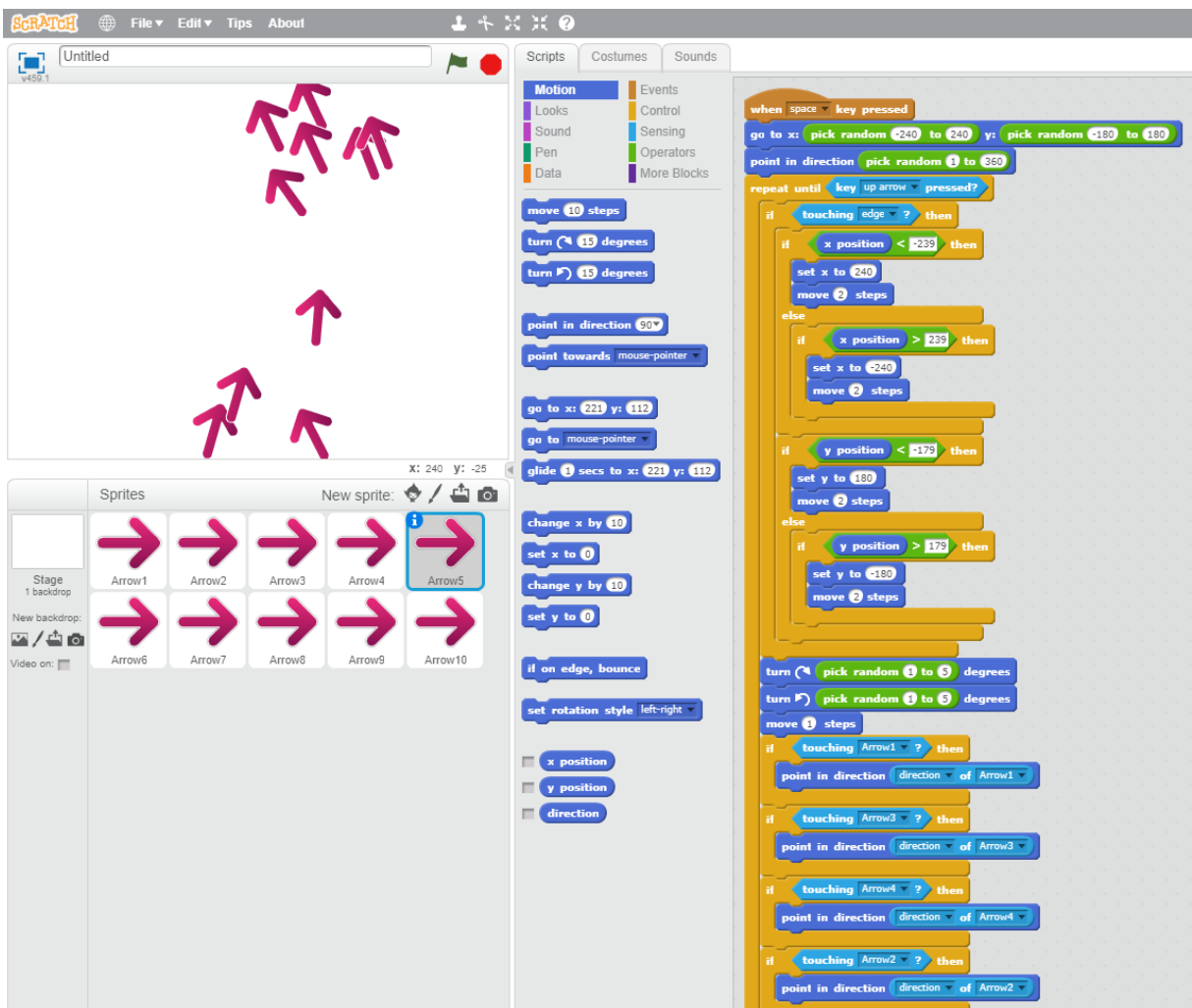


Figure 129 – Scratch: Interface

## **Participant Information Sheet For Project Entitled:**

### SITUATION AWARENESS IN GROUPS

This project forms part of a series of experiments for the module 2H2 'Human Performance' in the School of Electronic, Electrical and Systems Engineering in the University of Birmingham.

The aim of the experiment is to explore how people work in teams to achieve goals.

You are invited to participate in this study as part requirement of the module 2H2 and will receive 5% of the final mark of this module if you participate in at least 5 experiments.

The study will require you to view videos, comment on what you see via an instant messaging screen and using these comments work as part of a team to determine the rules required to achieve the correct results. You will be given a task which will be different to the others in the group. Each of the videos are 8 minutes long and you will carry out the group task three times.

The only way the group can achieve a correct result is by each of the members updating the instant messaging screen with the result from their own individual task. The observer will inform you via the instant messaging screen of whether a correct result has been achieved or not.

Your aim is to achieve the highest number of correct responses.

### Confidentiality/anonymity and data security

Your data will be treated as confidential and you will be assigned a unique identifying code which will be used to identify your data. For all 2H2 experiments, data to be collected will be age and gender. No other personal data will be recorded about participants (no names, ethnicity, addresses etc.).

The results of the experiment will be stored electronically on secure University of Birmingham servers and paper copies will be destroyed.

The results of the experiment will be analysed and shared with other students on 2H2.

If the results prove interesting and noteworthy, then we may decide to produce a paper for publication in a journal or a conference. If this is the case, then you will be asked to sign a further form releasing your data for this purpose. You can decide not to release your data for this purpose (which would constitute withdrawal from the study).

### Contact details

Module Leader
Chris Baber (c.baber@bham.ac.uk)

## Consent Form For Project Entitled:

### SITUATION AWARENESS IN GROUPS

#### Fair Processing Statement

This information is being collected as part of a series of experiments for the module 2H2 'Human Performance' in the School of Electronic, Electrical and Systems Engineering in the University of Birmingham.

The information which you supply and that which may be collected as part of the research project will be entered into a database and will only be accessed by authorised personnel involved in the project. The information will be retained by the University of Birmingham and will be used for the purpose of teaching and research. It may form part of a publication in a technical journal or other forum.

By supplying this information you are consenting to the University storing your information for the purposes stated above. The information will be processed by the University of Birmingham in accordance with the provisions of the Data Protection Act 1998. No identifiable personal data will be published.

#### Statements of understanding/consent

- I confirm that I have read and understand the participant information sheet for this study. I have had the opportunity to ask questions if necessary and have had these answered satisfactorily.
- I understand that my participation is a requirement for the module 2H2.
- I understand that, should the results prove worthy of publication, I will be given the opportunity to either accept or reject the invitation for my results to be used. If I choose to reject this invitation, I understand that this constitutes withdrawal from the experiment and that I am free to do this without giving any reason. If I withdraw my data will be removed from the study and will be destroyed.
- I understand that my personal data will be processed for the purposes detailed above, in accordance with the Data Protection Act 1998.
- Based upon the above, I agree to take part in this study.

#### Name, signature and date

Name of participant:

Signature:

Date:

.....  
Name of researcher/individual  
obtaining consent:

.....  
Signature:

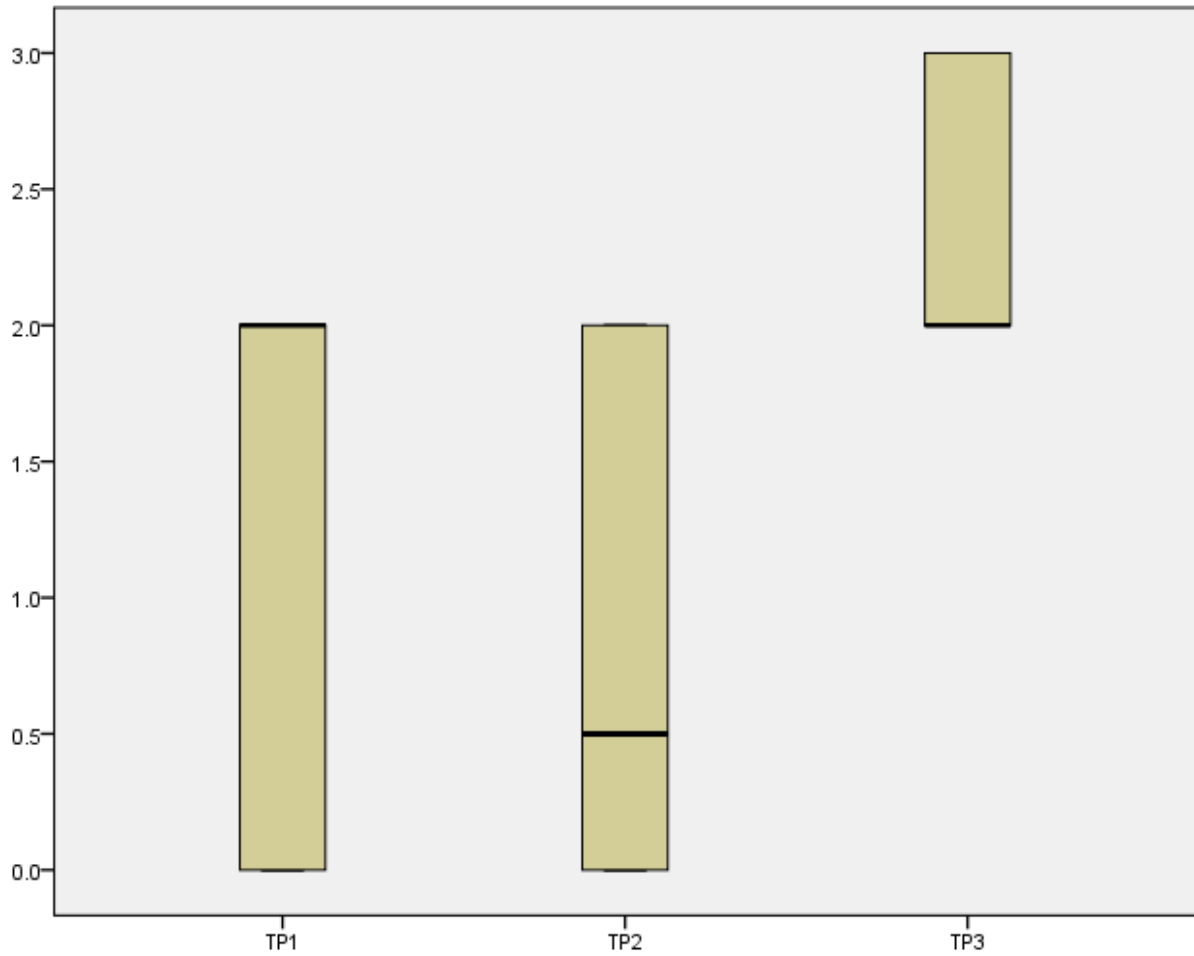
.....  
Date:

.....  
*A copy of the signed and dated consent form and the participant information sheet should be given to the participant and retained by the researcher to be kept securely on file.*

**Appendix H - Descriptive Statistics for the Performance Results of Teams in Chapter 4**

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
TP1	8	1.2500	1.03510	-.644	.752	-2.240	1.481
TP2	8	.8750	.99103	.312	.752	-2.358	1.481
TP3	8	2.3750	.51755	.644	.752	-2.240	1.481
Valid N (listwise)	8						

**Appendix I – Boxplots for the Performance Results of Teams in Chapter 4**



**Appendix J - Friedman Test of Performance in Chapter 4**

**Ranks**

	Mean Rank
TP1	1.69
TP2	1.50
TP3	2.81

**Test Statistics<sup>a</sup>**

N	8
Chi-Square	11.217
df	2
Asymp. Sig.	.004

a. Friedman Test

**Appendix K - Wilcoxon Signed Ranks of Performance in Chapter 4**

**Ranks**

		N	Mean Rank	Sum of Ranks
TP2 - TP1	Negative Ranks	2 <sup>a</sup>	2.50	5.00
	Positive Ranks	1 <sup>b</sup>	1.00	1.00
	Ties	5 <sup>c</sup>		
	Total	8		
TP3 - TP1	Negative Ranks	0 <sup>d</sup>	.00	.00
	Positive Ranks	6 <sup>e</sup>	3.50	21.00
	Ties	2 <sup>f</sup>		
	Total	8		
TP3 - TP2	Negative Ranks	0 <sup>g</sup>	.00	.00
	Positive Ranks	7 <sup>h</sup>	4.00	28.00
	Ties	1 <sup>i</sup>		
	Total	8		

- a. TP2 < TP1
- b. TP2 > TP1
- c. TP2 = TP1
- d. TP3 < TP1
- e. TP3 > TP1
- f. TP3 = TP1
- g. TP3 < TP2
- h. TP3 > TP2
- i. TP3 = TP2

**Test Statistics<sup>a</sup>**

	TP2 - TP1	TP3 - TP1	TP3 - TP2
Z	-1.089 <sup>b</sup>	-2.251 <sup>c</sup>	-2.401 <sup>c</sup>
Asymp. Sig. (2-tailed)	.276	.024	.016

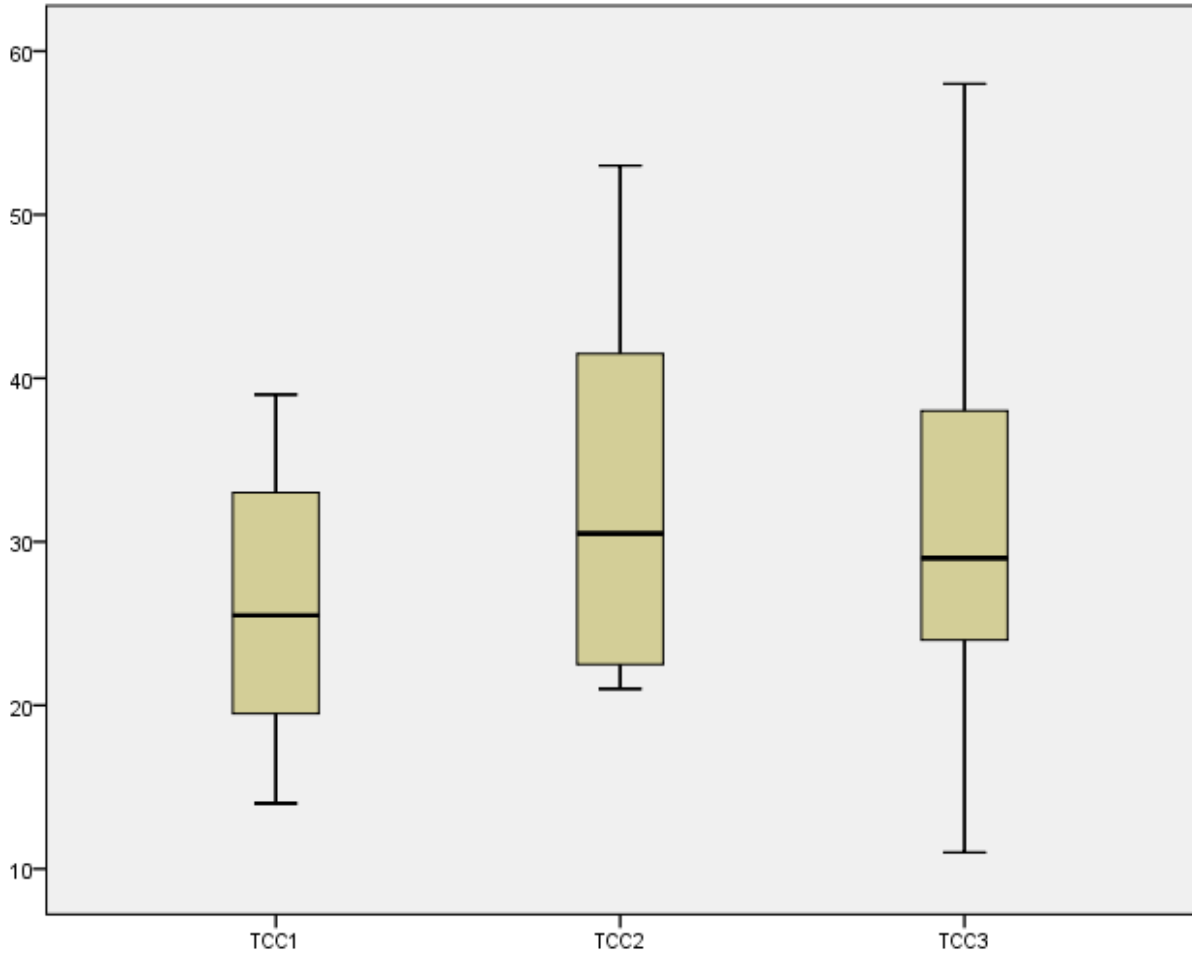
- a. Wilcoxon Signed Ranks Test
- b. Based on positive ranks.
- c. Based on negative ranks.

**Appendix L - Descriptive Statistics for Communication Results of Teams in Chapter 4**

**Descriptive Statistics**

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
TCC1	8	26.1250	8.82266	.138	.752	-1.462	1.481
TCC2	8	32.8750	11.65501	.653	.752	-.781	1.481
TCC3	8	31.3750	13.93800	.714	.752	1.353	1.481
Valid N (listwise)	8						

**Appendix M – Boxplots for the Communication Results of Teams in Chapter 4**



**Appendix N – One-way ANOVA of Total Comments and Paired Samples Statistics in Chapter 4**

**ANOVA  
TotalComments**

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	201.000	2	100.500	.739	.490
Within Groups	2855.625	21	135.982		
Total	3056.625	23			

**Paired Samples Statistics**

	Mean	N	Std. Deviation	Std. Error Mean
Pair 1 TCC1	26.1250	8	8.82266	3.11928
TCC2	32.8750	8	11.65501	4.12067
Pair 2 TCC1	26.1250	8	8.82266	3.11928
TCC3	31.3750	8	13.93800	4.92783
Pair 3 TCC2	32.8750	8	11.65501	4.12067
TCC3	31.3750	8	13.93800	4.92783

**Paired Samples Correlations**

	N	Correlation	Sig.
Pair 1 TCC1 & TCC2	8	.952	.000
Pair 2 TCC1 & TCC3	8	.797	.018
Pair 3 TCC2 & TCC3	8	.875	.004

**Paired Samples Test**

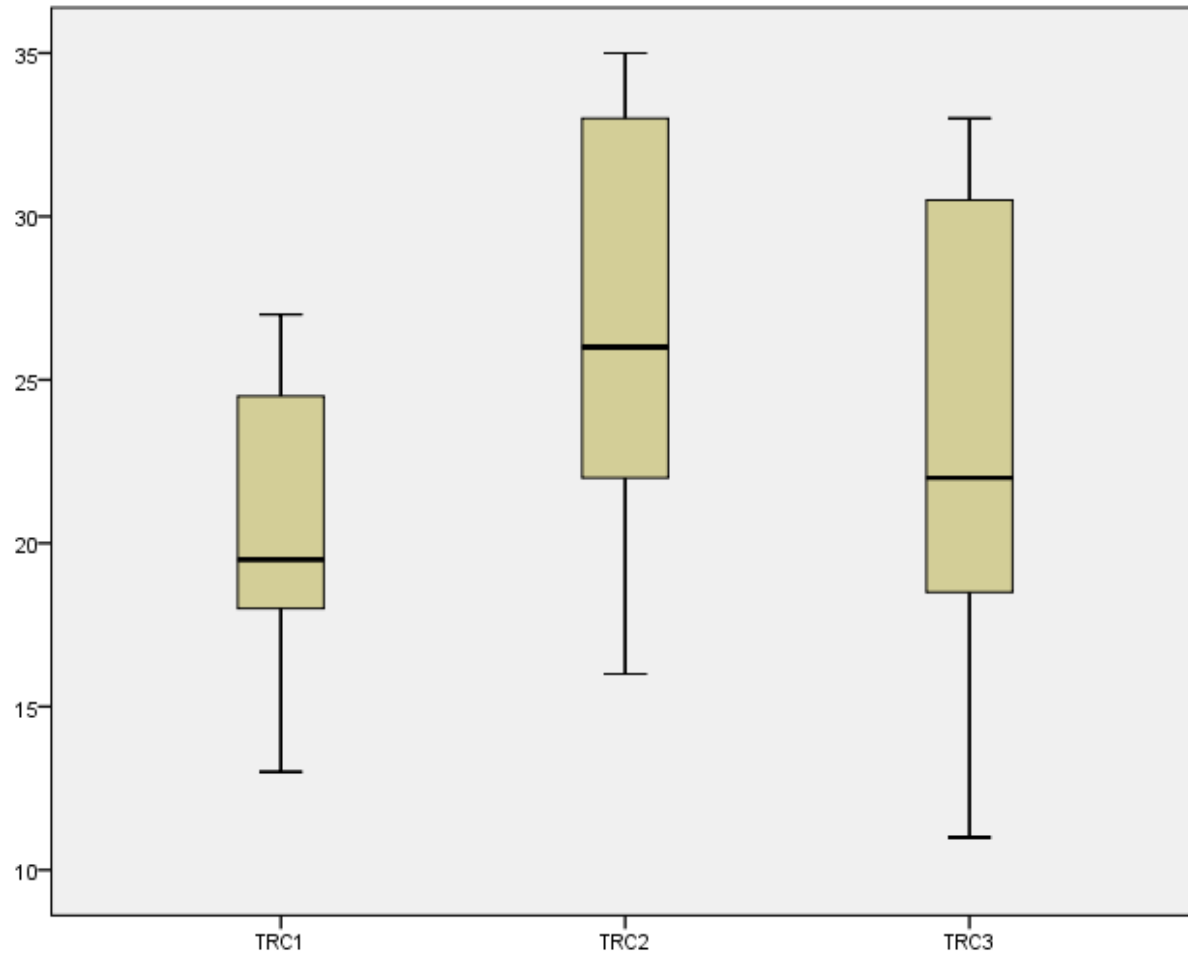
	Paired Differences	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference		t	df	Sig. (2-tailed)
					Lower	Upper			
Pair 1 TCC1 - TCC2		-6.75000	4.23421	1.49702	-10.28989	-3.21011	-4.509	7	.003
Pair 2 TCC1 - TCC3		-5.25000	8.73008	3.08655	-12.54853	2.04853	-1.701	7	.133
Pair 3 TCC2 - TCC3		1.50000	6.76123	2.39046	-4.15253	7.15253	.627	7	.550

**Appendix O - Descriptive Statistics for Task-Relevant Communication Results of Teams in Chapter 4**

**Descriptive Statistics**

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
TRC1	8	20.5000	4.81070	.144	.752	-.511	1.481
TRC2	8	26.6250	6.82302	-.109	.752	-1.076	1.481
TRC3	8	23.2500	7.62983	-.169	.752	-1.011	1.481
Valid N (listwise)	8						

**Appendix P – Boxplots for the Task-Relevant Communication Results of Teams in Chapter 4**



**Appendix Q – One-way ANOVA of Task-Relevant Comments and Paired Samples Statistics in Chapter 4**

**ANOVA**

**TaskRelevantComments**

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	150.583	2	75.292	1.766	.196
Within Groups	895.375	21	42.637		
Total	1045.958	23			

**Paired Samples Statistics**

	Mean	N	Std. Deviation	Std. Error Mean
Pair 1 TRC1	20.5000	8	4.81070	1.70084
TRC2	26.6250	8	6.82302	2.41230
Pair 2 TRC1	20.5000	8	4.81070	1.70084
TRC3	23.2500	8	7.62983	2.69755
Pair 3 TRC2	26.6250	8	6.82302	2.41230
TRC3	23.2500	8	7.62983	2.69755

**Paired Samples Correlations**

	N	Correlation	Sig.
Pair 1 TRC1 & TRC2	8	.690	.058
Pair 2 TRC1 & TRC3	8	.463	.248
Pair 3 TRC2 & TRC3	8	.441	.274

**Paired Samples Test**

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	TRC1 - TRC2	-6.12500	4.94072	1.74681	-10.25555	-1.99445	-3.506	7	.010
Pair 2	TRC1 - TRC3	-2.75000	6.88165	2.43303	-8.50321	3.00321	-1.130	7	.296
Pair 3	TRC2 - TRC3	3.37500	7.67068	2.71199	-3.03785	9.78785	1.244	7	.253

**Appendix R - Correlation results for total comments and performance in Chapter 4**

**Correlations**

		TCC1	TP1
TCC1	Pearson Correlation	1	.262
	Sig. (2-tailed)		.531
	N	8	8
TP1	Pearson Correlation	.262	1
	Sig. (2-tailed)	.531	
	N	8	8

**Correlations**

		TCC2	TP2
TCC2	Pearson Correlation	1	-.113
	Sig. (2-tailed)		.790
	N	8	8
TP2	Pearson Correlation	-.113	1
	Sig. (2-tailed)	.790	
	N	8	8

**Correlations**

		TCC3	TP3
TCC3	Pearson Correlation	1	.295
	Sig. (2-tailed)		.479
	N	8	8
TP3	Pearson Correlation	.295	1
	Sig. (2-tailed)	.479	
	N	8	8

**Appendix S - Correlation results for task-relevant comments and performance in Chapter 4**

**Correlations**

		TRC1	TP1
TRC1	Pearson Correlation	1	-.086
	Sig. (2-tailed)		.839
	N	8	8
TP1	Pearson Correlation	-.086	1
	Sig. (2-tailed)	.839	
	N	8	8

**Correlations**

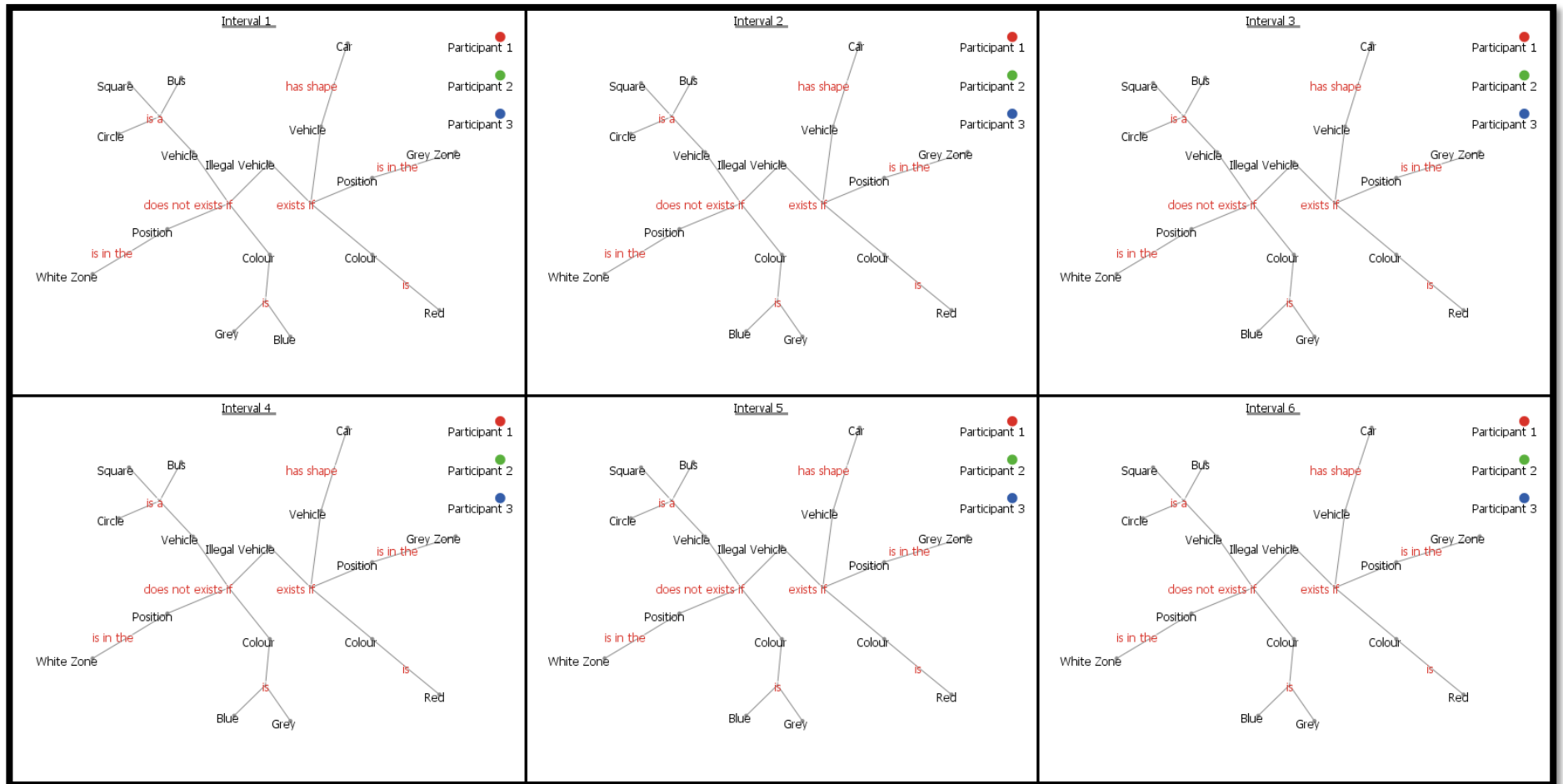
		TRC2	TP2
TRC2	Pearson Correlation	1	-.092
	Sig. (2-tailed)		.828
	N	8	8
TP2	Pearson Correlation	-.092	1
	Sig. (2-tailed)	.828	
	N	8	8

**Correlations**

		TRC3	TP3
TRC3	Pearson Correlation	1	-.244
	Sig. (2-tailed)		.560
	N	8	8
TP3	Pearson Correlation	-.244	1
	Sig. (2-tailed)	.560	
	N	8	8

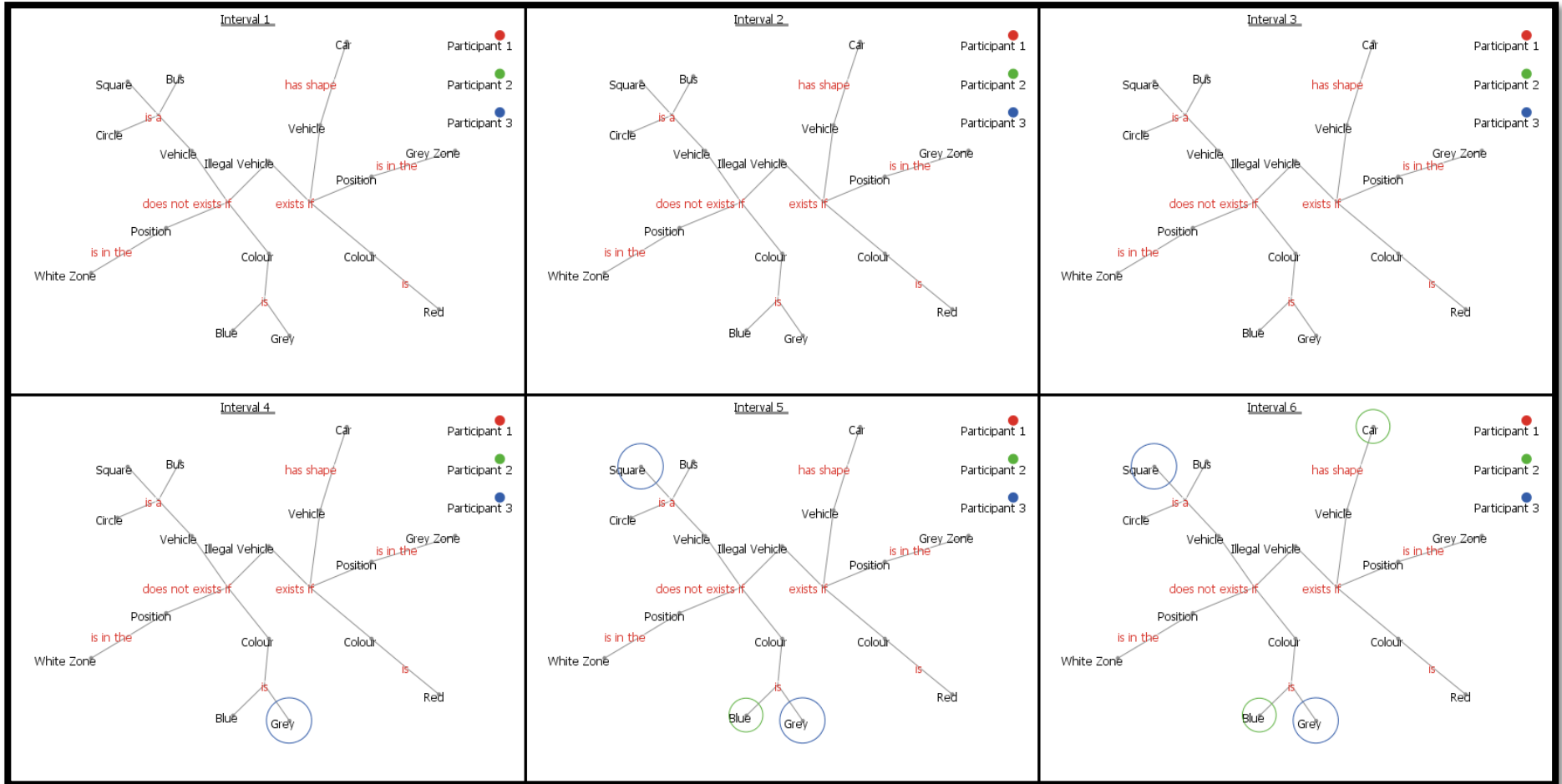
Appendix T - Condition 2: Separate Display, Group 2

### Group 2



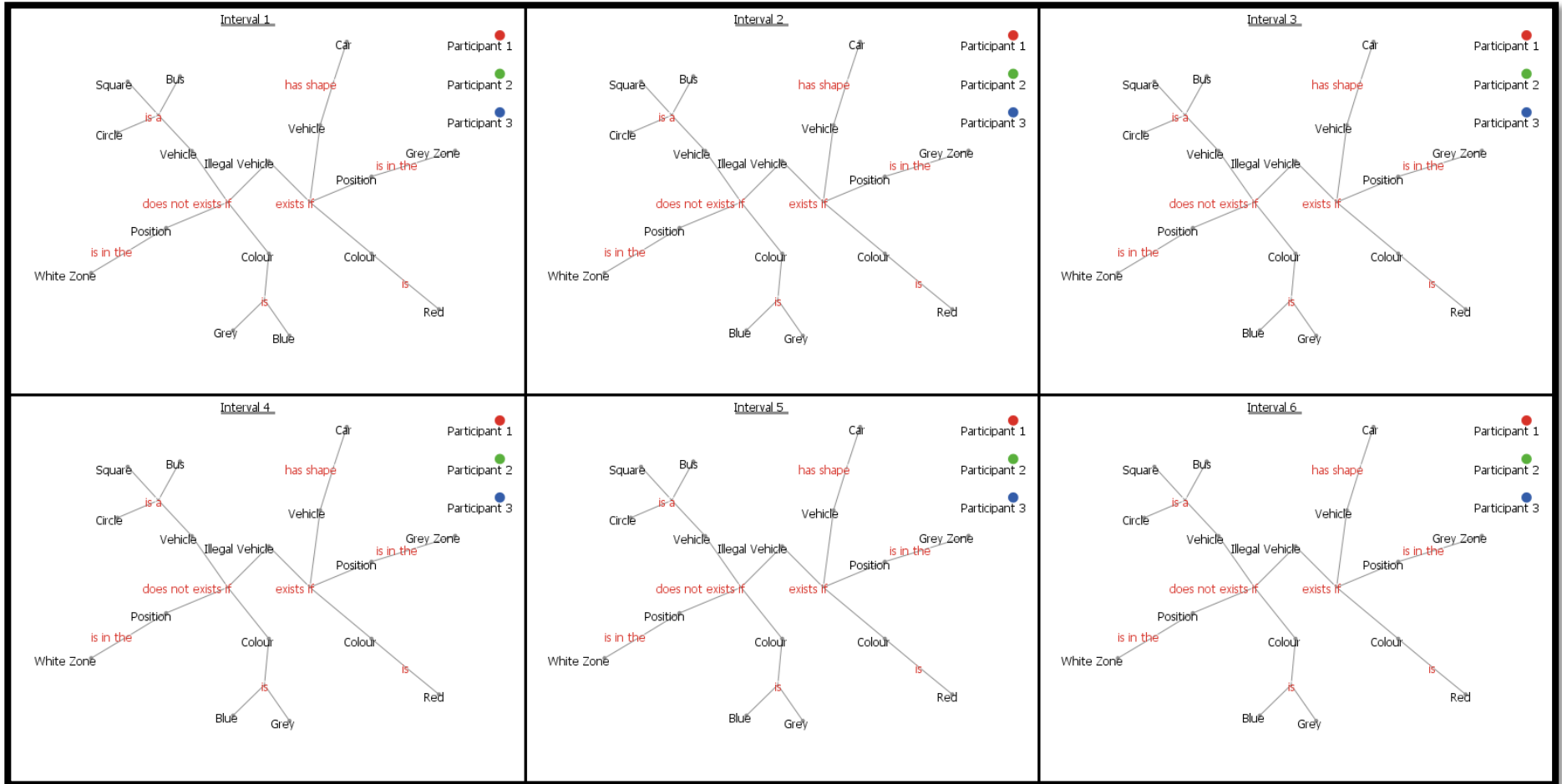
Appendix U - Condition 2: Separate Display, Group 3

Group 3



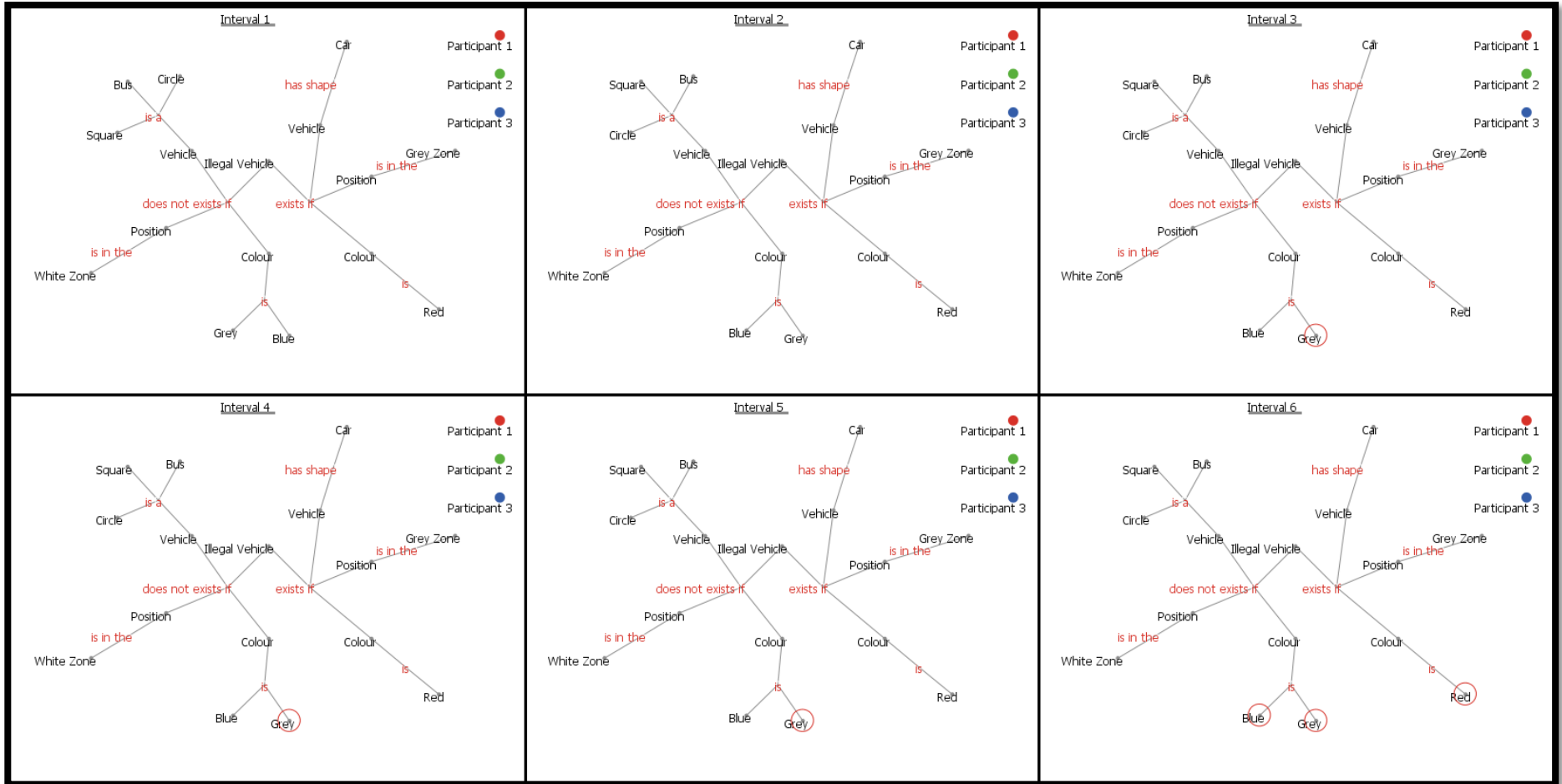
Appendix V - Condition 2: Separate Display, Group 4

### Group 4



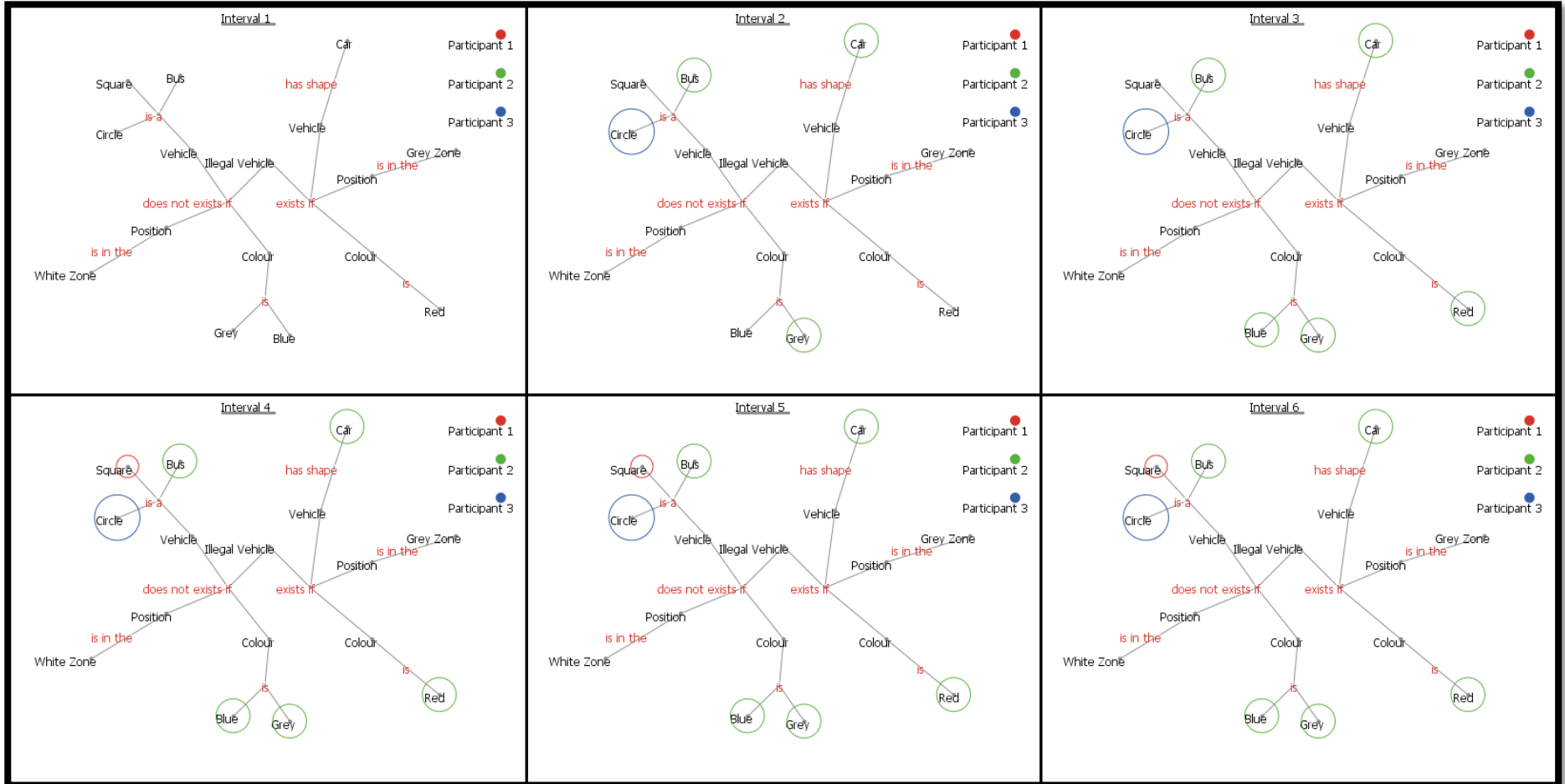
Appendix W - Condition 2: Separate Display, Group 5

Group 5



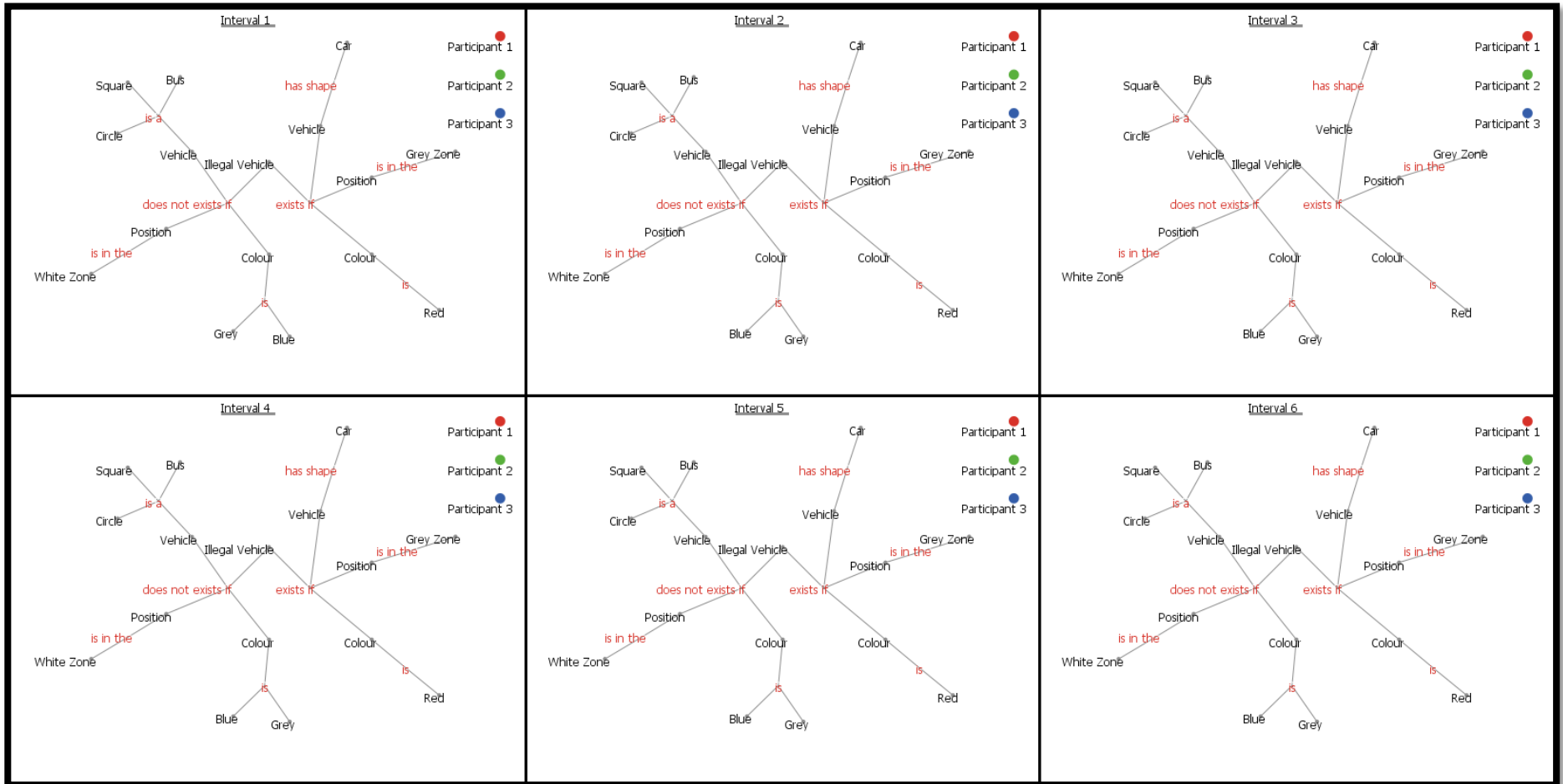
Appendix X - Condition 2: Separate Display, Group 6

## Group 6



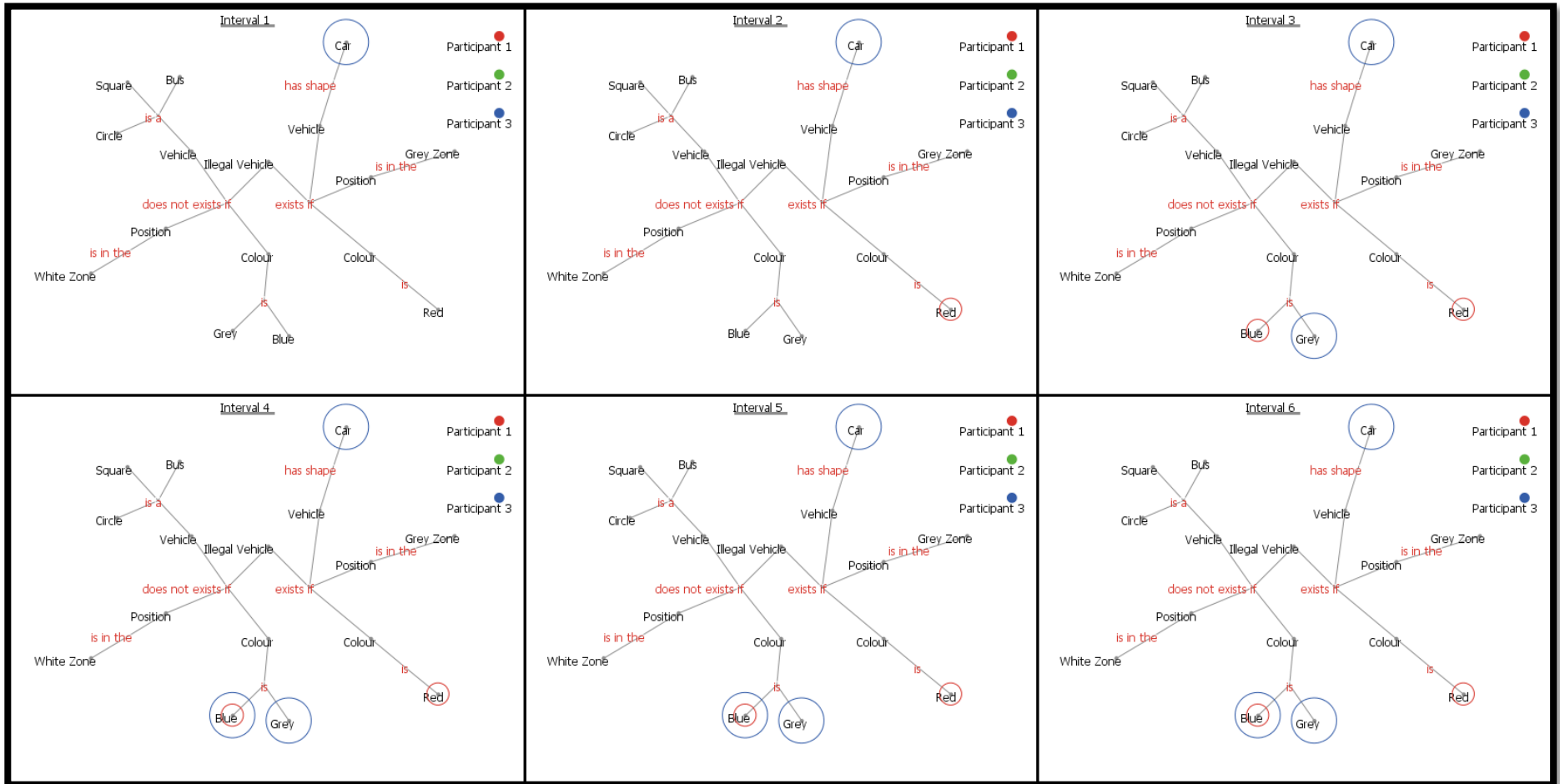
Appendix Y - Condition 2: Separate Display, Group 7

# Group 7



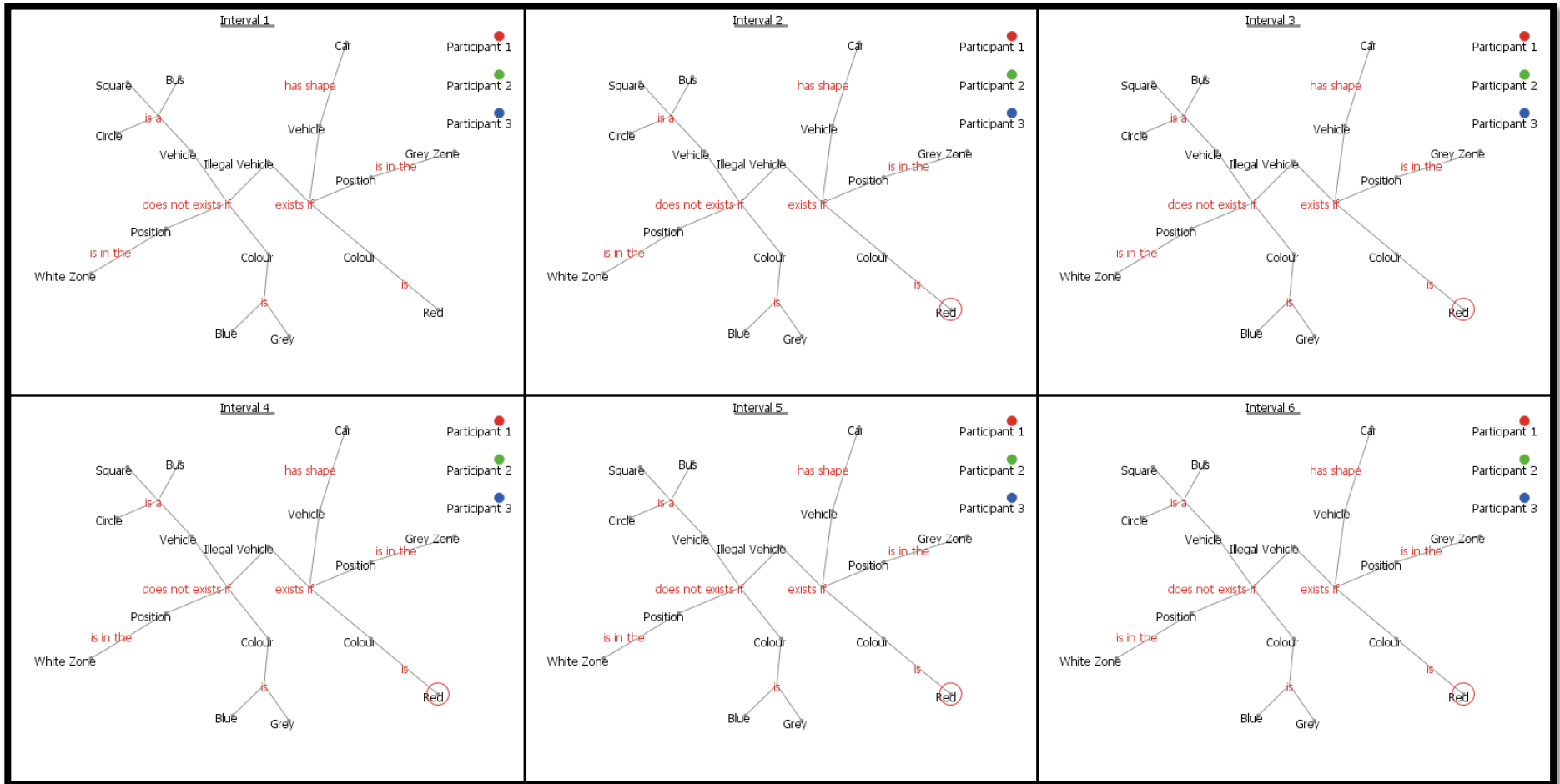
Appendix Z - Condition 2: Separate Display, Group 8

Group 8



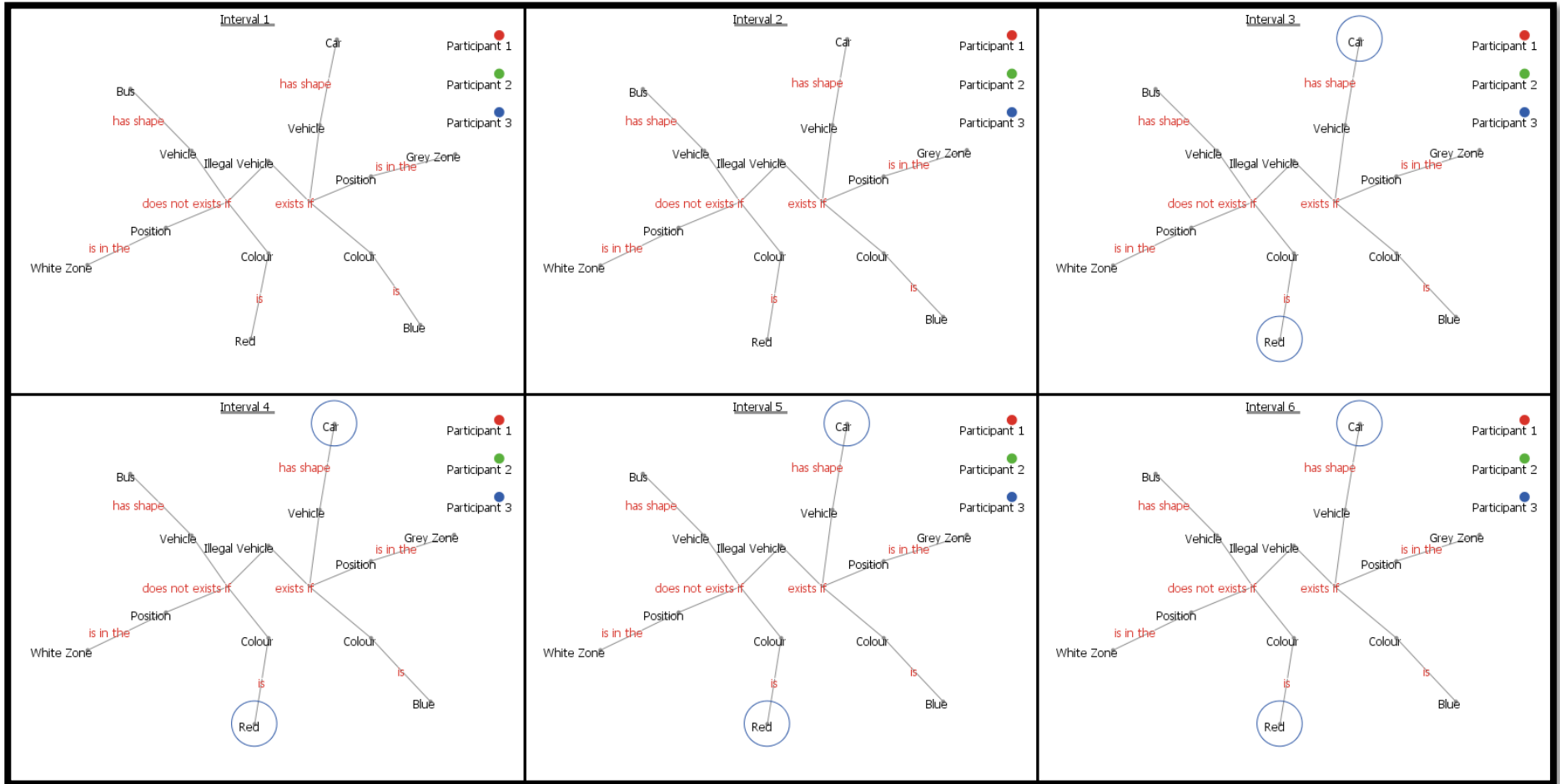
Appendix AA - Condition 2: Separate Display, Group 9

Group 9



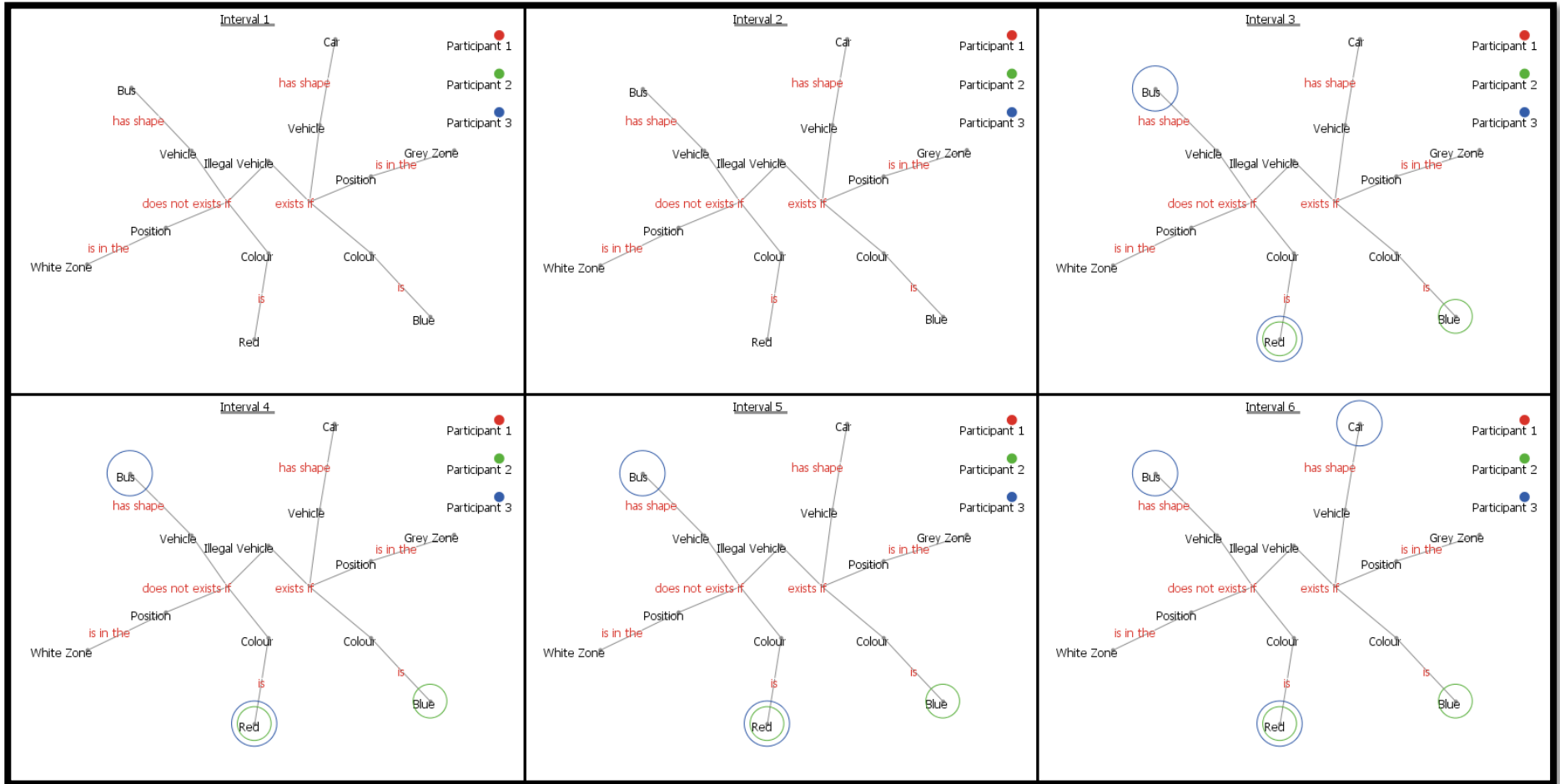
Appendix BB - Condition 3: Same Videos, Group 2

Group 2



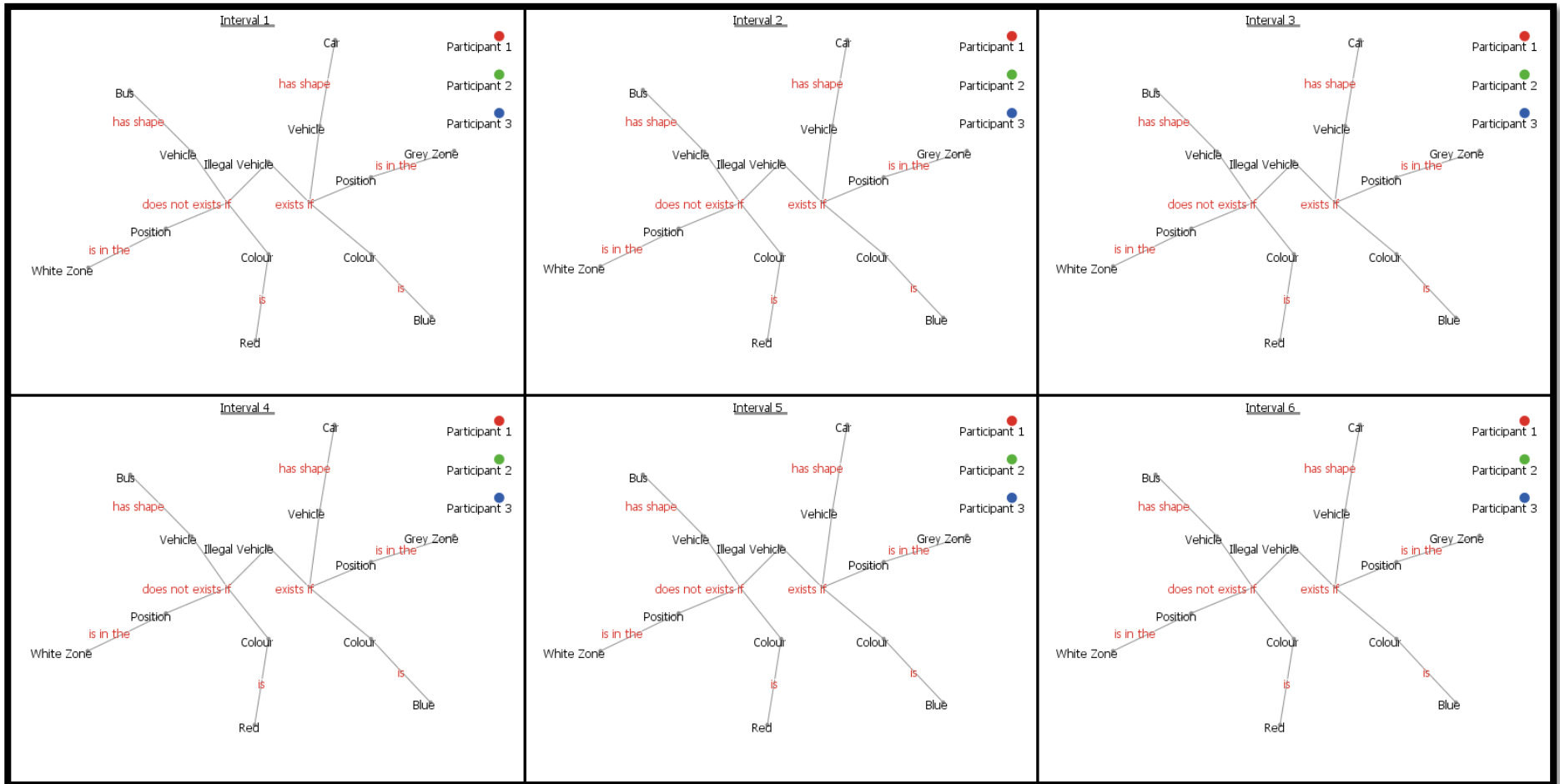
Appendix CC - Condition 3: Same Videos, Group 3

Group 3



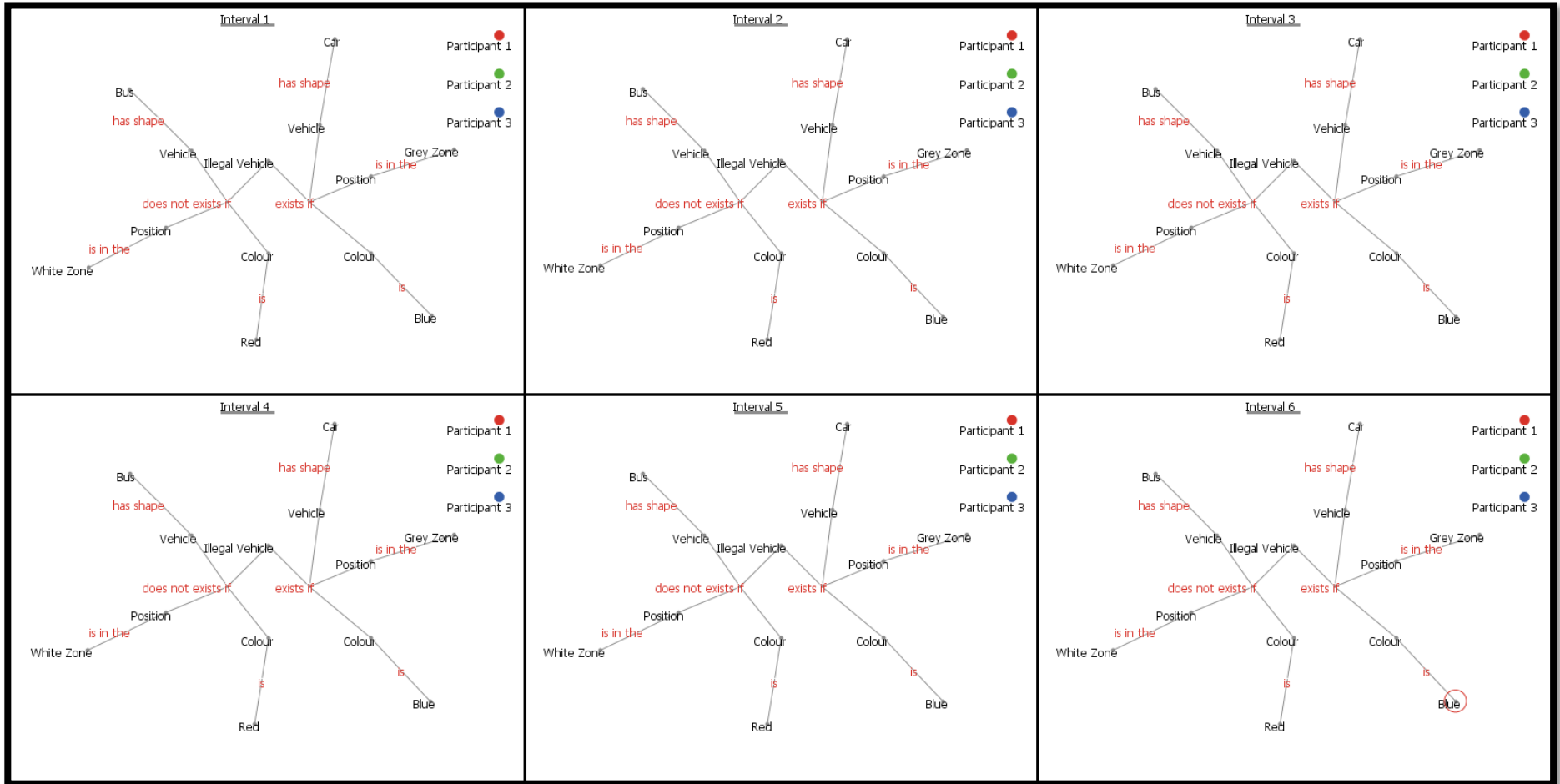
Appendix DD - Condition 3: Same Videos, Group 4

Group 4



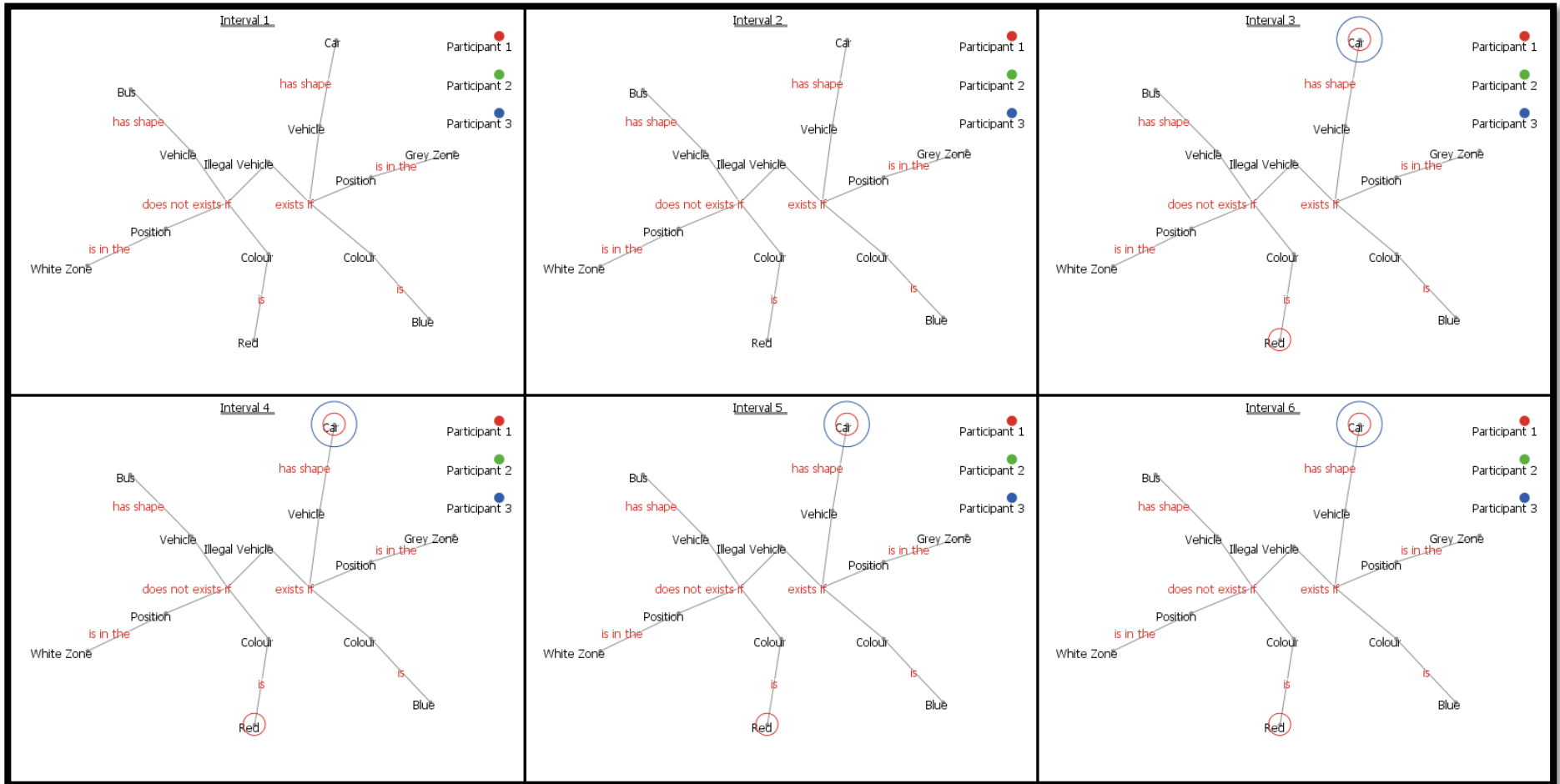
Appendix EE - Condition 3: Same Videos, Group 5

Group 5



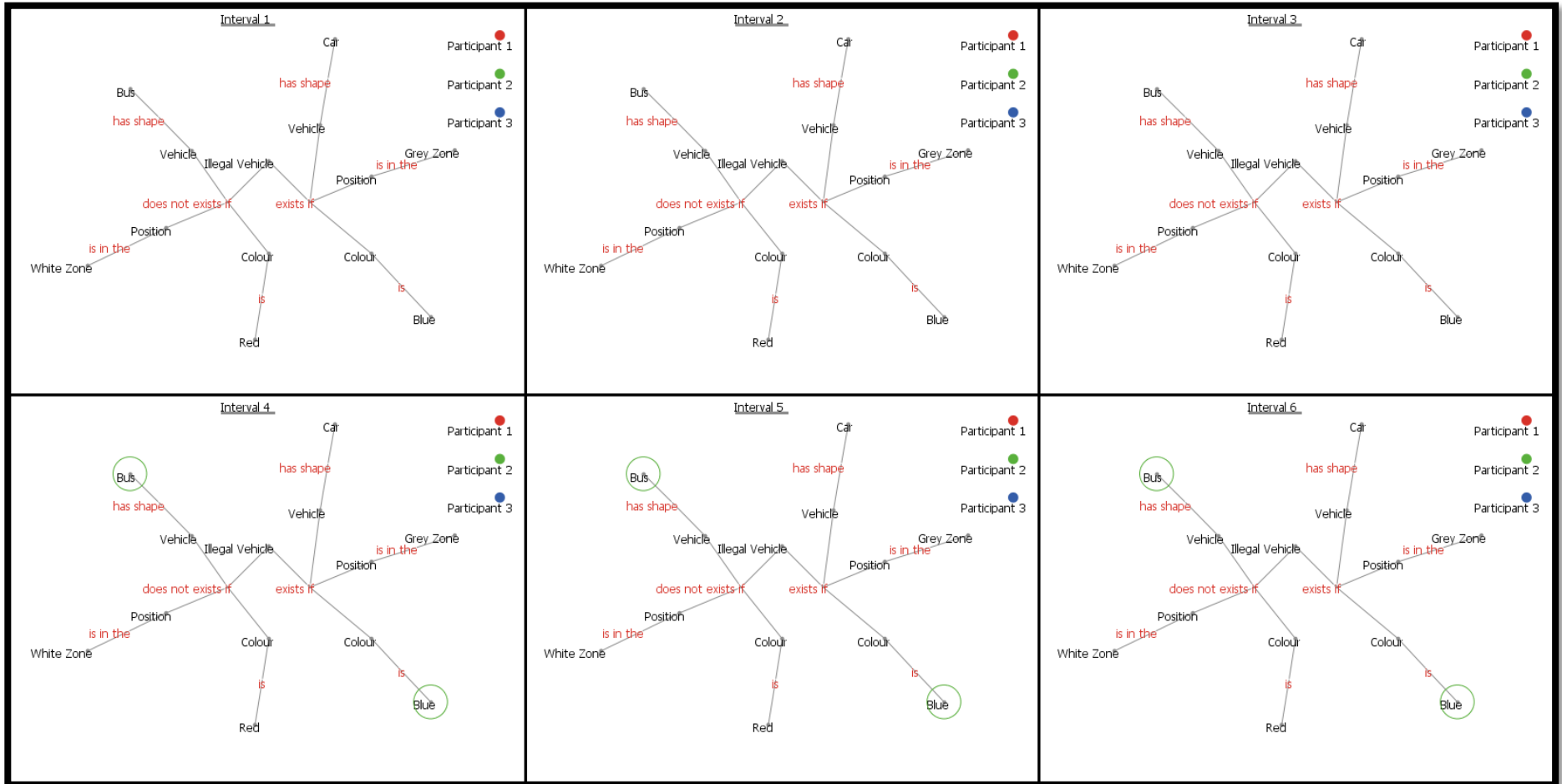
Appendix FF - Condition 3: Same Videos, Group 6

Group 6



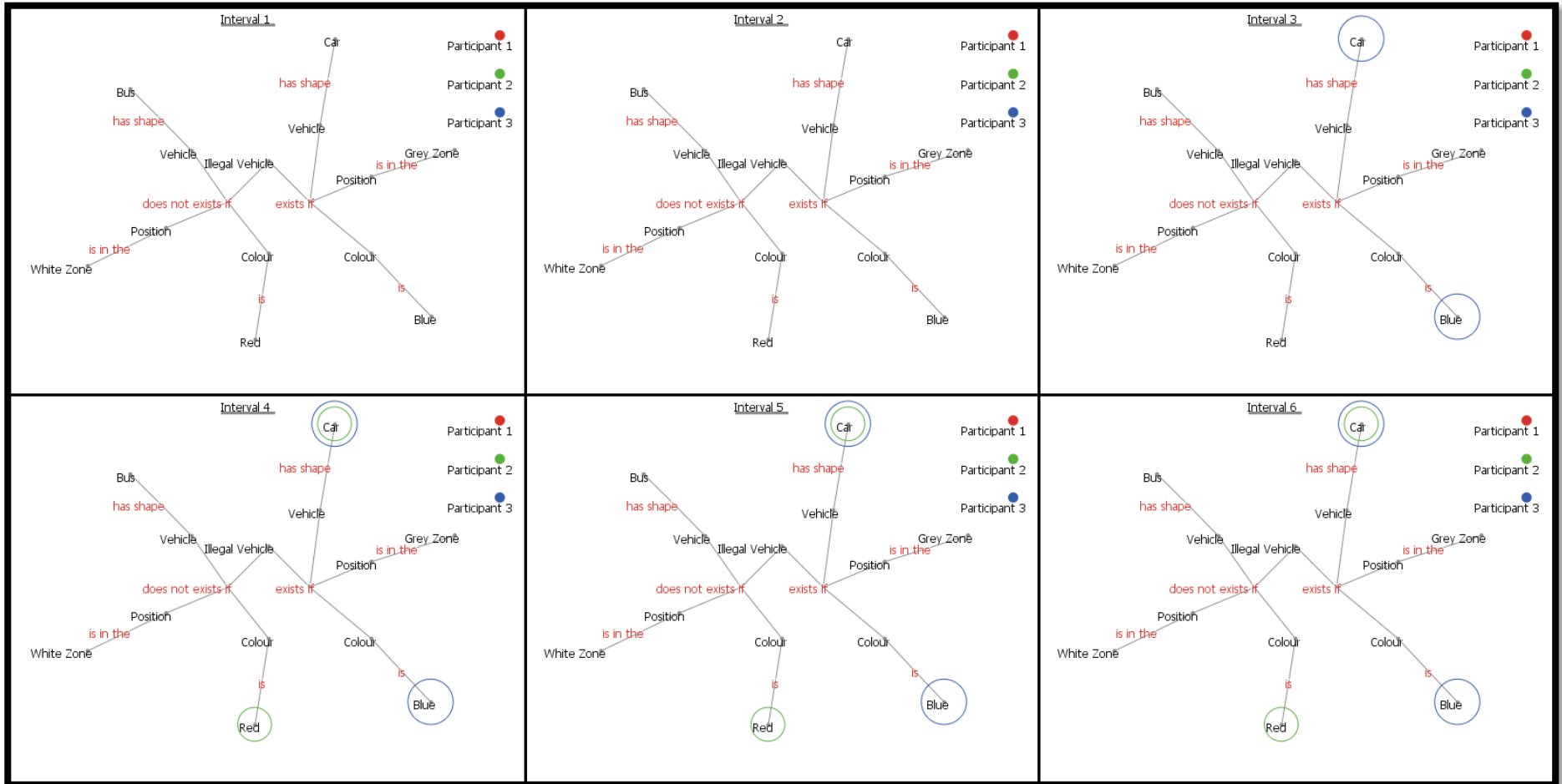
Appendix GG - Condition 3: Same Videos, Group 7

## Group 7



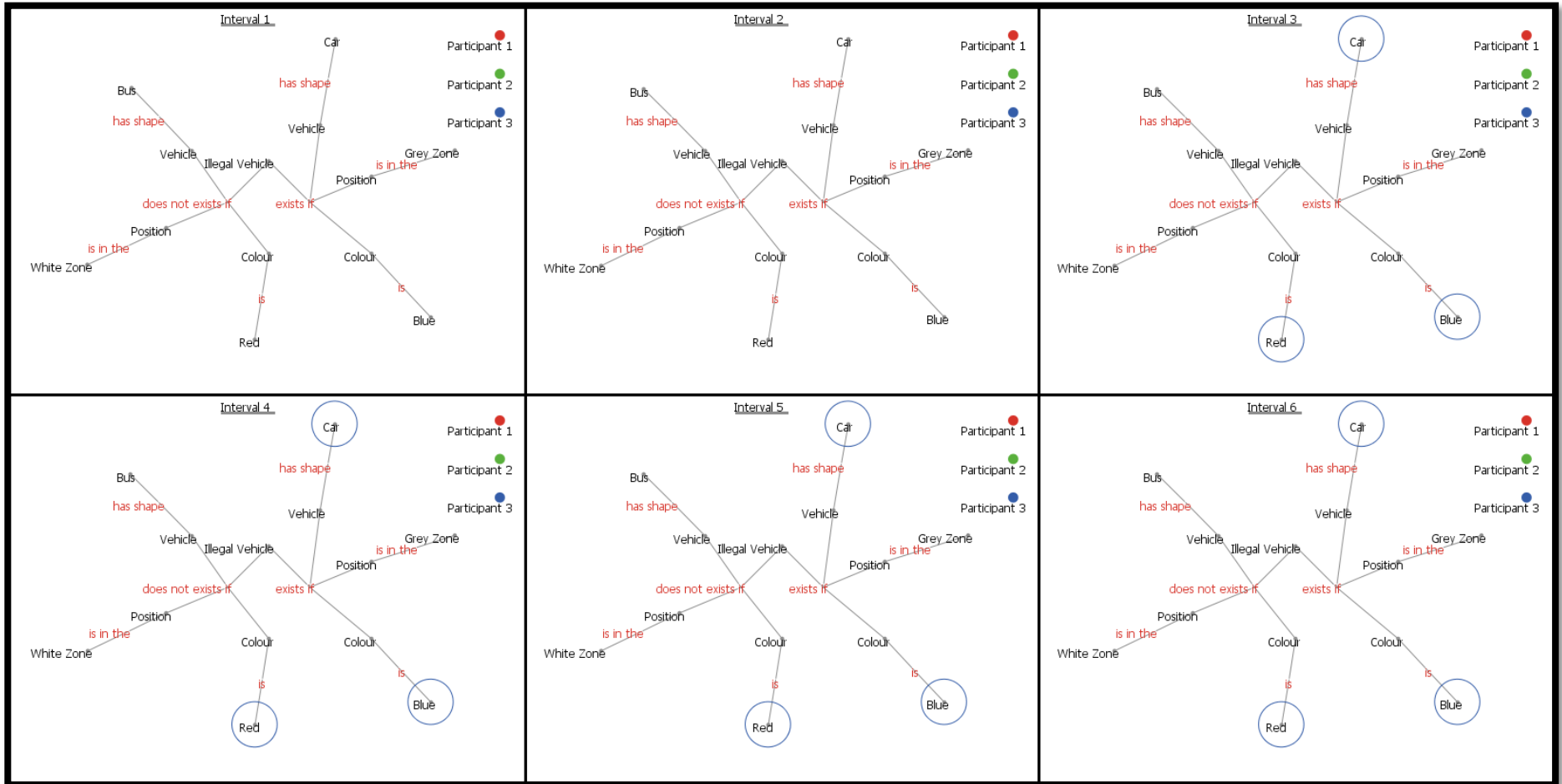
Appendix HH - Condition 3: Same Videos, Group 8

## Group 8



Appendix II - Condition 3: Same Videos, Group 9

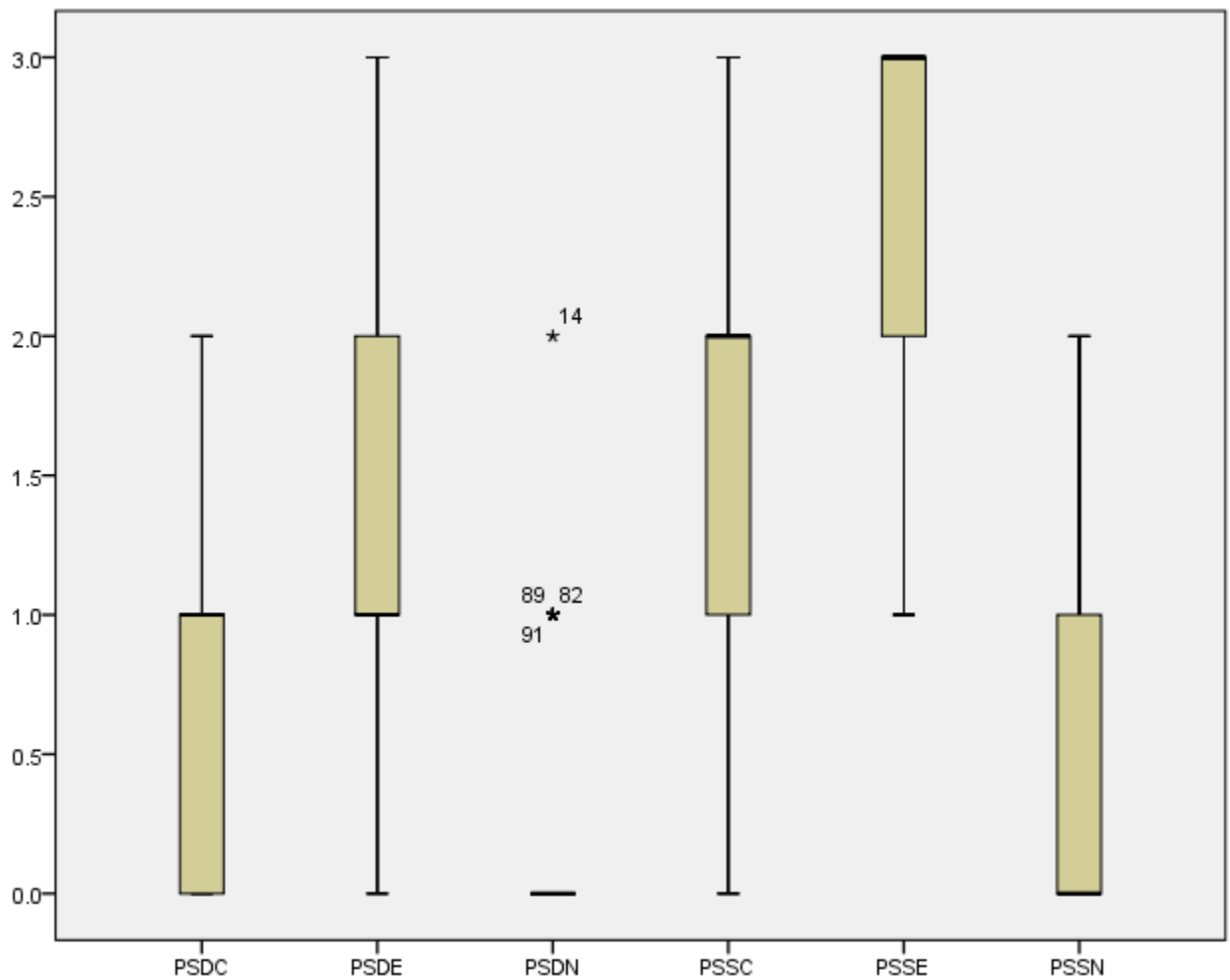
### Group 9



**Appendix JJ – Normal distribution stats for the performance scores of each model (calibrated, expert and novice) for both the shared and common display**

**Descriptive Statistics**

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
PSDC	308	.7468	.80359	.756	.139	-.277	.277
PSDE	100	1.2400	.81798	.319	.241	-.300	.478
PSDN	100	.1500	.38599	2.514	.241	5.872	.478
PSSC	100	1.8700	.83672	-.383	.241	-.364	.478
PSSE	100	2.6000	.53182	-.822	.241	-.496	.478
PSSN	100	.5200	.64322	.854	.241	-.310	.478
Valid N (listwise)	100						



**Appendix KK – Kruskal-Wallis Test for the performance scores of each model (calibrated, expert and novice) for both the shared and common display**

Ranks			
	Condition	N	Mean Rank
PerformanceD	.00	8	164.00
	1.00	100	168.56
	2.00	100	204.74
	3.00	100	89.44
	Total	308	
PerformanceS	.00	8	207.00
	1.00	100	166.24
	2.00	100	227.96
	3.00	100	65.10
	Total	308	

Test Statistics <sup>a,b</sup>		
	PerformanceD	PerformanceS
Chi-Square	102.880	186.361
df	3	3
Asymp. Sig.	.000	.000

a. Kruskal Wallis Test

b. Grouping Variable: Condition

**Appendix LL - Mann-Whitney Tests for the performance scores of each model (calibrated, expert and novice) for both the shared and common display**

**Mann-Whitney Test: 0 & 1 (Experiment & Calibrated)**

Ranks				
	Condition	N	Mean Rank	Sum of Ranks
PerformanceD	.00	8	54.38	435.00
	1.00	100	54.51	5451.00
	Total	108		
PerformanceS	.00	8	71.13	569.00
	1.00	100	53.17	5317.00
	Total	108		

Test Statistics <sup>a</sup>		
	PerformanceD	PerformanceS
Mann-Whitney U	399.000	267.000
Wilcoxon W	435.000	5317.000
Z	-.013	-1.679
Asymp. Sig. (2-tailed)	.990	.093

a. Grouping Variable: Condition

### Mann-Whitney Test: 0 & 2 (Experiment & Expert)

Ranks				
	Condition	N	Mean Rank	Sum of Ranks
PerformanceD	.00	8	43.75	350.00
	2.00	100	55.36	5536.00
	Total	108		
PerformanceS	.00	8	42.88	343.00
	2.00	100	55.43	5543.00
	Total	108		

Test Statistics <sup>a</sup>		
	PerformanceD	PerformanceS
Mann-Whitney U	314.000	307.000
Wilcoxon W	350.000	343.000
Z	-1.081	-1.279
Asymp. Sig. (2-tailed)	.280	.201

a. Grouping Variable: Condition

### Mann-Whitney Test: 0 & 3 (Experiment & Novice)

Ranks				
	Condition	N	Mean Rank	Sum of Ranks
PerformanceD	.00	8	74.88	599.00
	3.00	100	52.87	5287.00
	Total	108		
PerformanceS	.00	8	102.00	816.00
	3.00	100	50.70	5070.00
	Total	108		

Test Statistics <sup>a</sup>		
	PerformanceD	PerformanceS
Mann-Whitney U	237.000	20.000
Wilcoxon W	5287.000	5070.000
Z	-2.954	-4.917
Asymp. Sig. (2-tailed)	.003	.000

a. Grouping Variable: Condition

### Mann-Whitney Test: 1 & 2 (Calibrated & Expert)

Ranks				
	Condition	N	Mean Rank	Sum of Ranks
PerformanceD	1.00	100	87.62	8762.00
	2.00	100	113.38	11338.00
	Total	200		
PerformanceS	1.00	100	76.01	7601.00
	2.00	100	124.99	12499.00
	Total	200		

Test Statistics <sup>a</sup>		
	PerformanceD	PerformanceS
Mann-Whitney U	3712.000	2551.000
Wilcoxon W	8762.000	7601.000
Z	-3.398	-6.492
Asymp. Sig. (2-tailed)	.001	.000

a. Grouping Variable: Condition

### Mann-Whitney Test: 1 & 3 (Calibrated & Novice)

Ranks				
	Condition	N	Mean Rank	Sum of Ranks
PerformanceD	1.00	100	127.43	12743.00
	3.00	100	73.57	7357.00
	Total	200		
PerformanceS	1.00	100	138.06	13806.00
	3.00	100	62.94	6294.00
	Total	200		

Test Statistics <sup>a</sup>		
	PerformanceD	PerformanceS
Mann-Whitney U	2307.000	1244.000
Wilcoxon W	7357.000	6294.000
Z	-7.574	-9.563
Asymp. Sig. (2-tailed)	.000	.000

a. Grouping Variable: Condition

## Mann-Whitney Test: 2 & 3 (Expert & Novice)

Ranks				
	Condition	N	Mean Rank	Sum of Ranks
PerformanceD	2.00	100	137.00	13700.00
	3.00	100	64.00	6400.00
	Total	200		
PerformanceS	2.00	100	148.54	14854.00
	3.00	100	52.46	5246.00
	Total	200		

Test Statistics <sup>a</sup>		
	PerformanceD	PerformanceS
Mann-Whitney U	1350.000	196.000
Wilcoxon W	6400.000	5246.000
Z	-9.784	-12.167
Asymp. Sig. (2-tailed)	.000	.000

a. Grouping Variable: Condition

**Appendix MM - Paired Samples t-test comparing the performance scores for each model (calibrated, expert & novice) using the shared and common display**

**Paired Samples Statistics**

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	PSDC	.8400	100	.70668	.07067
	PSSC	1.8700	100	.83672	.08367
Pair 2	PSDE	1.2400	100	.81798	.08180
	PSSE	2.6000	100	.53182	.05318
Pair 3	PSDN	.1500	100	.38599	.03860
	PSSN	.5200	100	.64322	.06432

**Paired Samples Correlations**

		N	Correlation	Sig.
Pair 1	PSDC & PSSC	100	-.036	.726
Pair 2	PSDE & PSSE	100	.060	.551
Pair 3	PSDN & PSSN	100	.090	.376

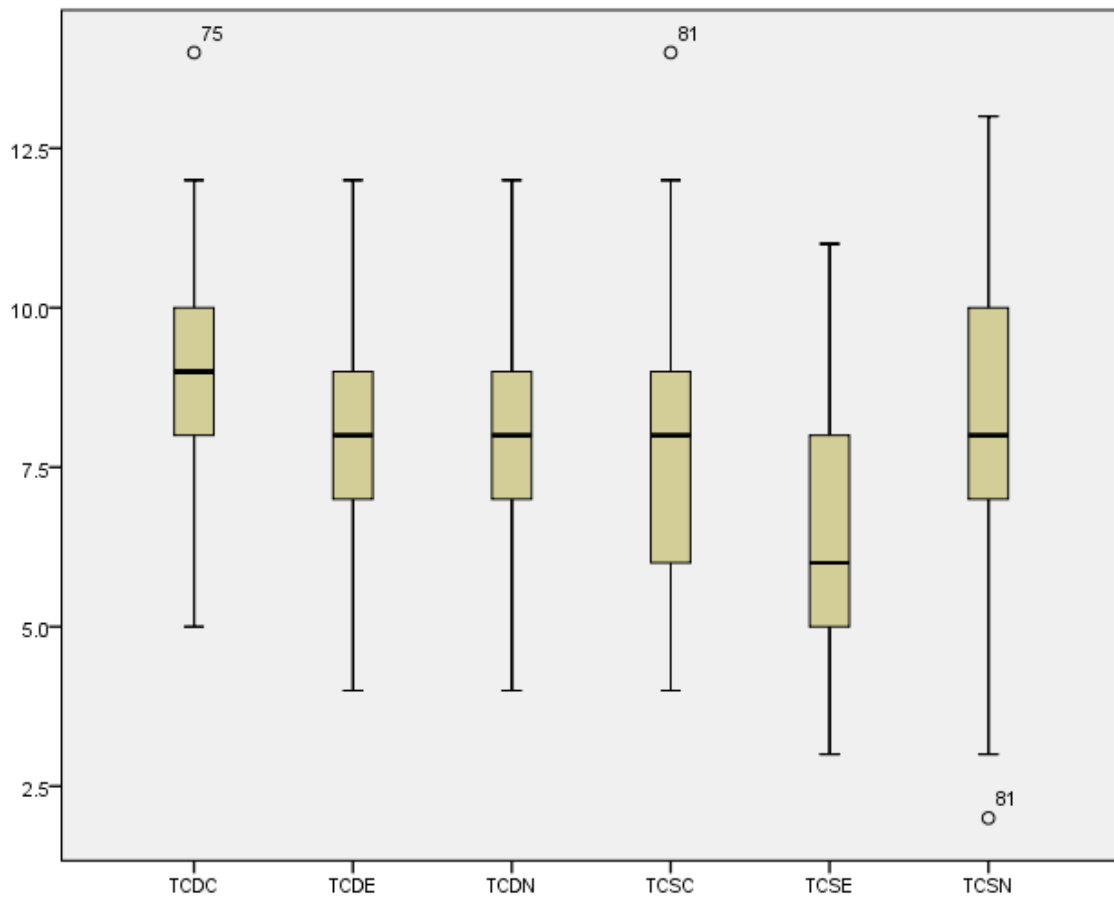
**Paired Samples Test**

		Paired Differences				t	df	Sig. (2-tailed)	
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower				Upper
Pair 1	PSDC - PSSC	1.03000	1.11423	.11142	-1.25109	-.80891	-9.244	99	.000
Pair 2	PSDE - PSSE	1.36000	.94836	.09484	-1.54818	-1.17182	14.340	99	.000
Pair 3	PSDN - PSSN	-.37000	.71992	.07199	-.51285	-.22715	-5.139	99	.000

**Appendix NN - – Normal distribution stats for the total comments made in each model (calibrated, expert and novice) for both the shared and common display**

**Descriptive Statistics**

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
TCDC	100	8.5300	1.57925	.187	.241	.425	.478
TCDE	100	8.1000	1.60492	.043	.241	.197	.478
TCDN	100	8.2500	1.79435	-.117	.241	-.365	.478
TCSC	100	7.9900	2.12011	.338	.241	-.415	.478
TCSE	100	6.6700	1.76987	.170	.241	-.903	.478
TCSN	100	8.3400	2.16594	-.420	.241	.339	.478
Valid N (listwise)	100						



**Appendix OO – One Way ANOVA comparing the total comments of each model (calibrated, expert and novice) for both the shared and common display**

**ANOVA**

		Sum of Squares	df	Mean Square	F	Sig.
CommentsD	Between Groups	4718.033	3	1572.678	269.876	.000
	Within Groups	1771.535	304	5.827		
	Total	6489.568	307			
CommentsS	Between Groups	4535.010	3	1511.670	178.160	.000
	Within Groups	2579.415	304	8.485		
	Total	7114.425	307			

**Appendix PP – Independent samples t-tests comparing the total comments of each model (calibrated, expert and novice) for both the shared and common display**

**Independent Samples T-Test: 0 & 1 (Experiment & Calibrated)**

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
CommentsD	.00	8	32.8750	11.65501	4.12067
	1.00	100	8.5300	1.57925	.15793
CommentsS	.00	8	31.3750	13.93800	4.92783
	1.00	100	7.9900	2.12011	.21201

**Independent Samples Test**

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CommentsD	Equal variances assumed	186.663	.000	19.711	106	.000	24.34500	1.23510	21.89629	26.79371
	Equal variances not assumed			5.904	7.021	.001	24.34500	4.12369	14.59980	34.09020
CommentsS	Equal variances assumed	80.326	.000	15.424	106	.000	23.38500	1.51613	20.37913	26.39087
	Equal variances not assumed			4.741	7.026	.002	23.38500	4.93239	11.73048	35.03952

## Independent Samples T-Test: 0 & 2 (Experiment & Expert)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
CommentsD	.00	8	32.8750	11.65501	4.12067
	2.00	100	8.1000	1.60492	.16049
CommentsS	.00	8	31.3750	13.93800	4.92783
	2.00	100	6.6700	1.76987	.17699

**Independent Samples Test**

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CommentsD	Equal variances assumed	177.713	.000	19.992	106	.000	24.77500	1.23927	22.31803	27.23197
	Equal variances not assumed			6.008	7.021	.001	24.77500	4.12379	15.02976	34.52024
CommentsS	Equal variances assumed	94.041	.000	16.940	106	.000	24.70500	1.45838	21.81362	27.59638
	Equal variances not assumed			5.010	7.018	.002	24.70500	4.93100	13.05111	36.35889

## Independent Samples T-Test: 0 & 3 (Experiment & Novice)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
CommentsD	.00	8	32.8750	11.65501	4.12067
	3.00	100	8.2500	1.79435	.17944
CommentsS	.00	8	31.3750	13.93800	4.92783
	3.00	100	8.3400	2.16594	.21659

**Independent Samples Test**

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CommentsD	Equal variances assumed	162.230	.000	19.365	106	.000	24.62500	1.27160	22.10392	27.14608
	Equal variances not assumed			5.970	7.027	.001	24.62500	4.12457	14.87940	34.37060
CommentsS	Equal variances assumed	77.572	.000	15.112	106	.000	23.03500	1.52428	20.01297	26.05703
	Equal variances not assumed			4.670	7.027	.002	23.03500	4.93259	11.38039	34.68961

## Independent Samples T-Test: 1 & 2 (Calibrated & Expert)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
CommentsD	1.00	100	8.5300	1.57925	.15793
	2.00	100	8.1000	1.60492	.16049
CommentsS	1.00	100	7.9900	2.12011	.21201
	2.00	100	6.6700	1.76987	.17699

**Independent Samples Test**

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CommentsD	Equal variances assumed	.075	.784	1.910	198	.058	.43000	.22516	-.01402	.87402
	Equal variances not assumed			1.910	197.949	.058	.43000	.22516	-.01402	.87402
CommentsS	Equal variances assumed	1.507	.221	4.780	198	.000	1.32000	.27618	.77538	1.86462
	Equal variances not assumed			4.780	191.878	.000	1.32000	.27618	.77527	1.86473

## Independent Samples T-Test: 1 & 3 (Calibrated & Novice)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
CommentsD	1.00	100	8.5300	1.57925	.15793
	3.00	100	8.2500	1.79435	.17944
CommentsS	1.00	100	7.9900	2.12011	.21201
	3.00	100	8.3400	2.16594	.21659

**Independent Samples Test**

	Levene's Test for Equality of Variances	t-test for Equality of Means								
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CommentsD	Equal variances assumed	1.055	.306	1.171	198	.243	.28000	.23903	-.19138	.75138
	Equal variances not assumed			1.171	194.857	.243	.28000	.23903	-.19143	.75143
CommentsS	Equal variances assumed	.027	.869	1.155	198	.250	-.35000	.30309	-.94769	.24769
	Equal variances not assumed			1.155	197.909	.250	-.35000	.30309	-.94769	.24769

## Independent Samples T-Test: 2 & 3 (Expert & Novice)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
CommentsD	2.00	100	8.1000	1.60492	.16049
	3.00	100	8.2500	1.79435	.17944
CommentsS	2.00	100	6.6700	1.76987	.17699
	3.00	100	8.3400	2.16594	.21659

**Independent Samples Test**

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
CommentsD	Equal variances assumed	1.532	.217	-.623	198	.534	-.15000	.24074	-.62474	.32474
	Equal variances not assumed			-.623	195.585	.534	-.15000	.24074	-.62477	.32477
CommentsS	Equal variances assumed	.936	.334	5.970	198	.000	-1.67000	.27971	2.22159	1.11841
	Equal variances not assumed			5.970	190.439	.000	-1.67000	.27971	2.22173	1.11827

**Appendix QQ - Paired Samples t-test comparing the total comments for each model (calibrated, expert & novice) using the shared and common display**

**Paired Samples Statistics**

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TCDC	8.5300	100	1.57925	.15793
	TCSC	7.9900	100	2.12011	.21201
Pair 2	TCDE	8.1000	100	1.60492	.16049
	TCSE	6.6700	100	1.76987	.17699
Pair 3	TCDN	8.2500	100	1.79435	.17944
	TCSN	8.3400	100	2.16594	.21659

**Paired Samples Correlations**

		N	Correlation	Sig.
Pair 1	TCDC & TCSC	100	-.074	.465
Pair 2	TCDE & TCSE	100	.062	.543
Pair 3	TCDN & TCSN	100	-.069	.496

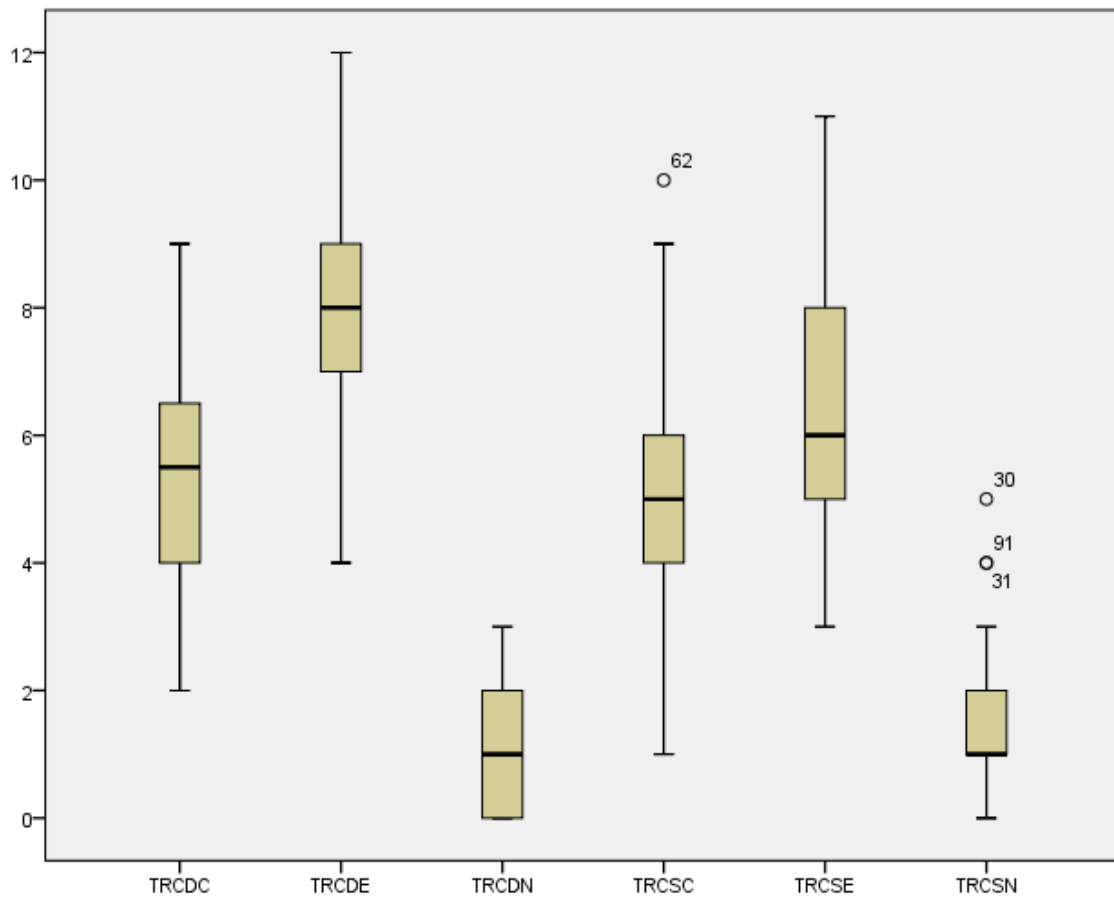
**Paired Samples Test**

		Paired Differences				t	df	Sig. (2-tailed)	
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower				Upper
Pair 1	TCDC - TCSC	.54000	2.73555	.27355	-.00279	1.08279	1.974	99	.051
Pair 2	TCDE - TCSE	1.43000	2.31488	.23149	.97068	1.88932	6.177	99	.000
Pair 3	TCDN - TCSN	-.09000	2.90626	.29063	-.66667	.48667	-.310	99	.757

**Appendix RR – Normal distribution stats for the task relevant comments in each model (calibrated, expert and novice) for both the shared and common display**

**Descriptive Statistics**

	N	Mean	Std. Deviation	Skewness		Kurtosis	
	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Std. Error
TRCDC	100	5.4400	1.78840	.089	.241	-.654	.478
TRCDE	100	8.0300	1.62962	.022	.241	.097	.478
TRCDN	100	1.1200	.84423	.076	.241	-.985	.478
TRCSC	100	4.8800	1.69539	.242	.241	.311	.478
TRCSE	100	6.6000	1.79787	.164	.241	-.856	.478
TRCSN	100	1.3200	1.07196	.833	.241	.594	.478
Valid N (listwise)	100						



**Appendix SS – One Way ANOVA comparing the task-relevant comments of each model (calibrated, expert and novice) for both the shared and common display**

**ANOVA**

		Sum of Squares	df	Mean Square	F	Sig.
TRCommentsD	Between Groups	6127.444	3	2042.481	636.192	.000
	Within Groups	975.985	304	3.210		
	Total	7103.429	307			
TRCommentsS	Between Groups	4258.401	3	1419.467	383.292	.000
	Within Groups	1125.820	304	3.703		
	Total	5384.221	307			

**Appendix TT – Independent samples t-tests comparing the task relevant comments of each model (calibrated, expert and novice) for both the shared and common display**

**Independent Samples T-Test: 0 & 1 (Experiment & Calibrated)**

Group Statistics					
	Condition	N	Mean	Std. Deviation	Std. Error Mean
TRCommentsD	.00	8	26.6250	6.82302	2.41230
	1.00	100	5.4400	1.78840	.17884
TRCommentsS	.00	8	23.2500	7.62983	2.69755
	1.00	100	4.8800	1.69539	.16954

Independent Samples Test										
		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
TRCommentsD	Equal variances assumed	77.290	.000	23.419	106	.000	21.18500	.90460	19.39155	22.97845
	Equal variances not assumed			8.758	7.077	.000	21.18500	2.41892	15.47778	26.89222
TRCommentsS	Equal variances assumed	92.687	.000	19.567	106	.000	18.37000	.93883	16.50868	20.23132
	Equal variances not assumed			6.796	7.055	.000	18.37000	2.70287	11.98888	24.75112

## Independent Samples T-Test: 0 & 2 (Experiment & Expert)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
TRCommentsD	.00	8	26.6250	6.82302	2.41230
	2.00	100	8.0300	1.62962	.16296
TRCommentsS	.00	8	23.2500	7.62983	2.69755
	2.00	100	6.6000	1.79787	.17979

**Independent Samples Test**

	Levene's Test for Equality of Variances	t-test for Equality of Means								
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TRCommentsD	Equal variances assumed	82.835	.000	21.474	106	.000	18.59500	.86595	16.87817	20.31183
	Equal variances not assumed			7.691	7.064	.000	18.59500	2.41780	12.88830	24.30170
TRCommentsS	Equal variances assumed	97.945	.000	17.298	106	.000	16.65000	.96257	14.74162	18.55838
	Equal variances not assumed			6.159	7.062	.000	16.65000	2.70354	10.26857	23.03143

## Independent Samples T-Test: 0 & 3 (Experiment & Novice)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
TRCommentsD	.00	8	26.6250	6.82302	2.41230
	3.00	100	1.1200	.84423	.08442
TRCommentsS	.00	8	23.2500	7.62983	2.69755
	3.00	100	1.3200	1.07196	.10720

**Independent Samples Test**

	Levene's Test for Equality of Variances	t-test for Equality of Means								
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
TRCommentsD	Equal variances assumed	200.570	.000	35.894	106	.000	25.50500	.71056	24.09625	26.91375
	Equal variances not assumed			10.566	7.017	.000	25.50500	2.41378	19.80015	31.20985
TRCommentsS	Equal variances assumed	168.616	.000	26.915	106	.000	21.93000	.81478	20.31462	23.54538
	Equal variances not assumed			8.123	7.022	.000	21.93000	2.69968	15.55034	28.30966

## Independent Samples T-Test: 1 & 2 (Calibrated & Expert)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
TRCommentsD	1.00	100	5.4400	1.78840	.17884
	2.00	100	8.0300	1.62962	.16296
TRCommentsS	1.00	100	4.8800	1.69539	.16954
	2.00	100	6.6000	1.79787	.17979

**Independent Samples Test**

	Levene's Test for Equality of Variances	t-test for Equality of Means								
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
TRCommentsD	Equal variances assumed	2.293	.132	10.705	198	.000	-2.59000	.24195	3.06713	2.11287
	Equal variances not assumed			10.705	196.313	.000	-2.59000	.24195	3.06716	2.11284
TRCommentsS	Equal variances assumed	2.542	.112	-6.960	198	.000	-1.72000	.24712	2.20732	1.23268
	Equal variances not assumed			-6.960	197.322	.000	-1.72000	.24712	2.20733	1.23267

## Independent Samples T-Test: 1 & 3 (Calibrated & Novice)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
TRCommentsD	1.00	100	5.4400	1.78840	.17884
	3.00	100	1.1200	.84423	.08442
TRCommentsS	1.00	100	4.8800	1.69539	.16954
	3.00	100	1.3200	1.07196	.10720

**Independent Samples Test**

	Levene's Test for Equality of Variances	t-test for Equality of Means								
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
TRCommentsD	Equal variances assumed	46.175	.000	21.844	198	.000	4.32000	.19777	3.93000	4.71000
	Equal variances not assumed			21.844	141.035	.000	4.32000	.19777	3.92903	4.71097
TRCommentsS	Equal variances assumed	13.862	.000	17.748	198	.000	3.56000	.20059	3.16444	3.95556
	Equal variances not assumed			17.748	167.248	.000	3.56000	.20059	3.16400	3.95600

## Independent Samples T-Test: 2 & 3 (Expert & Novice)

**Group Statistics**

	Condition	N	Mean	Std. Deviation	Std. Error Mean
TRCommentsD	2.00	100	8.0300	1.62962	.16296
	3.00	100	1.1200	.84423	.08442
TRCommentsS	2.00	100	6.6000	1.79787	.17979
	3.00	100	1.3200	1.07196	.10720

**Independent Samples Test**

	Levene's Test for Equality of Variances	t-test for Equality of Means								
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
TRCommentsD	Equal variances assumed	22.187	.000	37.650	198	.000	6.91000	.18353	6.54807	7.27193
	Equal variances not assumed			37.650	148.569	.000	6.91000	.18353	6.54733	7.27267
TRCommentsS	Equal variances assumed	37.557	.000	25.225	198	.000	5.28000	.20932	4.86722	5.69278
	Equal variances not assumed			25.225	161.491	.000	5.28000	.20932	4.86665	5.69335

**Appendix UU - Paired Samples t-test comparing the task relevant comments for each model (calibrated, expert & novice) using the shared and common display**

**Paired Samples Statistics**

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	TRCDC	5.4400	100	1.78840	.17884
	TRCSC	4.8800	100	1.69539	.16954
Pair 2	TRCDE	8.0300	100	1.62962	.16296
	TRCSE	6.6000	100	1.79787	.17979
Pair 3	TRCDN	1.1200	100	.84423	.08442
	TRCSN	1.3200	100	1.07196	.10720

**Paired Samples Correlations**

		N	Correlation	Sig.
Pair 1	TRCDC & TRCSC	100	-.082	.415
Pair 2	TRCDE & TRCSE	100	.035	.728
Pair 3	TRCDN & TRCSN	100	.203	.043

**Paired Samples Test**

		Paired Differences				t	df	Sig. (2-tailed)	
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower				Upper
Pair 1	TRCDC - TRCSC	.56000	2.56361	.25636	.05132	1.06868	2.184	99	.031
Pair 2	TRCDE - TRCSE	1.43000	2.38368	.23837	.95703	1.90297	5.999	99	.000
Pair 3	TRCDN - TRCSN	-.20000	1.22268	.12227	-.44261	.04261	1.636	99	.105

**Appendix VV - Pearson Correlations for total comments and performance for the separate display**

**Calibrated Model**

**Correlations**

		TCDC	PSDC
TCDC	Pearson Correlation	1	.113
	Sig. (2-tailed)		.263
	N	100	100
PSDC	Pearson Correlation	.113	1
	Sig. (2-tailed)	.263	
	N	100	308

**Expert Model**

**Correlations**

		TCDE	PSDE
TCDE	Pearson Correlation	1	.089
	Sig. (2-tailed)		.377
	N	100	100
PSDE	Pearson Correlation	.089	1
	Sig. (2-tailed)	.377	
	N	100	100

**Novice Model**

**Correlations**

		TCDN	PSDN
TCDN	Pearson Correlation	1	.033
	Sig. (2-tailed)		.746
	N	100	100
PSDN	Pearson Correlation	.033	1
	Sig. (2-tailed)	.746	
	N	100	100

**Appendix WW - Pearson Correlations for total comments and performance for the common display**

**Calibrated Model**

**Correlations**

		TCSC	PSSC
TCSC	Pearson Correlation	1	-.143
	Sig. (2-tailed)		.156
	N	100	100
PSSC	Pearson Correlation	-.143	1
	Sig. (2-tailed)	.156	
	N	100	100

**Expert Model**

**Correlations**

		TCSE	PSSE
TCSE	Pearson Correlation	1	-.335**
	Sig. (2-tailed)		.001
	N	100	100
PSSE	Pearson Correlation	-.335**	1
	Sig. (2-tailed)	.001	
	N	100	100

\*\* . Correlation is significant at the 0.01 level (2-tailed).

**Novice Model**

**Correlations**

		TCSN	PSSN
TCSN	Pearson Correlation	1	.126
	Sig. (2-tailed)		.213
	N	100	100
PSSN	Pearson Correlation	.126	1
	Sig. (2-tailed)	.213	
	N	100	100

**Appendix XX - Pearson Correlations for task relevant comments and performance for the separate display**

**Calibrated Model**

**Correlations**

		TRCDC	PSDC
TRCDC	Pearson Correlation	1	.392**
	Sig. (2-tailed)		.000
	N	100	100
PSDC	Pearson Correlation	.392**	1
	Sig. (2-tailed)	.000	
	N	100	308

\*\* . Correlation is significant at the 0.01 level (2-tailed).

**Expert Model**

**Correlations**

		TRCDE	PSDE
TRCDE	Pearson Correlation	1	.101
	Sig. (2-tailed)		.319
	N	100	100
PSDE	Pearson Correlation	.101	1
	Sig. (2-tailed)	.319	
	N	100	100

**Novice Model**

**Correlations**

		TRCDN	PSDN
TRCDN	Pearson Correlation	1	.378**
	Sig. (2-tailed)		.000
	N	100	100
PSDN	Pearson Correlation	.378**	1
	Sig. (2-tailed)	.000	
	N	100	100

\*\* . Correlation is significant at the 0.01 level (2-tailed).

**Appendix YY - Pearson Correlations for task relevant comments and performance for the common display**

**Calibrated Model**

**Correlations**

		TRCSC	PSSC
TRCSC	Pearson Correlation	1	.338**
	Sig. (2-tailed)		.001
	N	100	100
PSSC	Pearson Correlation	.338**	1
	Sig. (2-tailed)	.001	
	N	100	100

\*\* . Correlation is significant at the 0.01 level (2-tailed).

**Expert Model**

**Correlations**

		TRCSE	PSSE
TRCSE	Pearson Correlation	1	-.338**
	Sig. (2-tailed)		.001
	N	100	100
PSSE	Pearson Correlation	-.338**	1
	Sig. (2-tailed)	.001	
	N	100	100

\*\* . Correlation is significant at the 0.01 level (2-tailed).

**Novice Model**

**Correlations**

		TRCSN	PSSN
TRCSN	Pearson Correlation	1	.708**
	Sig. (2-tailed)		.000
	N	100	100
PSSN	Pearson Correlation	.708**	1
	Sig. (2-tailed)	.000	
	N	100	100

\* . Correlation is significant at the 0.01 level (2-tailed).