The Effect of Urban versus Nature Exposures on Cognitive Control and Well-being

by

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Abstract

This thesis explores the effect of urban versus natural environments on 1) proactive and reactive cognitive control; 2) the influence of top-down and bottom-up processes on attention allocation towards emotional face stimuli; 3) behavioural adjustment; and 4) well-being. To do this, I utilized two types of experiments. In the first type, young adult participants were briefly exposed to urban versus natural environments then completed a task with face stimuli. In the second type, young adult participants provided their home postcode during childhood so that their childhood environments could be categorised based on various features, such as neighbourhood greenness or population size. Afterwards, they completed either a face attention task, the Go/No-go task or the Depression, Anxiety, and Stress Scale (21-items). To measure cognitive control, I was interested in the magnitude of the congruency sequence effect. I found that brief physical urban exposure promoted reactive control whereas physical nature exposure promoted proactive control. Neither brief artificial nor chronic childhood exposure to these environments affected cognitive control. The influence of top-down and bottom-up processes on attention allocation towards emotional face stimuli was measured by 1) the extent to which emotional face distractors interfered with task performance, as well as 2) participants brain responses (P1 event related potential component and theta oscillation) to emotional face stimuli that was measured via electroencephalography. These showed that brief artificial urban versus nature exposures resulted in greater influence of both bottom-up and top-down processes on attention allocation. Notably, this effect may be underpinned by exposure to faces within urban environments. In contrast with artificial exposures, brief physical and chronic childhood exposure to urban versus natural environment did not modulate the influence of either top-down or bottom-up processes. Moving on to behavioural adjustment, this was measured via the extent to which participants' reaction times slowed on trials after erroneous versus correct responses. This revealed that young adults who were raised in greener neighbourhoods displayed greater behavioural adjustment, demonstrating that chronic childhood exposure to natural environments modulated behavioural adjustment. In contrast, neither population size nor air pollution levels of childhood environments

affected behavioural adjustment. Finally, to measure well-being, participants rated the extent to which they experienced depressive, anxiety, and stress symptoms. Somewhat confusingly, I found that young adults who were raised in areas with higher neighbourhood greenness, air pollution levels and population size reported marginally greater well-being, demonstrating that childhood exposure to both urban and natural environments affected well-being to some extent in young adulthood. Collectively, these results suggest that urban versus nature exposures modulate a range of cognitive processes as well as well-being beyond that typically investigated within the literature.

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Publications, Presentations and Contributions

From my doctoral thesis at the University of Birmingham, the following articles have been submitted for publication and/or contributed to presentations at conferences. The work presented here was designed, conducted, analysed and interpreted by myself. However, advice on study design, data analysis and editorial guidance during writing was provided by my supervisors, Professor Jane E. Raymond and Dr Ali Mazaheri. Thomas Faherty assisted with assigning air pollution scores to some of the postcodes in Chapter 5. Additionally, third-year project students, Jessica Dow, Pavleta Markova, Charlotte Robson, Saima Choudhury, Sophie Currie, Ashna Omar, Hannah McBreaty, Laynie Thornton, Sophie Shatford, Madeleine Berry, Radha Yagnik, Dillon Thompson, Ronan Nagle-Weaver, Alaa Wanis, Delilah Barratt and Laurie Whyte, assisted with some data collection for Chapters 2 (Experiment 2) and 4.

Papers submitted for publication from this doctoral research

1. Toth, E., Mazaheri, A., & Raymond, J. E. (2020). Urban and natural contexts differentially module attention bias towards threat.
2. Toth, E., Faherty, T., Mazaheri, A., & Raymond, J. E. (2021). Changes to student mental health during the Covid-19 pandemic.

Conference presentations arising from this research

Toth, E., Raymond, J. & Mazaheri, A. (2019). Processing of emotional faces after forest versus city exposure. BIFoR annual meeting (poster presentation).

Toth, E., Raymond, J. & Mazaheri, A. (2020). Brain responses to faces after urban versus nature exposures. BIFoR annual meeting (poster presentation).

Toth, E., Raymond, J. & Mazaheri, A. (2020). Differential modulation of brain responses to face stimuli after exposure to urban versus forest environments. ANTNeuro annual conference (poster presentation).

Toth, E., Raymond, J. & Mazaheri, A. (2020). Brain responses to faces after urban versus nature exposures. Cognitive Neuroscience annual conference (poster presentation).

Toth, E., Mazaheri, A. & Raymond, J. (2021). The effect of exposure to natural environments on well-being. BIFoR annual meeting (oral presentation).

Chapter 1. Introduction

For the first century, most people spend more time in urban than natural environments. This is seemingly not without consequence. Indeed, in urban versus natural environments, people are exposed to higher levels of noise (Dzhambov & Dimitrova, 2015; van Renterghem & Bottledooren, 2016) and air pollution (Hewitt, Ashwroth, & MacKenzie, 2020) as well as fewer places for exercise (Frumkin, Frank, Frank, & Jackson, 2004). Furthermore, substantial literature has linked living in relatively urban areas that contain little natural space with increased risk of schizophrenia and mood disorders, including depression (Lundberg, Cantor-Graae, Rukundo, Ashaba, & Östergren, 2009; Peen, Schoevers, Beekman, & Dekker, 2010; Sørensen et al., 2014; Engemann et al., 2018; 2019; 2020; Gascon et al., 2018; Liu et al., 2019; Perrino et al., 2019). Notably, these disorders involve deficits in proactive but not reactive cognitive control (Lesh et al., 2013; Vanderhasselt et al., 2014). Considering the link between our environment and mental disorders and that between mental disorders and cognitive control, urban versus natural environments may differentially modulate cognitive control. Although this has been largely overlooked within the literature, Attention Restoration Theory (ART; Kaplan & Kaplan, 1989; Kaplan, 1995; 2001) a very influential theory that has been developed to explain and predict the effect of urban versus natural environments on selective attention makes predictions that may be relevant. According to ART, urban environments induce whereas natural environments resolve ego-depletion, making it difficult to apply demanding processes, such as proactive control (Braver, 2012). This suggests that urban exposures may promote reactive control that is less effortful (Braver, 2012) while nature exposures may promote proactive control. However, this remains untested.

Importantly, cognitive control is a broad construct that includes several cognitive processes, such as selective attention and behavioural adjustment (Miyake et al., 2000), and it has been linked to well-being (Ochsner & Gross, 2005; McRea, Jacobs, Ray, John, & Gross, 2012). A substantial body of literature has investigated the effect of urban versus natural environments on selective attention.

This consistently shows that nature but not urban exposures improve top-down attention allocation towards a non-face target and away from non-face distractors (see Ohly et al., 2016; Stevenson, Schilhab, & Bentsen, 2018; White & Shah, 2019; for reviews). Three ideas have been developed to predict the effect of these environments on selective attention. ART (Kaplan & Kaplan, 1989; Kaplan, 1995; 2001) argues that urban environments induce whereas natural environments resolve ego-depletion thus modulating top-down processes. In contrast, the ‘cities train the brain’ notion states that urban environments train the brain of the elderly to effectively apply top-down processes (Cassarino & Setti, 2015; Cassarino, O’Sullivan, Kenny, & Setti, 2018). Finally, the ‘shifting’ notion argues that urban environments shift the mode of attentional processing from a focused towards an exploratory mode, thus reducing but not impairing use of top-down processes (Linnell & Caparos, 2020). Despite selective attention receiving lots of interest, how urban versus nature exposures modulate attention allocation to emotional face stimuli remains unclear.

In contrast with selective attention, the effect of urban versus natural environments on behavioural adjustment has been completely overlooked. Nevertheless, ART’s prediction that urban environments induce whereas natural environments resolve ego-depletion that has been linked to diminished behavioural adjustment (Lorist, Boksem, & Ridderinkhof, 2005; Boksem, Meijman, & Lorist, 2006) suggests that urban versus nature exposures may result in poorer behavioural adjustment.

Similar to selective attention, numerous experiments have also examined the effect urban versus natural environments on well-being. These show that in the short-term, nature versus urban exposures reliably increase positive and decrease negative mood including stress, indexing greater well-being (see McMahan & Estes, 2015 for review). According to the Psycho-Evolutionary Framework (PEF; Ulrich, 1983; 1993), these results are underpinned by certain features of natural environments, such as absence of threat, rapidly evoking positive mood that in turn reduces negative emotions, including stress. Notably, urban environments do not contain these features and therefore, are not predicted to modulate mood and thus well-being. Importantly, despite the substantial literature investigating the effect of urban versus natural environments on well-being, the length of period for which these effects last remains overlooked by both experimental and theoretical work.

Overall, the aim of this thesis was to investigate the effect of urban versus natural environments on 1) proactive and reactive cognitive control; 2) the attention allocation towards emotional face stimuli; 3) behavioural adjustment; and 4) well-being.

This thesis is presented in presented in six chapters. Chapter 1 reviews the literature on cognitive control, including selective attention and behaviour adjustment, as well as well-being. Furthermore, it discusses how these are affected by urban and nature exposures. Chapter 2 investigates the effects of both brief and chronic exposures to urban versus natural environments on cognitive control and attention allocation to fearful face stimuli. Chapter 3 examines the effect of brief artificial urban versus nature exposures on the neurobiological mechanisms that underpin top-down and bottom-up attention allocation to face stimuli using electroencephalography (EEG). Additionally, this chapter investigates whether the effects of urban exposure are due to exposure to faces in urban settings. Chapter 4 tests the effect of chronic childhood exposure to urban versus natural environments and their various features on behavioural adjustment in young adulthood. Chapter 5 studies the effect of chronic childhood exposure to these on well-being in young adulthood. Finally, Chapter 6 provides general discussion of the effect of urban versus nature exposures on cognitive control, including selective attention and behavioural adjustment as well as well-being.

Urbanization

Humans evolved in natural environments (Brunet et al., 2002). However, due to rapid urbanization over the last century, currently more than half (55%) of the world's population resides in cities, a number estimated to increase to 66% by 2050 (Dye, 2008). Importantly, urbanization has diminished people's contact with nature (Zenghelis & Stern, 2016, Nieuwenhuijsen, Khreis, Triguero-Mas, Gascon, & Dadvand, 2017). Indeed, visits to natural areas have decreased over the last few decades (Pregrams & Zaradic, 2008). Currently, approximately half of England's population visit natural environments only one or two times per week (Dunnett, Swanwick, & Woolley, 2002), suggesting that for the first century, most people spend more time in urban than natural environments.

For the purposes of this thesis, natural environments are defined as areas that are, at least in part, covered with water, grass, trees or other vegetation and contains wildlife (Hartig, 2014). In comparison, cities are defined as areas of dense human population supported by industry and community services (World Health Organization, 2010; van Os, Friessen, Gunther, & Delespaul, 2000).

Cognitive control

This is seemingly not without consequence. Living in relatively urban and less natural areas has been linked to increased risk of schizophrenia and mood disorders, including depression (Peen, Schoevers, Beekman, & Dekker, 2010; Sørensen et al., 2014; Engemann et al., 2018; 2019; 2020; Gascon et al., 2018, Liu et al., 2019; Perrino et al., 2019). Importantly, these involve deficits in cognitive control (Lesh et al., 2013; Vanderhasselt et al., 2014). Cognitive control refers to the ability to perform an unrehearsed response instead of a rehearsed but unsuitable response (Miller & Cohen, 2001). This includes selecting task-relevant stimuli for engagement and appropriately adjusting cognitive processes to achieve success on a task (Botvinick et al., 2001; Ridderinkhof et al., 2004). Interestingly, cognitive control can be applied either before the occurrence of a cognitively demanding event (proactive control) or afterwards when conflict between the event's demands and behaviour has been detected (reactive control; Braver, Gray, & Burgess, 2007; Braver, 2012). This means that proactive control is applied during planning to prevent anticipated interference whereas reactive control is applied to resolve interference after it has been detected.

The application of these processes is easily seen in tasks where the target is presented with either a congruent (identical) or incongruent (non-identical) distractor (Egner, 2007). On these tasks, RTs are typically faster on incongruent trials that are preceded by incongruent trials ('repeat' trials) than on incongruent trials that are preceded by congruent trials ('novel' trials; Egner & Hirsch, 2005; Egner, 2007; see *Fig. 1.*1). This is called the congruency sequence effect. When reactive control is applied, the congruency sequence effect is especially pronounced as unlike repeat trials, novel trials require the retrieval of task goals and disengagement from the incorrectly attended incongruent distractor after stimulus presentation before a response can be made (Braver, 2012). In comparison, when proactive control is used, this effect is relatively small as attention is biased towards the target before stimulus presentation and therefore, the distractor cannot capture attention away from the target on either repeat or novel trials (Braver, 2012).

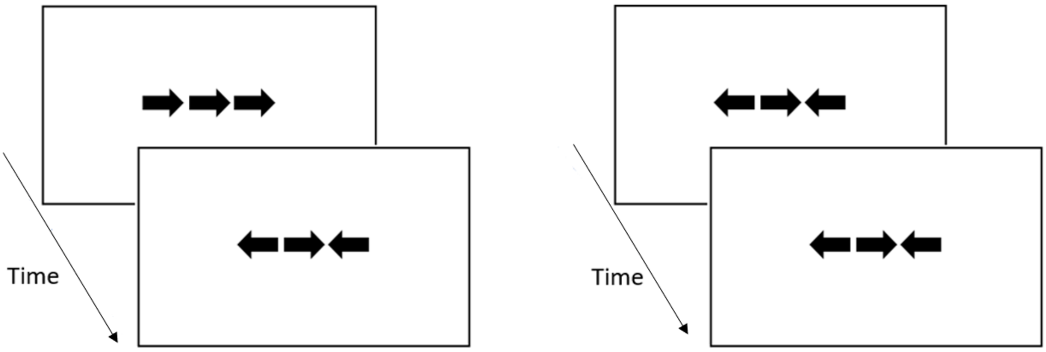

Figure 1.1. An illustration of 'novel' (left) and 'repeat'(right) trials. 'Novel' trials are incongruent trial that were preceded by a congruent trial. In contrast, 'repeat' trials are incongruent trials that were preceded by another incongruent trial.

Cognitive control and ego-depletion

Proactive control is thought to be effortful (Braver et al., 2012), suggesting that it may be impaired by ego-depletion. Ego-depletion (also known as mental fatigue) is a state characterized by tiredness as well as reduced vigilance and cognitive performance (Grandjean, 1980). This state is traditionally believed to be elicited by prolonged cognitively demanding tasks. These deplete central cognitive resources, and thus impair subsequent performance of demanding tasks or the application of demanding processes, such as proactive control. Central cognitive resources have been suggested to be underpinned by glucose (Gailliot & Baumeisiter, 2007; Gailliot et al., 2007; DeWall, Baumesiter, Gailliot, & Maner, 2008), a notion supported by several studies reporting that glucose levels are not only reduced after performing a demanding task, but they also predict performance on a subsequent demanding task (Gailliot et al., 2007). However, many failed to replicate such findings (Job, Walton, Bernecker, & Dweck, 2013; Lange & Eggert, 2014; Lange, Seer, Rapior, Rose, & Eggert, 2014) and recent meta-analyses show that glucose is unlikely to underpin central cognitive resources (Dang, 2016; Vallido et al., 2016), casting doubt on this notion.

Surprisingly, not many studies have investigated the effect of ego-depletion of cognitive control. Nevertheless, there is some evidence that performing cognitive tasks, such as the Tower of London (van der Linden, Frese, & Maijman, 2003) and switch (Lorist et al., 2000) tasks, for a prolonged period results in increased preparation time. As proactive not reactive control is applied during preparation, these findings suggest that ego-depletion diminishes the effectiveness of proactive control but may not affect reactive control.

Importantly, the idea that ego-depletion is only induced by demanding tasks may be oversimplistic (see Hockey, 2011 for review). In addition to excessive use of such processes, stressful negative life events also reduce self-control, an index of ego-depletion (Duckworth, Kim, & Tsukayama, 2013), supposedly because stress also consumes central cognitive resources (Baumeister, Muraven, & Tice, 2000). Similarly, overcoming ego-depletion may not be limited to replenishing central cognitive resources (via rest or glucose intake; see Hockey et al., 2011 for review). For example, across four experiments, Tice, Baumesiter, Scmueli and Muraven (2007) demonstrated that participants who underwent positive mood inducement after ego-depletion performed as well on a subsequent self-control task as non-depleted participants, illustrating that positive mood can also resolve ego-depletion. Moreover, depleted participants performed better on a subsequent self-control task after positive mood inducement versus rest, highlighting the importance of positive mood in resolving ego-depletion. Notably, this effect was not present after negative or neutral mood inducement, demonstrating that this impact is specific to positive mood.

Cognitive control and the environment

Similar to ego-depletion, proactive but not reactive control is impaired in schizophrenia and mood disorders (Lesh et al., 2013; Vanderhasselt et al., 2014). That are more likely to be developed by people who live in relatively urban versus natural neighbourhoods (Peen, Schoevers, Beekman, & Dekker, 2010; Sørensen et al., 2014; Engemann et al., 2018; 2019; 2020; Gascon et al., 2018; Liu et al., 2019; Perrino et al., 2019). Considering the link between these mental disorders and cognitive control and that between our environment and these disorders, it is possible that these environments may also modulate cognitive control in the absence of mental disorders. To my knowledge, this was only investigated by Laumann, Gärling and Stormark (2003) who asked participants to complete the Posner Attention Orientation Task (instead of a more traditional task with congruent and incongruent stimuli) to measure reactive control. In this task, the upcoming target's location is cued either correctly or incorrectly. On trials where the target's location is incorrectly cued, participants detect a conflict between the expected and actual target location, meaning that they need to apply reactive control to disengage from the expected location and attend to the target. Notably, participants responded more quickly on trials where the target's location was correctly versus incorrectly cued both at baseline and after watching an urban video, suggesting that urban exposure did not modulate reactive control. Importantly, however, participants responded with similar speed to both correctly and incorrectly cued targets after watching a nature video, showing that nature exposure improved disengagement from incorrectly cued locations, indexing improved reactive control. This shows that urban versus natural environments differentially modulate reactive control. However, whether these environments differentially affect proactive control as well remains untested. Furthermore, it is unclear how urban versus natural environments affect cognitive control on tasks where both proactive and reactive control can be used.

Link to theories

To my knowledge, no theory has been developed to address the effect of urban versus natural environments on cognitive control. Notably, however, the Attention Restoration Theory (ART) and the 'shifting' notion that were developed to predict and explain the effect of these environments on selective attention may be applicable to cognitive control too. Importantly, as these were developed to address the effect of urban versus natural environments on attention, they will be discussed in more detail in the 'Selective attention and the environment' section.

According to ART (Kaplan & Kaplan, 1989; Kaplan, 1995; 2001), cities provide a cognitively demanding environment, where goal-relevant but uninteresting objects often need to be effortfully attended while interesting salient distractors need to be suppressed. For example, whilst looking for a shop, buildings on the side of the road need to be surveyed, whereas advertisements specifically designed to capture attention need to be ignored. Ensuring that attention is captured by the correct stimulus is very effortful and therefore, in line with traditional ego-depletion ideas, ART argues that this quickly depletes central cognitive resources. This is thought to result in a state of ego-depletion. Although not stated within ART, ego-depletion makes it difficult to apply demanding processes, such as proactive control (Braver, 2012), suggesting that urban exposures may also impair proactive control whilst leaving reactive control intact.

In comparison with urban settings, ART argues that natural environments are filled with interesting stimuli that capture attention automatically and require little effort to be processed. This allows the brain to rest, replenishing central cognitive resources and thus resolving ego-depletion. As ego-depletion seems to diminish proactive control, resolving it is likely to restore proactive control. Furthermore, natural environments allow reflection upon unsolved problems that reduces their internal burden and frees additional resources (Basu, Duvall, & Kaplan, 2019), that could also be used by proactive control. Notably, as ego-depletion seems not to affect reactive control, nature exposures may not modulate it either.

In contrast with ART, the ‘shifting’ notion (Linnell & Caparos, 2020) argues that our environment does not impair cognition. Instead, urban living shifts the mode of attention from a focused towards an exploratory mode that is characterised by sensitivity to a range of stimuli instead of a task-relevant ones only. In contrast, living in remote natural environments shift attention towards a focused mode. Although not stated within the ‘shifting’ notion, exploratory mode of attention is comparable to reactive control as they both allow all stimuli to capture attention, whereas focused mode of attention is comparable to proactive control as they both bias attention towards task-relevant stimuli thus reducing distractibility. Therefore, the ‘shifting’ notion also predicts urban environments to promote reactive control and natural environments to promote proactive control. Importantly, according to this notion, urban environments do not impair proactive control, merely enhance the likelihood of reactive control being applied.

Notably, as ART suggests that natural environments do not modulate reactive control and the ‘shifting’ notion predicts nature exposure to promote proactive control, neither can explain why nature exposure improved reactive control in Laumann et al.’s (2003) experiment. This suggests that the prediction of both theories may be wrong at least to some extent.

Aspects of cognitive control

Importantly, cognitive control is a broad construct that includes numerous cognitive processes, including selective attention and behavioural adjustment (Miyake et al., 2000). Furthermore, cognitive control is closely linked to various other factors, such as well-being, as several experiments have shown that better cognitive control abilities have been associated with greater well-being (Ochsner & Gross, 2005; McRea, Jacobs, Ray, John, & Gross, 2012). Therefore, in this thesis, I will also discuss selective attention, behaviour adjustment and well-being, and how these may be modulated by natural and urban environments.

Selective attention

Every day, we are surrounded by vast environments filled with a variety of stimuli that compete for neural representation (Desimone & Duncan, 1995). Due to the brain’s limited capacity (Becker & Pashler, 2005), selective attention needs to select important stimuli at the expense of irrelevant information (Posner & Rothbart, 2007). This mechanism is thought to depend on top-down and bottom-up processes (Lang, 1995; Itti & Koch, 2000; Corbetta & Shulman, 2002; Vuilleumier, 2005).

Bottom-up processes capture attention automatically by the onset of a novel or salient stimulus (Jonides & Yantis, 1988; Theeuwes, 1992; 1994). Consequently, when participants need to respond to such stimuli, their reaction times (RT) are faster, and accuracy is higher (Posner & Cohen, 1984; Turatto & Galfano, 2000). In comparison, when such stimuli need to be ignored, performance on these measures deteriorate (Theeuwes, 1992; Gaspelin, Leonard, & Luck, 2015) because attention is captured by the distractor instead of the target. This notion is supported by EEG experiments studying the P1 event related potential (ERP) component that is larger for attended versus unattended stimuli, suggesting that it is evoked by early attention processing (Luck et al., 1994; Luck & Hillyard, 1995; Hillyard, Vogel, & Luck, 1998; Klimesch, 2011). For example, bright stimuli presented suddenly in an unattended location elicit a P1 (Hopfinger & Mangun, 1998; 2001; Fu, Fan, Chen, & Zhuo, 2001), demonstrating that attention is quickly captured by unattended but salient stimuli. Furthermore, sudden luminance change versus no change of a task-irrelevant stimulus evokes a larger P1 amplitude (Hopfinger & Maxwell, 2005), illustrating that salient events capture more attention than non-salient ones.

Similar to salient stimuli, emotional stimuli also preferentially capture attention. Although it has been suggested that emotional stimuli may be captured by a third attentional processes (Brosch, Pourtois, Sander, & Vuilleumier, 2011; Pourtois et al., 2013; Pool, Brosch, Delplanque, & Sander, 2016), generally it is often considered to capture attention via bottom-up processes. Supporting this, in dot probe paradigms, simple line targets presented in the location of emotional versus neutral stimuli are detected faster (Mogg, Bradley, & Hallowell, 1994; Pourtois, Grandjean, Sander, & Vuilleumier, 2004; Wirth & Wentura, 2020), and elicit larger P1 amplitude (Pourtois et al., 2004; Fox, Derakshan & Shoker, 2008), reflecting enhanced bottom-up attention capture. Importantly, RTs slowed when a neutral target is presented with a task-irrelevant emotional versus neutral distractor (Fox et al., 2000; Eastwood, Smilek & Merikle, 2001; Barratt & Bundesen, 2012; Grose-Fifer, Rodrigues, Hoover, & Zottoli, 2013), illustrating that similar to salient stimuli, emotional stimuli can capture attention away from the target, resulting in enhanced distractibility.

Notably, while attention allocation to salient and novel stimuli has been linked to the frontoparietal network (Brosch, Pourtois, Sander, & Vuilleumier, 2011; Li & Zhao, 2015), attention allocation to face stimuli, particularly those with emotional expressions, is thought to be underpinned by a network involving the amygdala that biases sensory processing towards emotional stimuli (see Vuilleumier, 2005 for review). The amygdala's role is supported by findings that anxious participants, a population characterized by amygdala hyperactivity (Etkin et al., 2004; Phan, Fitzgerald, Nathan, & Tancer, 2006), show enhanced vigilance towards fear-related stimuli compared to non-anxious participants (see Bar-Haim et al., 2007 for review). Furthermore, Selective Serotonin Reuptake Inhibitors (SSRIs), that have been found to suppress amygdala activity (Browning, Reid, Cowen, Goodwin, & Harmer, 2007), as well as to reduce attention allocation towards emotional stimuli (Sheline et al., 2001; Murphy, Yiend, Lester, Cowen, & Harmer, 2009), further supporting the central role of the amygdala in emotional attention capture.

Bottom-up attention capture can be inhibited by top-down processes. These processes use mental templates of goal-relevant or expected target features to bias sensory processing towards these. Therefore, only stimuli matching the templates are processed, resulting in reduced distractibility by task-irrelevant salient and emotional stimuli (Posner, Snyder & Davidson, 1980; Yantis & Johnston, 1990; Desimone & Duncan, 1995). Application of top-down processes is underpinned by the prefrontal cortex (PFC; Leito et al., 2013; 2015), a notion supported by findings that PFC activity positively correlates with success at distractors suppression (Suzuki, 2013), a key marker of top-down processes. Furthermore, lesion (Heilman & Valenstrein, 1972; Mesulam, 1981; Chao & Knight, 1995) and TMS (Taylor, Nobre & Rushworth, 2007; Miller, Vytlacil, Fegen, Pradhan, & D'Esposite, 2011) studies demonstrated that both temporary and permanent PFC impairment increases distractibility, further supporting the PFC's involvement in distractor suppression and thus the application of top-down processes.

Although the top-down and bottom-up attention processes can capture attention independently of each other (Berger et al., 2005; Pourtois, Schettino, & Vuilleumier, 2013), in everyday life, stimulus selection is often modulated by a combination of these (Pourtois, Schettino & Vuilleumier, 2013). The interaction between top-down and bottom-up processes has been especially well documented. Numerous studies have shown that salient distractors are often only detected or interfere with task performance if their colour matches the target's (Kaptein, Theeuwes, & Van der Heijden, 1995; Most, Scholl, Clifford, & Simons, 2005; Folk, Leber & Egeth, 2002; Becker & Leidenger, 2011), demonstrating that bottom-up attention capture can be limited by top-down mental templates. Additionally, salient stimuli that are the same versus different colour as the target (Zhang & Luck, 2009) or are presented in an expected versus unexpected location (Hopfinger & West, 2006) evoke a larger P1 amplitude, showing that the effects of these processes are summed.

Selective attention and working memory capacity

The success at which bottom-up and top-down processes are applied and thus can influence attention capture has been linked to several factors. For example, more successful application of top-down processes has been associated with relatively high working memory capacity (WMC). WMC refers to the number of items (typically between 3 and 5) that can be temporarily stored and manipulated (Cowan, 2010; Baddeley, Eysenck, & Anderson, 2015; Egner, 2017; Oberauer, 2019). Indeed, participants with relatively high versus low WMC display smaller congruency sequence effect (Redick & Engle, 2006; Heitz & Engle, 2007; Hutchison, 2011; Ahmed & de Fockert, 2012) and are faster to respond to the target while suppressing distractors on a range of tasks, such as Stroop and visual search tasks (Long & Prat, 2002; Kane & Engle, 2003; Sobel, Gerrie, Poole, & Kane, 2007; Poole & Kane, 2009; Hutchison, 2011; Morey et al., 2012), indexing superior application of top-down processes.

To investigate the causal relationship between WMC and top-down processes, Hutchison (2011) used two versions of the traditional Stroop task, where participants report the colour of a word naming either a congruent or incongruent colour. In one version, most trial were incongruent, so the task goal needed to be maintained throughout the task to successfully report the colour instead of the incongruent meaning of each word. In contrast, on the other version where most trials were congruent, task goal maintenance was not necessary because reporting the congruent meaning instead of the colour of each word also yielded a correct response. Critically, if task goal is abandoned on this version, accuracy on the rare incongruent versus frequent congruent trials would be very low. Importantly, this was shown by participants with relatively low but not high WMC, a result that has since been replicated by Morey et al. (2012). This shows that participants with relatively low versus high WMC are more likely to abandon task goal, suggesting that their weakened ability to suppress distractors may be underpinned by a greater tendency to discard task goal from working memory. Therefore, WMC may contribute to differences in the success at which top-down processes are applied.

This notion is further supported by findings that increasing WMC via various training programs has been shown to improve top-down processes. For example, after regularly performing various working memory tasks, participants show faster RTs on a Stroop task (Chein & Morrison, 2010) and faster and more stable RTs as well as higher accuracy on a continuous performance task (Coleman, Marion, Rizzo, Turnbull, & Nolty, 2019) compared to baseline. Importantly, however, many studies find no evidence that working memory training improves the application of top-down processes (meta-analysis by Melby-Lervåg, & Hulme, 2012), suggesting that although WMC may contribute to successful application of top-down processes, it is unlikely to underpin them.

In comparison with top-down processes, bottom-up attention capture is unaffected by WMC. For example, participants with relatively high versus low WMC detected salient targets at a similar speed (Sobel et al., 2007) and display similar preparation for and orienting towards the location of an upcoming stimulus, both of which are underpinned by bottom-up processes (Redick & Engle, 2006). Although the relationship between WMC and emotional attention capture remains untested, as emotional processes (similar to bottom-up processes) capture attention automatically, emotional processes are unlikely to be affected by WMC.

Selective attention and mood

The success at which top-down processes are applied is also influenced by mood, an affective state that, unlike emotion, is prolonged and can be experienced some time after the cause that is often a general event (Ekkekakis, 2012). For instance, positive mood diminishes top-down processes. Indeed, participants respond more slowly to a target presented among distractors after positive versus negative mood inducement (Breishbach & Goschke, 2004; Rowe, Hirsch, & Anderson, 2007), reflecting weakened distractor suppression. Additionally, positive mood diminishes the extent to which participants rely on top-down processes, a notion supported by studies using the Global/Local task (also known as Navon task; see *Fig.* 1.2) where stimuli are large (global) shapes made of smaller (local) ones. In this task, processing of local stimuli depends on top-down processes whereas processing of global stimuli depends on bottom-up processes (Navon, 1977; Miller & Navon, 2002). These report that participants are more likely to choose a stimulus that matches the target on a global compared to local level after viewing a video to induce positive versus negative or neutral mood (Basso, Schefft, Ris, & Dember, 1996; Frederickson & Branigan, 2005), indexing a shift away from top-down processes.

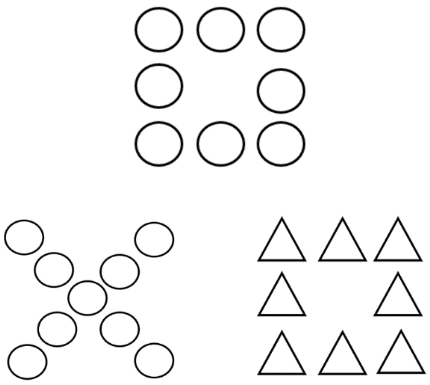

Figure 1.2. An illustration of an example trial of the Global/Local task. The target is presented on the top. Its global shape is a square; however its local shape is a circle. The target is presented with two stimuli (bottom), each of which matches the target on either global or local level. In this example, the stimulus on the bottom left matches the target on a local level as both shapes are made of small circles. The stimulus on the bottom right, however, matches the target on a global level as the small elements of both stimuli makes up a large square. Participants are asked to report which stimulus on the bottom matches the target.

In comparison with positive mood, the effect of stress, a negative mood describing physiological and psychological responses to any demand that one may not be able to fulfil (Lazarus, & Folkman, 1984; Evans & Cohen, 1987), is less consistent. Several studies report that stress impairs top-down processes. For example, stressed versus non-stressed participants respond more slowly and less accurately to a target presented among distractors (Sato et al., 2012; Sänger, Becktold, Schoofs, Blaszkewicz & Waschler, 2014; Tiferet-Dweck et al., 2016), indexing greater distractibility and thus weakened top-down processes. In line with this, targets presented among distractors evoke reduced P1 amplitude during stress versus control condition (Tiferet-Dweck et al., 2016), indicating greater distractibility. Others, however, find that stress leads to more successful application of top-down processes. For instance, stressed versus non-stressed participants report the colour of words in traditional Stroop tasks more quickly (O'Malley & Polawsky, 1971; O'Malley & Gallas, 1977; Kofman, Meiran, Greenberg, Balas, & Cohen, 2006; Booth & Sharma, 2009), indexing reduced distractibility that marks superior application of top-down processes. Such inconsistency may be explained by the Yerkes-Dodson law (Yerkes & Dodson, 1908) that states that task performance is impaired by both below and above optimal level of arousal. This suggests that in experiments that report diminished top-down processes, stress results in sub- or supra-optimal arousal level, however, in experiments that report enhanced top-down processes, stress leads to optimal arousal level.

In addition to modulating top-down processes, both positive mood and stress enhance emotional attention capture. Notably, positive mood increases attention allocation towards positive stimuli, a notion supported by findings that participants spend more time gazing at positive images (Wadlinger & Isaacowitz, 2006; Isaacowitz et al., 2008; Sanchez et al., 2014) and are more likely to notice task-irrelevant happy faces (Becker & Leinenger, 2011) after positive versus negative or neutral mood inducement. Furthermore, in a dot-probe paradigm, participants who report positive mood prior to the experiment respond more quickly to a simple target presented in the location of a reward versus neutral word (Tamir & Robinson, 2007), indexing greater attention allocation to positive stimuli.

In comparison, stress enhances attention allocation to both positive and negative stimuli. Indeed, in dot probe paradigms, stressed versus non-stressed participants respond more quickly to a simple target presented in the location of fearful and happy versus neutral stimuli (Mogg, Mathews, Bird, & Macgregor-Morris, 1990; Brüne, Nadolny, Güntürkün, & Wolf, 2013), demonstrating enhanced attention allocation to emotional stimuli. In line with this, stressed versus non-stressed participants show enhanced amygdala activity to emotional versus neutral targets and distractors (van Marle, Hermans, Qin, & Fernández, 2009; Oei et al., 2012), suggesting that such stimuli are processed more deeply. Importantly, stressed versus non-stressed participants report the colour of threatening versus non-threatening words more slowly on a Stroop task (Mogg et al., 1990) as well as respond more slowly to neutral targets presented among emotional distractors (Oei et al., 2012), indexing increased distractibility by emotional stimuli under stress.

Similar to stress, negative mood also enhances attention allocation towards negative stimuli (see Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & Van Ijzendoorm, 2007 for review). Indeed, in a Stroop task, anxious versus non-anxious participants report the colour of threatening words more slowly (Bar-haim et al., 2007). Furthermore, anxious versus non-anxious participants respond more quickly to negative stimuli (Chen, Yao, Qian, & Lin, 2016; Dodd, Vogt, Turkileri, & Notebaert, 2017) as well as simple targets presented in the location of a negative stimulus (Fox, 1993; Bar-Haim et al., 2007; Klumpp & Amir, 2009), indexing enhanced attention allocation towards negative stimuli. Importantly, non-anxious participants spend more time viewing negative stimuli (Isaacowitz et al., 2008) and are more likely to notice task-irrelevant negative faces after negative versus positive and neutral mood inducement (Wang, LaBar, & McCarthy, 2006; Becker & Leinenger, 2011), demonstrating that this effect is not specific to anxiety.

Selective attention and ego-depletion

Similar to cognitive control, ego-depletion diminished top-down processes. For example, on an extended Global/Local task, RTs increased with time spent on trials where participants needed to report the identity of local stimuli, attending to which requires top-down processes (Van den Linden & Eling, 2006). Furthermore, accuracy is lower at the end versus beginning of a task where a target is presented among distractors (Faber, Mauritz & Loris, 2012), suggesting that ego-depletion leads to weakened distractor suppression. This is further supported by findings that distractors evoke larger N2b ERP component at the end versus beginning of a prolonged task, indicating increased attention allocation to distractors (Boksem, Meijman, & Loris, 2005).

Selective attention and the environment

Methodology used in experiments investigating the effect of nature and urban exposures on selective attention

Numerous studies have investigated the way natural and urban environments modulate top-down processes. In these experiments, participants were exposed to a range of natural environments, including urban parks, forests, water scenes, wildlife preserves, gardens, rural areas, countryside, grassland, and rock outcrop. Despite that the definition of natural environments includes settings that are only partially covered by natural features, all of these environments were very natural with few human-built objects. In contrast, urban environments used by these experiments included streets among various buildings such as offices or houses, predominantly containing traffic and people. These occasionally included some form of vegetation or water feature. Additionally, instead of a full urban experience, some experiments only exposed participants to a particular aspect of cities, such as a concrete roof or noise made by man-made objects. In addition to comparing natural versus urban environments, some experiments compared the effect of natural and indoor spaces, such as a small room, or the effect of several natural settings to each other. As these also contribute to our understanding of how natural environments modulates top-down processes, they will be discussed in this chapter too. Summarized methodology of the experiments included in the 'Effect of nature and urban exposures on top-down processes' section of the chapter are shown in *Table* 1.1.

Exposure to various environments were delivered in various ways, including physical exposure, such as walking or resting, as well as artificial exposures, such as viewing videos or pictures, or listening to sounds. Some experiments asked participants to view various environments through a window. Importantly, artificial methods typically limited participants' experiences to the visual and auditory aspects of these environments. Therefore, the effects of olfactory or tactile features of these environments on top-down processes have been neglected. The most popular exposure method was walking however, the use of videos and pictures was also common.

Exposure lengths in experiments investigating the effect of a single exposure varied greatly from 40 seconds to one hour, with an average length of 18 minutes (s.d = 16). Notably, physical exposures lasted longer (mean = 30 minutes, s.d. = 16) whereas artificial exposures were shorter (mean = 7 minutes, s.d. = 5) than this. Although such variety allows the investigation of the minimum length of exposure required for these environments to modulate top-down processes, it complicates the direct comparison of experiments as well as various exposure methods. Instead of a brief exposure, several experiments investigated the effect of long-term exposures that lasted for several weeks or the consequences of living in relatively urban versus green, remote, or rural areas. Unlike experiments using single exposures, these have the advantage of measuring the effect of environments that people are regularly exposed to in everyday life.

Typically, physical exposures to and recordings of these environments occurred during summer, often on sunny days. Consequently, the effects of these environments on top-down processes during cold or wet days remains unclear.

The application of top-down processes was measured using a range of tasks. Most popular of these were the Attention Network Task and Necker Cube Pattern Control Task, both of which will be explained in detail in the next section of the chapter.

In addition to measuring top-down processes after exposure to various environments, several experiments included a baseline or control conditions to investigate whether urban exposures indeed impair and exposure to natural environments improve top-down processes. Additionally, some experiment induced ego-depletion prior to exposures to maximise their effects on top-down processes. Notably, one experiment (Hartig, Evans, Jamner, Davis, & Gärling, 2003) included both ego-depletion and non-depletion conditions as well as exposure to natural and urban environments.

Reference	Subjects	Baseline	Ego-depletion	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Bailey et al., 2018	10 University students (age: mean = 20 yrs).	Yes	No	Walk	Nature: nature trail. Indoor: in an Aqua Centre.	30 minutes	Stroop task	Within	Stroop interference decreased in both conditions. Task was completed faster after Nature than Indoor condition.
Berman et al., 2008 (study 2)	12 University students (age: mean = 24 yrs).	Yes	No	Pictures	Nature: Nova Scotia. Urban: Ann Arbor, Detriot, Chicago, USA.	10 minutes	ANT	Within	RT on executive function improved more in Nature than Urban condition.
Berto, 2005	64 University students (age: mean = 23 yrs).	Yes	No	Pictures	Nature: lakes/rivers/sea/hills. Urban: street/industrial zone/houses. Control: geometric patterns.	6.5 minutes	SART	Between	Faster RTs and higher accuracy in Nature than other conditions. No difference between Urban and Control conditions.
Bremner et al., 2016	336 persons (age: 3 yrs to adulthood).	No	N/A	Dwelling	Great Britain. Northern Namibian (Himba) city. Northern Namibian (Himba) remote village.	N/A	Ebbinghaus illusion	Between	Himba groups had higher accuracy than British from age of 9/10 yrs. Smaller illusion in remote than urban Himba across all age groups.
Caparos et al., 2012	Studies 1 & 2: 63 Japanese (mean age: 20 yrs). 62 British (mean age: 24 yrs). 70 urbanised Himba (mean age: 27 yrs). 241 traditional Himba (mean age: 27 yrs).	No	N/A	Dwelling	Great Britain. Northern Namibian (Himba) city. Northern Namibian (Himba) remote village.	N/A	Study 1: Ebbinghaus illusion. Study 2: Global/Local task.	Between	Study 1: Himba groups had higher accuracy than British and Japanese. Smaller illusion in remote than urban Himba. Study 2: more local matches were made by Himba groups vs British and Japanese as well as by traditional vs urbanised Himba. Number of global
Craig et al., 2015	48 adults (age: mean = 20 yrs).	Yes	No	Pictures	Nature: grassland, river, landscapes.	4 minutes 10 seconds	SART	Between	Ability to inhibit response improved after exposure in participants who did not report depression symptoms but did not change in those who did.

Reference	Subjects	Baseline	Ego-depletion	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Crossan & Salmoni, 2019	22 University students (age: mean = 23 yrs).	Yes (before & after ego-depletion)	Stroop task (all subjects)	Video while walking on treadmill	Nature: forest. Nature with task: forest while hitting birds and adjusting balance. Control: blank screen.	10 minutes	NCPCT	Within	No effect.
Dadvand et al., 2015	2593 primary school children (age: mean = 8.5 yrs).	Yes	No	Dwelling	Greenness of home (250 m radius), commute route and school.	N/A	ANT	Between	Higher greenness was associated with lower RT variability.
Dadvand et al., 2017	888 children (age: 4-5 yrs). 987 children (age: 7 yrs).	No	No	Dwelling	Greenness of 100 m, 300 m and 500 m radius of home.	N/A	Conners' Kiddie Continuous Test, ANT	Between	Higher greeness was associated with fewer ommissions and lower RT variance on CKCP as well as lower RT variability on ANT.
Davidoff et al., 2008 (study 1)	52 Himba (mean age: 25 yrs).	No	No	Dwelling	Great Britain. Northern Namibiam (Himba) remote village.	N/A	Global/ Local task	Between	Himba made more local matches than the British.
De Fockert et al., 2011	Study 1: 55 Himba (mean age: 26 yrs). 35 English (mean age: 21 yrs). Study 2: 28 Himba (mean age: 25 yrs). English (mean age: 24 yrs).	No	No	Dwelling	Great Britain vs Northern Namibian (Himba).	N/A	Study 1: flanker task. Study 2: distraction task.	Between	Study 1: Himba showed smaller flanker interference. Study 2: moving distractor slowed RTs of the British to a greater extent.
Emfield & Neider, 2014	2 02 University students (age: mean = 20 yrs).	Yes	No	Sound and/or pictures	Nature: beach/ocean. City: people and man-made objects. Control: no exposure.	6 minutes	ANT	Between	No effect.

Reference	Subjects	Baseline	Ego-depletion	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Gamble et al., 2014	30 elderly (mean age: 69 yrs). 26 University students (mean	Yes	No	Pictures	Nature: Nova Scotia. City: Ann Arbor, Detriot, Chicago, USA.	6 minutes	ANT	Between	RT on executive function improved in both age groups in Nature condition only.
Gatersleben & Andrews, 2013 (study 2)	2 groups of 17 University students (group 1 mean age: 23 yrs; group 2 mean age: 21 yrs)	Yes (after ego-depletion)	Stroop task (all subjects)	Walking, Video	Nature 1: forest with high visibility, few hiding places. Nature 2: forest with low visibility, many hiding places.	10 minutes	NCPCT	Between	Number of perspective switches decreased in Nature 1 and increased in Nature 2 condition. Larger effects in walking conditions.
Georgi et al., 2019	266 retired elderly (aged: 60-74 yrs)	No	No	Dwelling	Capital. Town. Rural area.	N/A	Go/No-go	Between	Capital dwellers had faster RTs than town or rural dwellers.
Greenwood & Gatersleben 2016	120 adolescents (age: 16-18 yrs)	Yes	Memory & sorting tasks, arithmetic (all subjects)	Resting	Nature: grass field. Indoors: in a small room.	20 minutes	NCPCT	Between	Number of perspective switches reduced more in Nature than Indoor condition.
Haga et al., 2016	90 young adults (age: mean = 25 yrs).	Yes (before and after ego-depletion)	Prose memory test (all subjects)	Pink noise interspersed with white noise.	Nature: told sound of waterfall. Industry: told sound of industry. Control: told nothing about source.	3 minutes	ANT	Between	No effect.
Hartig et al., 2003	112 students (mean age: 21 yrs).	Yes	Stroop & classification tasks (all subjects)	Walking	Nature: vegetation and wildlife preserve. Urban: office and retail area.	50 minutes	NCPCT	Between	Number of perspective switches reduced in Urban condition and did not change in Nature condition.

Reference	Subjects	Baseline	Ego-depletion	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Jenkin et al., 2018 (study 1)	75 children.	Yes	No	Video	Nature: beach and countryside. City: people and traffic. Control: squiggly lines.	3 minutes	Stroop task	Between	No effect.
Johnson et al., 2019	90 children (age: 8-15 yrs).	No	No	Walk	Nature: park. City: downtown.	30 minutes	Combined Attention System Task	Between	Better endogenous alerting and orienting in Nature condition.
Kelz et al., 2015	133 adolescents (mean age: 14 yrs)	Yes	No	Schoolyard	Green. Non-green.	6-7 weeks	ANT	Between	No effect.
Lee et al., 2015	150 University students (mean age: 20 yrs).	Yes	No	Roof	Green: covered in grass and flowers. Concrete.	40 seconds	SART	Between	RT variability reduced in Green condition and increases in Concrete condition. Response inhibition was unaffected.
Lee et al., 2018	225 young adults (mean age: 23 yrs).	Yes	No	Roof	Green: covered in grass and flowers. Concrete.	90 seconds	Error identification task	Between	More errors were identified in the Green condition.
Linnell et al., 2013 (studies 1, 4 & 5)	Study 1: 35 traditional Himba (mean age: 25 yrs), 56 urban Himba (mean age: 27 yrs). Study 4: 71 traditional Himba (mean age: 22 yrs), 57 urban Himba (mean age: 25 yrs), 53 urban British (mean age: 23 yrs). Study 5: 32 traditional Himba (mean age: 25 yrs), 29 urban Himba (mean age: 27 yrs), urbaniBritish (mean age: 22 yrs).	No	N/A	Dwelling	Northern Namibian (Himba) city. Northern Nambian (Himba) remote village. Great Britain.	N/A	Flanker task	Between	Study1: traditional versus urbanised Himba have superior distractor suppression. When task was designed to be more engaging in studies 4 & 5, urbanised participants could focus attention similar to traditional Himba.

Reference	Subjects	Baseline	Ego-depletion	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Ottosson & Grahn, 2005	15 elderly (mean age: 86	Yes	No	Resting	Garden. Indoor.	60 minutes	NCPCT	Within	Fewer perspective switches in Garden condition
Sahlin et al., 2016	51 adults (mean age: 45 yrs).	Yes	No	Guided progressive relaxation	Indoor: room. Outdoor 1: park. Outdoor 2: edge of woods.	30 minutes	NCPCT	Within	Fewer perspective switches in Outdoor conditions.
Schutte et al., 2017	17 4-year-olds, 16 5-yr-olds. 17 7- and 8-yr-olds.	No	Jigsaw puzzle (all subjects)	Walk	Nature: trees, flower, vegetation. City: busy streets.	20 minutes	Go/No-go task	Within	Faster RTs in Nature condition. Older versus younger children only performed better in Nature condition.
Sonntag- Öström et al., 2014	20 adults with exhaust disorder (mean age: 42 yrs).	Yes	No	Walk	Nature 1: lake. Nature 2: rock outcrop. Nature 3: forest. Urban: busy street with trees.	10 minutes	NCPCT	Within	Fewer perspective switches in Nature 2 and 3 than Urban condition. More focused reversals in all Nature than Urban conditions.
Stevenson et al., 2019	33 children (mean age: 12 yrs).	Yes	Digit span task (all subjects)	Walk	Rural area. City.	30 minutes	ANT	Within	Faster RTs with lower RT variability in Rural condition.
Tennessen & Cimprich, 1995	72 University students (mean age: 20 yrs).	No	No	Dwelling	Naturalness of home window view	N/A	NCPCT	Between	Fewer perspective switches in green versus urban neighbourhoods.
Zhang et al., 2017	70 University students.	Yes	Reasoning task (all subjects)	Resting in park	Nature: birds and insects. Traffic. Machine: grass mower.	40 minutes	Comple-ment task	Between	Most targets were identified in Nature and least in Machine condition.

Table 1.1. Summarized methodology of the experiments included in the ‘Effect of nature and urban exposures on top-down processes’ section of the chapter. (Notes: ANT = Attention Network Task, NCPCT = Necker Cube Pattern Control Task, SART = Sustained Attention to Response Task).

Effect of nature and urban exposures on top-down processes

To investigate the effects of exposure to natural and urban environments, on top-down processes, numerous experiments applied tasks where the target is presented among several distractors, using distractor suppression as an index of top-down processes. These consistently demonstrated that nature exposure results in superior application of top-down processes. For example, on a flanker task, adults who live in a remote natural versus urbanized environment responded more quickly to the target (de Fockert, Caparos, Linnell, & Davidoff, 2011), demonstrating that adults who live in remote natural environments can suppress distractors more effectively. This is further supported by experiments using the Ebbinghaus Task, where participants compare the size of two circles (targets) that are surrounded with either smaller or larger circles (inducers). If inducers are attended, this creates the illusion that of the two equally sized targets the one that is surrounded with smaller stimuli is larger than the other (see *Fig.* 1.3). However, if the inducers are suppressed, the two targets appear the same size. On these trials, people who live in a remote natural versus urbanized environment reached higher accuracy (de Fockert, Davidoff, Fagot, Parron, & Goldstein, 2007; Caparos et al., 2012; Bremner et al., 2016), indicating more effective suppression of the surrounding task-irrelevant distractor circles and thus superior application of top-down processes. Interestingly, however, when the attention task is engaging, participants who live in an urbanised environment were able to suppress distractors to the same extent as those who live in a remote natural environment (Linnell, Caparos, de Fockert, & Davidoff, 2013), demonstrating that urbanites can but are unlikely to apply top-down processes. In line with this, on Global/Local tasks, adults who live in a remote natural versus urbanised environment had a greater tendency to pair stimuli that match on a local level (Davidoff, Fonteneau, & Fagot, 2008; Caparos et al., 2012). This demonstrates that while people who live in a remote natural environment rely on top-down processes, urban dwellers rely on bottom-up attentional capture.

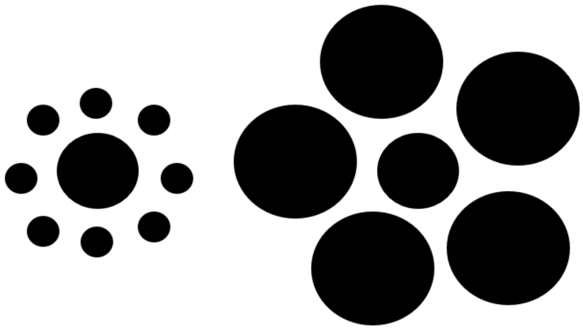

Figure 1.3. An illustration of an example critical trial in the Ebbinghaus task. Two equally sized circles (targets) are surrounded with either smaller (left) or larger (right) stimuli (inducers). If the surrounding stimuli are effectively suppressed, the two targets appear the same size. However, if the surrounding stimuli are not suppressed, they create the illusion that the circle on the left is larger than the one on the right.

Similar to living in a remote natural environment, brief exposure to a natural green versus urban environments has also been associated with more successful application of top-down processes. Indeed, participants detected more targets on visual search tasks after various nature versus urban exposures, such as watching a forest versus urban video (van den Berg, Koole, & van der Wulp, 2003), listening to natural versus traffic or machine noise (Zhang, Kang & Kang, 2017), or viewing a green roof covered in grass and flowers compared to concrete (Lee, Sargent, Williams, & Williams, 2018), demonstrating that exposure to natural stimuli improve top-down processes.

This notion is further supported by studies that used the Attention Network Task (ANT; see *Fig*. 1.4), that was specifically designed to distinguish between three stages of visual attention. These are 1) preparing for an upcoming stimulus (alerting); 2) orienting towards the location of an upcoming stimulus (orienting); and 3) processing a task-relevant stimulus while suppressing congruent or incongruent distractors (executive function; Fan et al., 2002; 2007; Posner & Rothbart, 2007). These studies report that compared to baseline, viewing pictures of green but not urban environments led to more similar RTs on congruent and incongruent trials (Berman, Jones & Kaplan, 2008; Gamble, Howard, & Howard, 2014), illustrating that green exposures improve distractor suppression. Although the reason for this improvement is unclear, Haga, Halin, Holmgren and Sörqvist (2016) showed that when all participants listened to the same noise, those who were informed that they were listening to a noise of a waterfall versus an industrial area did not perform better on the ANT. This demonstrates that the mere belief of being exposed to a natural environment may be insufficient to elicit such results.

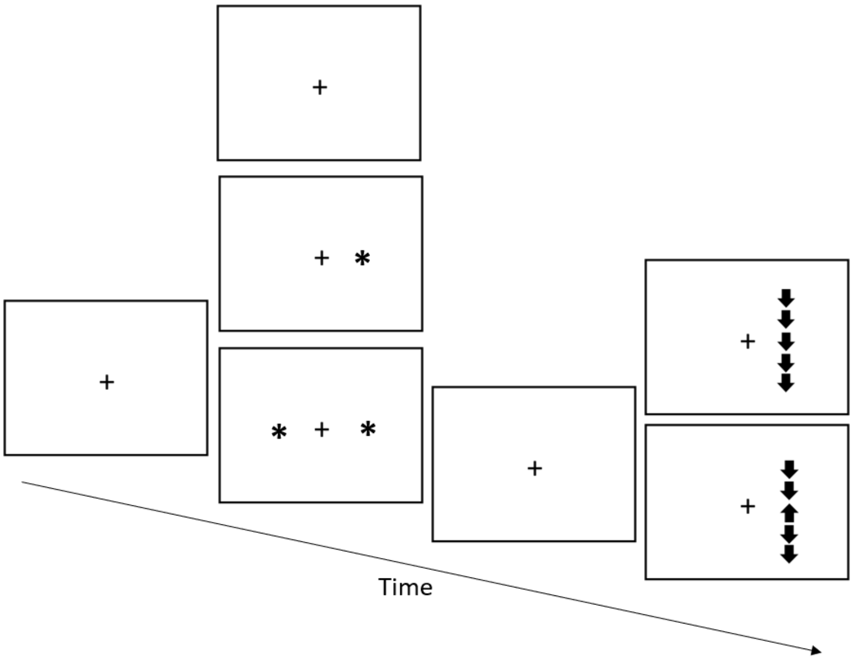

Figure 1.4. An illustration of the display sequence presented in each trial of the Attention Network Task (ANT). After a fixation cross, one of three equally likely cue displays is shown: no cue (top), valid spatial cue (middle) or double cue (bottom). After the fixation cross is presented again, the target array appears, presenting a central arrow with either four congruent (top) or incongruent (bottom) distractor arrows. Participants are asked to report the direction (up, down) of the central arrow as quickly and accurately as possible. Differences in RTs and accuracy for different conditions can distinguish between three stages of visual attention. These are 1) preparing for an upcoming stimulus (alerting); 2) orienting towards the location of an upcoming stimulus (orienting); and 3) processing a task-relevant stimulus while suppressing congruent versus incongruent distractors (executive function; Fan et al., 2002; 2007; Posner & Rothbart, 2007). Alerting is indexed by the difference between double and no cue trials. Orienting is indexed by the difference between valid spatial cue and no cue trials. Executive function is indexed by difference between congruent and incongruent distractor trials.

In comparison with adults, the effect of green exposures on ANT performance is less consistent in children and adolescents. Some studies report superior application of top-down processes after exposure to green versus urban environments. For example, Johnson, Snow, Lawrence and Rainham (2019) reported that 8- to 15-year-olds performed better on the top-down alerting and orienting components of the Combined Attention System Task, a modified version of the ANT, after walking in a park versus city. Others, however, found that nature exposure leads to more general improvements in attention functioning. For example, children who live in a relatively green (Dadvand et al., 2015; 2017) or walked in a rural (Stevenson, Dewhurst, Schilhab, Bentsen, 2019) versus urban area had faster and more stable RTs on the ANT, indicating that benefits of green exposure in children may not be specific to top-down processes. To my knowledge, only Kelz, Evans, Röderer (2015) found no benefit of a natural environment on the ANT performance. They reported comparable ANT performance of 13- to 15-year-olds after attending school with a green versus regular schoolyard for six- to seven-weeks. Notably, the lack of improvement in this experiment may be because schoolyard greenness does not accurately reflect participants' overall green exposure as it does not incorporate the amount of time they spend in a natural setting outside of school.

Similar to distractors presented in spatially distinct locations, exposure to a green environment also boosts suppression of a distracting feature of the target, further supporting the notion that green exposure improves the application of top-down processes. For example, on the traditional Stroop task, RTs were faster after walking along a nature trail but not indoors in an Aquatic Recreational Centre compared to baseline (Bailey, Allen, Herdon, & Demastus, 2018), demonstrating improved distractor suppression. Further support comes from experiments using the Necker Cube Patter Control Task (NCPCT, see *Fig.* 1.5), where a particular perspective of a cube's outline needs to be maintained. Demonstrating that this task measures top-down processes, Hurlbut (2011) showed that participants performed worse on the NCPCT after versus before inducement of ego-depletion that has been shown to diminish top-down processes (Boksem et al., 2005; Van den Linden & Eling, 2006; Faber et al., 2012). Importantly, people who live in a relatively green versus urban neighbourhood reported fewer perspective switches (Tennessen & Cimprich, 1995), indicating more successful suppression of the distracting target feature (Hurlbut, 2011). Likewise, compared to baseline, participants reported fewer perspective switches after walking or resting outdoors in a green versus urban (Sonntag-Öström et al., 2014; Sahlin et al., 2016) or indoor setting (Ottosson & Grahn, 2005; Greenwood & Gatersleben, 2016) as well as while walking on a treadmill while viewing a forest video versus blank wall (Crossan & Salmoni, 2019). Although Hartig, Evans, Jamner, Davis and Gärling (2003) found no improvement in NCPCT performance after exposure to a green environment in a wildlife preserve compared to baseline, the overall evidence supports the notion that green exposures improve distractor suppression, indexing enhanced application of top-down processes.

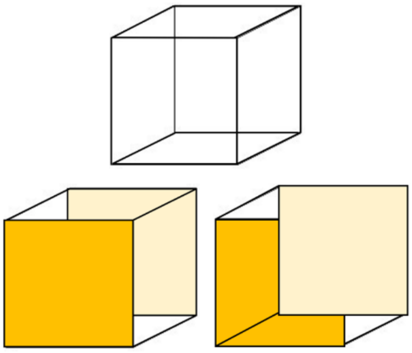

Figure 1.5. An illustration of the Necker Cube Patter Control Task (NCPCT). The outline of a three-dimensional cube (top) is presented to the participants. This can be viewed from two perspectives (shown on the bottom). The cube on the bottom left illustrates the first perspective where the orange square appears as if it is in front of the yellow square. The cube on the bottom right illustrates the second perspective where the yellow square appears as if it is in front of the orange square. Participants are asked to maintain one of these perspectives and report each time their perspective switches.

Notably, not every natural environment benefit top-down processes equally. For example, viewing pictures of water scenes presented with sound did not change executive function performance on the ANT compared to baseline (Emfield & Neuder, 2014). Similarly, watching a video showing mainly water scenes did not modulate Stroop performance compared to baseline (Jenkin et al., 2018), indicating that unlike green environments, water scenes may not benefit distractor suppression. Yet, the ability to intentionally reverse perspective of a cube's outlines on the NCPCT was similarly superior after walking in a forest and near a lake versus in a urban environment (Sonntag- Öström et al., 2014), suggesting that water scenes may improve some aspects of top-down processes. Interestingly, while exposure to a forest with clear field of vision and few hiding places decreased the number of perspective switches on the NCPCT compared to baseline, exposure to a forest without clear field of vision and numerous hiding places increased them (Gatersleben & Andrews, 2013). Furthermore, walking on a treadmill while viewing a forest video improved whereas including the additional tasks of hitting oncoming virtual birds and unexpectedly adjusting balance did not affect NCPCT performance

(Crossan & Salmoni, 2019). These highlight that seemingly small factors can influence whether green spaces improve or impair distractor suppression, and thus top-down processes.

Exposure method also modulates the extent to which exposure to a natural environment improves top-down processes. Compared to baseline, NCPCT performance improved more after walking outside in a wooded area versus watching a video of the same environment (Gatersleben & Andrews, 2013), presumably because physical exposure allows the effects of the different (i.e., visual and auditory) features of the natural environment to be combined.

In contrast with green environments, most experiment found that urban exposures, regardless of whether they contain natural features, do not modulate top-down processes on relatively brief attention tasks (Laumann et al., 2003; Berto, 2005; Berman et al., 2008; Emfield & Neider, 2014; Gamble et al., 2014; Sonntag- Öström et al., 2014; Jenkin et al., 2018; Johnson et al., 2019; Stevenson et al., 2019). To my knowledge, only Hartig et al. (2003) reported reduced number of perspective switches on the NCPCT performance after walking in an urban environment relative to baseline, providing some evidence that urban exposure can impair distractor suppression. Overall, this suggests that urban exposures either do not diminish top-down processes, or they do so only in very specific circumstances.

In addition to relatively brief tasks, exposure to green environments also boosts top-down processes on prolonged tasks, such as the Sustained Attention to Response Task (SART) or the Go/No-Go task, where participants are asked to respond to all except one stimulus. For example, children had faster RTs on the SART after walking in a green versus urban environment (Schutte, Torquato, & Beattie, 2017). Similarly, compared to baseline, adults had faster RTs and higher accuracy after viewing pictures of green but not urban environments (Berto, 2005; Craig, Klein, Menon, & Rinaldo, 2015), demonstrating that green exposures improve the ability to apply top-down processes. In contrast with these, Lee et al. (2015) found no improvement on the SART after viewing a green roof. As Lee et al. (2018) in another experiment found enhanced visual search performance after viewing a green roof for 90 seconds, indicating enhanced top-down processes, lack of improvement in Lee et al.'s (2015) experiment suggests that the 40-second exposure used in this experiment may have been too short to evoke similar results.

Interestingly, Lee et al. (2015) found higher RTs variability in the second half of the SART after viewing the concrete roof relative to baseline, suggesting that exposure to a city-like environment reduces the period for which top-down processes can be successfully applied. Notably, as other experiments found no evidence that urban exposures modulate SART performance, this impairment may not generalise to urban environments. Alternatively, it is possible that similar to Hartig et al.'s (2003) results, Lee et al.'s finding indicates that urban exposure might impair top-down processes under certain circumstances only. However, what these circumstances may be remains unclear.

Surprisingly, Georgi et al. (2019) reported that elderly participants who live in Prague versus in non-urban settlements in the Czech Republic had faster RTs on the Go/No-Go task, indexing more successful application of top-down processes. Based on this, they concluded that cities are beneficial for the elderly's ability to apply top-down processes. However, it is unclear how much green space participants were exposed to in everyday life, making it difficult to compare this with Gamble et al.'s (2014) results that brief urban exposure does not modulate top-down processes of the elderly.

In addition to sustained application of top-down processes, the SART and Go/No-Go task also measure response inhibition, another mechanism underpinned by top-down processes (Egner, 2017). Response inhibition is indexed by accuracy on trials where participants needed to withhold a response. In these trials, Craig et al. (2015) found higher accuracy after viewing pictures of natural green but not urban scenes compared to baseline, suggesting that green exposure may also improve response inhibition, further supporting the notion that they boost top-down processes. In contrast, Lee et al. (2015) found no benefit of viewing a green roof, however, as mentioned before this may be because the exposure was too short. Notably, Berto et al. (2005) did not report accuracy on these trials, therefore, neither Craig et al.'s nor Lee et al.'s result regarding green environments has been replicated yet. Importantly, Georgi et al. (2019) found no effect of residency on response inhibition, suggesting, in line with Craig et al. (2015) and Lee et al.'s (2015) results, that cities may not modulate response inhibition, casting further doubt on the notion that urban exposures impair top-down processes.

In summary, exposure to most, but not all, natural environments enhance the application of top-down processes. However, certain natural environments, such as water scenes or forests with many hiding places and no clear field of vision, do not modulate top-down processes. The reason for this distinction remains unclear. In contrast with green environment, most experiments found no effect of urban exposures, casting doubt on the idea that cities modulate top-down processes.

Attention Restoration Theory

Three ideas, the Attention Restoration Theory, 'train the brain' and 'adaptation' notions, have been developed to predict and explain how natural and urban environments modulate top-down processes, each predicting a distinct effect and proposing different underlying mechanisms.

ART (Kaplan & Kaplan, 1989; Kaplan, 1995; 2001) is the most influential and widely tested theory in this field. As previously discussed in the 'Link to theories' section, ART argues that in urban environments, goal-relevant but uninteresting objects often need to be effortfully attended, thus inducing ego-depletion that is thought to diminish subsequent application of top-down processes. In contrast, it argues that natural environments restore top-down processes by resolving ego-depletion and allowing reflection that reduces their internal burden and frees additional central cognitive resources (Basu, Duvall, & Kaplan, 2019). Notably, ART also highlights the importance of natural environments allowing an escape from one's usual environment, being compatible with one's goals and having broad but coherent spatial extent in order to resolve ego-depletion (Kaplan & Talbot, 1983). However, these have been largely overlooked within the literature and therefore, will not be discussed in this chapter.

In summary, ART predicts that urban exposure impairs whereas nature exposure improves top-down processes. Furthermore, it proposes that this effect is underpinned by three key differences between urban and nature exposures. These are: 1) natural environments capture attention more automatically and are processed more effortlessly than cities; 2) natural environments resolve whereas cities induce ego-depletion; and 3) natural environments, but not cities, allow reflection.

As discussed in the 'Effect of nature and urban exposures on top-down processes' section of this chapter, numerous experiments demonstrated that most natural environments enhance the application of top-down processes, providing some support for ART. However, certain natural environments, such as water scenes or forests with many hiding places and no clear field of vision, do not modulate top-down processes, demonstrating that the relationship between natural environments and top-down processes is more complex than predicted by ART. Furthermore, most experiments find no effect of urban exposure on top-down processes, casting doubt on the idea that cities impair these processes. Inaccuracy relating to the effect of nature and urban exposures may be due to ART making incorrect assumptions about how these environments differ and how such differences may affect people's cognitive states. Therefore, next, I will discuss each of the three key differences between exposure to natural and urban environments that were proposed by ART.

The first difference proposed by ART is that natural environments capture attention more automatically and are processed more effortlessly than cities. Automatic attention capture is typically thought to be underpinned by bottom-up processes that promote engagement with salient stimuli. Despite such stimuli being abundant in cities and often scarce in natural settings (Joye & Dewitte, 2018), Grassini et al. (2019) demonstrated that pictures of green versus urban environments evoke larger P1 amplitudes, reflecting enhanced bottom-up attentional capture. In line with this, in a dot probe paradigm, participants responded more quickly and accurately to a simple target presented in the location of a picture displaying a green versus urban environment (Joye, Pals, Steg, & Lewis-Evans, 2014), further supporting the notion that green settings capture attention automatically in a bottom-up fashion. Notably, whether natural environments that do not improve top-down processes also capture attention automatically, or whether automatic attention capture indeed contributes to improved top-down processes after green exposures remains untested.

Experiments focusing on the effort required to process various environments consistently report that both green and non-green natural environments are processed more effortlessly than cities. For instance, on a Go/No-Go task, participants responded more quickly and accurately on trials displaying pictures of sea and mountains versus urban scenes (Rousselet, Joubert, & Fabre-Thorpe, 2005), demonstrating that pictures of natural versus urban environment are processed more quickly and thus more effortlessly. In line with this, eye tracking studies report that compared to cities, pictures of rural (Duport et al., 2017) and various natural environments (Berto et al., 2008; Valtchanov & Ellard, 2015; Duport et al., 2017; Franěk, Šefara, Petružálek, Cabal, & Myška, 2018) elicit fewer fixations and lower blinking rates, indexing reduced cognitive effort (Siegle, Ichikawa, & Steinhauer, 2008), and thus showing that natural settings are processed more effortlessly.

Although the underlying mechanisms of this are not explained within ART, the Perceptual Fluency Theory argues that natural environments are processed effortlessly because unlike cities they contain simple shapes that reoccur on increasingly smaller scales, called fractals (Joye & Van den Berg, 2011). Supporting this argument, cognitively demanding puzzles are perceived as easier as well as are solved more quickly and accurately while viewing pictures that contain many versus few fractals (Joye, Steg, Ünal, & Pals, 2015), indexing that fractals reduce the effort required to process pictures. However, whether fractals indeed contribute to effortless processing of natural environments remains untested. Likewise, it is unclear whether effortless processing indeed contributes to improved top-down processes after exposure to natural green environments.

The second difference proposed by ART is that cities require continuous application of top-down processes, thus evoking ego-depletion whereas natural environments capture attention automatically and effortlessly and therefore resolve it. A key weakness of this proposal is that it only considers the role of top-down processes, despite urban and natural environments differentially modulating several factors that have been linked to ego-depletion. For example, nature exposure consistently induces positive mood (meta-analysis by McMahan & Estes, 2015) and reduces stress (Wang, Rodiek, Wu, Chen, & Li, 2016; Triguero-Mas et al., 2017; Kobayashi et al., 2019), both of which reduce ego-depletion (Tice et al., 2007; Duckworth et al., 2013). Importantly, urban exposures do not consistently modulate positive mood nor stress. This predicts that cities do not induce ego-depletion and thus do not impair top-down processes, a notion that is supported by numerous experiments, unlike ART's prediction that cities impair top-down processes.

Regardless of the underlying factors, several experiments reported more severe ego-depletion after exposure to urban versus natural environments, as predicted by ART. For example, after viewing pictures (van der Wal, Schade, Krabbendam, & Van Vugt, 2013) or videos (Jenkin, Frampton, White, & Pahl, 2018) of urban versus natural environments, participants were less able to resist an immediate small reward in favour of a delayed large reward on the Delay Gratification Task, indicating more severe ego-depletion. Similar results were obtained in children who live in relatively urban versus natural environments (Taylor, Kuo, & Sullivan, 2002), further supporting the link between cities and ego-depletion. Importantly, as these experiments did not include a baseline measure of delay gratification, it remains unclear whether these results are indeed due to cities inducing and natural environments resolving ego-depletion, as proposed by ART.

To investigate whether this disparity in ego-depletion underpins differences in top-down processes after nature versus urban exposures, Hartig et al. (2003) conducted an experiment in which, after performing the NCPCT at baseline, half of the participants completed the Stroop and a binary classification task to induce ego-depletion. Next, all participants walked in either a wildlife preserve or an urban environment and completed the NCPCT again both halfway through and after the walks. Importantly, Hartig et al. found that regardless of ego-depletion, NCPCT performance decreased after the urban walk and did not change after the nature walk relative to baseline, suggesting that the effects of these environments on top-down processes may be independent of ego-depletion. In line with this, as discussed in the ‘Effect of nature and urban exposures on top-down processes’ section, experiments consistently report that nature exposures improve whereas urban exposures do not modulate top-down processes compared to baseline regardless of whether ego-depletion has been induced prior to the exposures, further supporting the notion that the effect of exposures to these environments may be independent of ego-depletion.

The final difference proposed by ART is that exposure to natural but not urban environments allows reflection on unsolved problems, thus reducing their internal burden and freeing central cognitive resources that can then be used to apply top-down processes. In line with this, several experiments demonstrated that ordinary natural scenes that have been shown to improve selective attention also allow reflection (Mayer, Frantz, Bruehlman-Senecal, & Dolliver, 2009; Basu et al., 2019). However, whether reflection indeed contributes to the cognitive benefits of nature exposures remains untested.

Importantly, ART distinguishes between exposure to natural environments and other recreational activities, such as watching television, that despite requiring little effort, are deeply engaging, and therefore are thought not to allow reflection or improve top-down processes (Basu et al., 2019). Although not stated within ART, this suggests that awe-inspiring natural scenes that are also deeply engaging (Joye & DeWitte, 2018) should not elicit reflection nor improve top-down processes. Yet, recent studies showed that awe-inspiring natural environments promote reflection (Jefferies & Lepp, 2012; Pearce, Strickland-Munro, & Moore, 2017) and although their effect on selective attention remains untested, they improve digit span to a similar degree as mundane natural environments that are not deeply engaging (Collado & Manrique, 2020). This suggests that deep engagement does not inhibit reflection nor diminish the cognitive benefits of exposure to natural environments. Interestingly, Collado & Manrique (2020) found that pictures of awe-inspiring but not mundane buildings improved digit span to a similar degree as pictures of natural environments. This shows that unlike proposed by ART, deep engagement may contribute to improvement in top-down processes after nature exposures.

Overall, ART correctly predicts that natural green environments improve top-down processes. However, in contrast with ART, this is unlikely to be underpinned by such environments replenishing central cognitive resources or allowing reflection. Furthermore, whether automatic attention capture or effortless processing of green environment indeed contributes to this effect remains unclear. ART cannot explain why certain natural environments do not modulate top-down processes, demonstrating that ART's prediction that every natural environments improve top-down processes is oversimplified. Although ART accurately predicts that urban exposures deplete central cognitive resources thus inducing ego-depletion, it incorrectly assumes that ego-depletion mediates the relationship between urban exposures and top-down processes, resulting in the incorrect prediction that cities impair top-down processes.

'Cities train the brain' notion

In sharp contrast with ART, Cassarino and colleagues (Cassarino & Setti, 2015; Cassarino, O'Sullivan, Kenny, & Setti, 2018) recently proposed a notion that cities improve the cognitive abilities of the elderly. They argue that unlike rural areas, cities elicit an optimal level of cognitive stimulation by requiring elderly to multi-task and make sense of a complex environment. This trains the brain, improves top-down processes, and builds resilience to cognitive aging.

As discussed in the 'effect of nature and urban exposures on top-down processes' section of this chapter, this notion is supported by Georgi et al. (2019) who found that elderly urban versus non-urban dwellers had faster RTs on the Go/No-Go task, indexing more successful application of top-down processes. However, whether urban living is similarly beneficial for children or young adults remains unclear.

In line with the 'cities train the brain' notion, several experiments demonstrated that cities hinder cognitive aging. For example, elderly who live in an urban versus non-urban settlement were less susceptible to sound induced flash illusion that refers to the perception of two flashes after hearing two beeps even though only one flash was presented, thus indexing superior cognitive function (Hirst, Cassarino, Kenny, Newell, & Setti, 2021). Moreover, elderly urban versus rural dwellers performed better on the Mini Mental State Exam (Gavrila et al., 2009; Nunes et al., 2010; Cassarino et al., 2018) and have been found to have a lower risk of developing Alzheimer’s disease (Russ, Batty, Hearnshaw, Fenton, & Starr, 2012**;** Cassarino & Setti, 2015; Contador, Bermejo-Pareja, Puertas-Martin, & Bertino-León, 2015), demonstrating lower prevalence of cognitive impairment and thus superior cognitive functioning in cities. Notably, however, some studies report an increased (Ma et al., 2016) or similar (Chan et al., 2013) risk of dementia in cities versus rural areas, highlighting that the relationship between cities and cognitive aging may be more complex than proposed by the ‘cities train the brain’ notion.

Notably, this notion does not address whether acute urban exposures have similar benefits to urban living in old age. To my knowledge, this was only investigated by Gamble et al. (2014). They found that similar to young adults, elderly participants did not perform better on the ANT after briefly viewing urban pictures compared to baseline, highlighting that, unlike nature exposure, very short urban exposures do not benefit the elderly’s ability to apply top-down processes. Notably, exposure in this environment only lasted for six minutes, therefore, whether a longer acute urban exposure would carry some benefits for the elderly remains unclear.

Similar to urban dwelling in old age, urban childhoods have also been suggested to contribute to resilience towards cognitive aging (White & Shah, 2019). However, when tested this, Hirst et al. (2021) found that elderly participants with urban versus rural childhoods were more susceptible to sounds induced flash illusion, indexing that rural instead of urban childhoods may build better resilience to cognitive aging.

Although the ‘cities train the brain’ notion focuses on the elderly only, several experiments investigated the effect of childhood environment on young adults. Neuroimaging studies found that adults who were raised in cities versus towns or rural areas have reduced grey matter volume in the PFC (Haddad et al., 2015; Besteher, Gaser, Spalthoff, & Nenadić, 2017; Zhang et al., 2018), suggesting that similar to old age, childhood environment may also modulate top-down processes in adulthood. In line with this, urban upbringing has been linked to increased risk of developing various mental disorders, such as schizophrenia and major depressive disorder (MDD; Krabbendam & Van Os, 2005; Lundberg, Cantor-Graae, Rukundo, Ashaba, & Östergren, 2009), both of which result in comparable PFC alterations as urban upbringing (Benes, Davidson, & Bird, 1986; Drevets et al., 1997) as well as diminished distractor suppression (Broomfield, Davies, MacMahon, Ali, & Cross, 2007; Smucny, Olincy, Eichman, Lyons, & Tregellas, 2013; Joorman & Vanderlind, 2014). This suggests that childhood environment may diminish top-down processes in adulthood.

Notably, the ‘cities train the brain’ notion does not directly address whether natural environments effect cognitive aging or the elderly’s ability to apply top-down process. However, as cities are thought to be beneficial for the elderly due to their complexity, this notion predicts that natural environments are unlikely to build resilience to cognitive aging or enhance the top-down processes due to their reduced complexity. In contrast with this, elderly who live in relatively green versus urban neighbourhoods showed reduced cognitive decline (de Keijzer et al., 2018; Zhu et al., 2019), reported fewer memory complaints (Astell-Burt & Feng 2020) and had lower risk of developing dementia (Astell-Burt, Navakatikyan, & Feng 2020; Paul et al., 2020; Tani, Hanazato, Fujiwara, Suzuki, & Kondo, 2021), suggesting that natural environments also build resilience to cognitive aging. Furthermore, compared to baseline, viewing nature pictures enhanced the elderly’s ability to ignore distractors (Gamble et al., 2014) and gardening enhanced their ability to maintain a particular perspective of a cube’s outlines on the NCPCT (Ottosson & Grahn, 2005), both suggesting that natural environments enhance the elderly’s ability to apply top-down processes. Although the effect observed by Ottosson and Grahn (2005) could be due to exercise that is involved in gardening, several studies have shown that exercise in a natural environment have greater benefit than exercise alone (see Thompson Coon et al., 2011 for review), casting doubt on this idea.

Overall, consistent with the ‘cities train the brain’ notion, urban living during old age seems to improve top-down processes and build resilience to cognitive aging. However, such benefits seem to be specific to old age as urban living during young adulthood and middle age does not benefit top-down processes and urban childhoods may impair top-down processes in adulthood as well as hinder cognitive aging. Furthermore, natural environments also build resilience to cognitive aging and improve top-down processes, demonstrating that the ‘cities train the brain’ notion incorrectly implies that natural environments promote cognitive aging and impair top-down processes.

‘Shifting’ notion

In contrast with ART and the ‘cities train the brain’ notion, the ‘shifting’ notion (Linnell & Caparos, 2020) argues that urban living does not alter the ability to apply top-down processes. Instead, it shifts the mode of attention from a focused towards an exploratory mode that is characterised by sensitivity to a range of stimuli instead of a task-relevant ones only. Therefore, unlike focused mode, exploratory mode of attention does not require the application of top-down processes. Overall, this suggests that central cognitive resources are available for urban dwellers, however, they are not used to apply top-down processes. This shift is thought to occur because exploratory mode of attention is more beneficial in cities where attention needs to be divided between several aspects of the environment, such as traffic, pedestrians, and the road. In contrast with urban living, living in remote natural environments shift the mode of attentional processing towards a focused mode, thus enhancing the likelihood of top-down processes being applied.

Supporting this notion, when an attention task was designed to be engaging, participants who live in urbanised environments were able to suppress distractors to the same extent as those who live in remote natural environments (Linnell, Caparos, de Fockert, & Davidoff, 2013), showing that urban living does not deplete central cognitive resources. Nevertheless, as discussed in the 'Effect of nature and urban exposures on top-down processes' section, numerous experiments found that participants who live in urbanised versus remote natural environments allocated more attention to task-irrelevant distractors (de Fockert et al., 2007; 2011; Davidoff et al., 2008; Caparos et al., 2012; Bremner et al., 2016), demonstrating that urban dwellers prioritise exploratory over focused attention, despite the availability of central cognitive resources. Furthermore, these experiments demonstrated that people who live in remote natural versus urbanised environments are more likely to apply top-down processes, further supporting the 'shifting' notion.

Notably, only the 'shifting' notion proposes a neural system that may underpin differential mode of attention in people who live in urbanised versus remote natural environments. It proposes that urban environments elicit stress that in turn enhances tonic activity in the locus coeruleus, a key regulator of attention functioning (Linnell et al., 2013; Linnell, Caparos, & Davidoff, 2014; Linnell & Caparos, 2020). This results in high sensitivity to external information and exploration of stimuli (exploratory attention) that is underpinned by bottom-up processes, thus reducing the likelihood of top-down processes being applied. In comparison, remote natural environments result in middling levels of tonic activity in the locus coeruleus that promotes task engagement and selective processing of task-relevant information (focused attention) via top-down processes. The locus-coeruleus' involvement is supported by findings that urban living has been shown to increase stress (Thompson et al., 2012) that in turn increases activity in the locus coeruleus (Aston-Jones & Cohen, 2005; McCall et al., 2015). Moreover, eye movements of children who live in an urban versus rural area revealed more widespread scanning of pictures of objects (Köster, Itakura, Yovsi, & Kärtner, 2018), indexing elevated activity in the locus coeruleus (Rajkowski, Kubiak, & Aston-Jones, 1994).

Although the ‘shifting’ notion focuses on chronic exposures only, it is also supported by findings that brief nature exposures consistently improve top-down processes, indexing a shift towards a focused mode of attentional processing. However, whether this indeed reflects increased likelihood of applying top-down processes instead of enhanced ability to do so remains unclear. As discussed in the ‘Selective attention and the environment’ section, most experiments using acute urban exposures find no evidence that cities shift the mode of attentional processing relative to baseline. This suggests that acute urban exposures do not modulate the mode of attentional processing, casting some doubt on the ‘shifting’ notion. An explanation for this may be that urban environments did not induce stress (Gidlow et al., 2016; Davudenko & Peetz, 2017; Kobayashi et al., 2019) and thus did not increase tonic activity in the locus coeruleus. Alternatively, most participants in these experiments are likely to live in urban environments and therefore, according to the ‘shifting’ notion, they were already deploying an exploratory mode of attentional processing prior to the exposures. However, as experiments do not report where participants live, this remains merely speculation.

Overall, the ‘shifting’ notion makes the several correct predictions. It accurately predicts that people who live in remote natural environments are more likely to apply top-down processes than urban dwellers as well as that urban dwellers allocate their attention widely despite their ability to apply top-down processes. Furthermore, brief nature exposures enhance top-down processes, providing further support. So far, the ‘shifting’ notion is only contradicted by findings that acute urban exposures do not modulate the mode of attentional processing. Notably, however, this might be due to most participants already living in cities and thus, according to the 'shifting' notion, are already allocating their attention widely and are unlikely to apply top-down processes.

Alternative explanations

Although ART as well as the 'cities train the brain' and the 'shifting' notions propose a range of explanations for divergent application of top-down processes after nature versus urban exposures, several alternative explanations are unexplored within the literature.

1) Working memory capacity

WMC has also been linked to the success at which top-down processes are applied and there is some evidence that enhancing WMC improves top-down processes (Chein & Morrison, 2010; Coleman et al., 2019), suggesting that enhanced top-down processes after green exposures could be underpinned by improved WMC. In most experiments, WMC was measured using the Digit Span Task, where participants are asked to repeat digit sequences of various lengths in either the same or reverse order as displayed. Importantly, longer correctly recalled sequences index higher WMC.

Using this task, most experiments reported higher WMC after exposure to natural versus urban environments. Indeed, longer sequences were correctly recalled after walking in a park versus urban environment (Taylor & Kuo, 2009) or spending time in a classroom with a view of a natural versus built environment (Li & Sullivan, 2016). Similar results were obtained in participants who generally spend more time outdoors (Ulset, Vitaro, Brendgen, Bekkhus, & Borge, 2017) or live in a relatively green versus urban area (Tennessen & Cimprich, 1995). In line with these, on a Reading Span Task, where participants are asked to recall the last word of a list of sentences, more items were correctly recalled in a room with versus without houseplants (Raanaas, Evensen, Rich, Sjøstrøm, & Patil, 2011). Importantly, several experiments demonstrated that the above results are due to green environments improving WMC. For example, compared to baseline, the length of correctly recalled sequences on the Digit Span Task increased after viewing pictures of a green versus urban environment (Berman et al., 2008; Gamble et al., 2014) or walking on a treadmill whilst watching a forest video versus a blank wall (Crossan & Salmoni, 2019). Similarly, compared to baseline, participants correctly recalled longer sequences after walking (Bailey et al., 2018) or resting (Ottosson & Grahn, 2005) in a green versus inside environment, suggesting that green environments may enhance WMC. To my knowledge, only Schutte et al. (2017) found no benefit of walking in a green versus urban setting on WMC, therefore, the overall evidence suggests that green exposures improve WMC.

Similar to top-down processes, not every natural environment benefits WMC. For example, sequences with comparable length were recalled on the Digit Span Task after viewing pictures of water scenes alone (Emfield & Neider, 2014) or intermixed with pictures of forest, desert, and snow scenes (Grassini et al., 2009) versus cities, suggesting that unlike green environments, non-green natural scenes may not benefit WMC. Furthermore, although walking on a treadmill while viewing a forest video improved digit span compared to baseline, this same exposure with the additional task of hitting oncoming virtual birds and unexpectedly adjusting balance had no effect on Digit Span task performance (Crossan & Salmoni, 2019), demonstrating that similar to top-down processes, a secondary task can counteract the benefit of green environments on WMC.

In comparison with green environments, most experiments find no effect of urban exposure on WMC compared to baseline (Berman et al., 2008; Grassini et al., 2009; Mayer et al., 2009; Emfield & Neider, 2014; Gidlow et al., 2016; Li & Sullivan, 2016; Crossan & Salmoni, 2019), illustrating that similar to top-down processes, cities do not affect WMC. Importantly, however, Collado and Manrique (2020) demonstrated that viewing pictures of awe-inspiring but not mundane buildings improved WMC compared to baseline, suggesting that exposure to awe-inspiring urban scenes may benefit WMC. However, this has not yet been tested.

Overall, there are numerous similarities between the effects of natural and urban environments on top-down processes and WMC. For instance, they are both improved by green environments but not water scenes or mundane urban environments. This suggests that enhancement of WMC could contribute to improved top-down processes after green exposures. However, despite several experiments measuring both WMC and top-down processes, the link between the effect of green exposures on these two processes has been overlooked.

2) Mood

Similar to WMC, mood has also been shown to influence the success at which top-down processes are applied. Numerous experiments have consistently shown more positive and less negative mood after green versus urban exposures via pictures (Berman et al., 2008; Mayer, Frantz, Bruehlman-Senecal, & Dolliver, 2009; Grassini et al., 2019), sounds (Jo et al., 2019) or walking (Hartig et al., 2003; Berman et al., 2008; Mayer et al., 2009; Sonntag-Öström et al., 2014; Song et al., 2014; Davudenko & Peetz, 2017). Importantly, however, unlike green exposures, positive mood diminishes top-down processes (Breishbach & Goschke, 2004; Rowe et al., 2007), illustrating that positive mood is unlikely to underpin enhanced top-down processes after green exposures.

Stress levels are also reduced by green versus urban exposures via videos (de Kort, Meijinders, Sponselee, & IJsselstejin, 2006; Wang et al., 2016), sounds, (Alvarsson, Wiens, & Nilsson, 2010; Benfield, Taff, Newman, & Smyth, 2014) or walking (Hartig et al., 2003; Song et al., 2014; Davudenko & Peetz, 2017**;** Triguero-Mas et al., 2017; Kobayashi et al., 2019). Notably, reduced stress levels in some cases result in enhanced top-down processing, however, this effect is less consistent than the effect of green exposures on top-down processes. This suggests that although reduced stress levels could occasionally contribute to improved top-down processes after green exposures, they are unlikely to account for the entire effect. Despite numerous experiments investigating the effect of exposure to natural environments on both top-down processes and stress levels, to my knowledge, the association between the two has not yet been investigated.

3) Air pollution

In addition to the factors discussed above, physical differences between natural and urban environments could also mediate the relationship between green exposure and improved top-down processes. Notably, natural and urban environments differ in numerous ways (Kuo, 2015), however, in this chapter, I will focus on air pollution that also has been shown to modulate attention functioning. Air pollution is a complex mixture of chemicals, volatile organic compounds, metals, and particulate matter of biomaterial (Schauer et al., 2006; Block et al., 2012; Genc, Zadeoglulari, Fuss, & Genc, 2012) that is typically more abundant in cities than natural settings (Hartig, Mitchell, De Vries, & Frumkin, 2014; Nowak, Hirabayashi, Bodine, & Greenfield, 2014; Hirabayashi & Nowak, 2016).

Importantly, chronic exposure to relatively high levels of various air pollutants, such as particulate matter$_{2.5}$ ($PM_{2.5}$), particulate matter$_{10}$ (PM_{10}), ozone (O_3) or nitrogen oxides (NO_x), has been associated with reduced volume of the PFC (Calderón-Garcidueñas et al., 2016; Power et al., 2018; Gale et al., 2020), a region that is thought to underpin the application of top-down processes. This suggests that top-down processes may be diminished by chronic air pollution exposure. Indeed, lifetime exposure to relatively high versus low levels of black carbon has been associated with poorer response inhibition in 7- to 14-year-old children (Chiu et al., 2013). Similarly, exposure to relatively high versus low levels of $PM_{2.5}$ between the ages of 4 and 7 years has been linked to a reduced ability to ignore incongruent distractors in 7- to 10-year-old children (Rivas et al., 2019), indexing diminished top-down processes. In contrast, Sunyer et al. (2017) found that attending school in an area with relatively high versus low levels of nitrogen dioxide is associated with slower overall RTs on the ANT, suggesting that the effects of chronic air pollution exposure on attention may be more general than the above studies suggest. Nevertheless, these results demonstrate that, similar to living in a relatively urban area, regular exposure to relatively high air pollution levels results in poorer attention functioning. Importantly, Dadvand et al. (2015) found that indoor elemental carbon levels explain 20-65% of the association between school greenness and RTs variability on the ANT of 7- to 10-year-old children, demonstrating that air pollution contributes to the weakened top-down processes of urban dwellers. This suggests that air pollution should also be considered by theories about how living in relative urban and green environments modulate attention functioning.

In contrast with chronic exposures the effect of brief air pollution exposure on top-down processes is less consistent. For example, Shehab and Pope (2019) found that distractor suppression on the Stroop task was unaffected by $PM_{2.5}$ exposure. However, the ability to identify targets on a visual search task reduced after $PM_{2.5}$ exposure via commuting but not a burning candle compared to baseline, demonstrating the inconsistent effect of acute air pollution exposure on top-down processes. Interestingly, Faherty et al. (2021) found that proactive control was impaired several hours but not immediately after a one-hour exposure to diluted diesel exhaust, indicating that a delay may be necessary for air pollution to impair top-down processes. This could explain why chronic air pollution exposure is more consistently associated with poorer attention functioning than acute exposure. Furthermore, this suggests that urban exposures could impair top-down processes several hours after the exposure, a notion that has not yet been investigated. Notably, Faherty et al. found no effect of clean air exposure neither several hours nor immediately after the exposure suggesting that low air pollution levels during acute green exposures is unlikely to account for the subsequent improvement in top-down processes.

Overlooked within the selective attention literature

Emotional attention capture has been entirely overlooked within the literature despite numerous evidence suggesting that nature versus urban exposures may differentially modulate attention allocation towards emotional stimuli. For example, living in (Lederbogen et al., 2011), as well as briefly viewing pictures of (Kim et al., 2010) urban versus rural environments has been associated with enhanced activity in the amygdala, a region implicated in emotional attention capture. Moreover, walking in (Song et al., 2014; Hassan et al., 2018), viewing a video of (Wang et al., 2016) as well as listening to the sound of (Jo et al., 2019) urban versus natural environments leads to elevated anxiety levels, that has been linked to enhanced attention allocation to negative stimuli (see Bar-Haim et al., 2007 for review). Considering the link between emotional attention capture and amygdala activity as well as anxiety, these suggest that exposure to a urban versus natural setting may increase attention allocation to emotional, particularly negative stimuli. As attention allocation towards emotional stimuli can be inhibited by top-down processes, this notion is further supported by findings that nature exposure enhances top-down processes, that in turn can inhibit emotional attention capture.

In addition to urban exposures in the present, urban upbringing may also affect emotional attention capture. Indeed, adults with urban versus non-urban childhoods show enhanced activity in the amygdala (Streit et al., 2013), the region that underpins emotional attention capture. Moreover, patients with schizophrenia and MDD, populations characterized by amygdala hyperactivity (Krishnan & Nestler, 2010; Pankow et al., 2013), show enhanced attention allocation towards negative stimuli compared to healthy controls. For example, these patient groups respond faster to a simple target line presented in the location of a negative versus positive or neutral stimulus (Donaldson, Lam, & Mathews, 2007; Bourke, Douglas, & Porter, 2010) and report the colour of negative words more slowly (Bentall & Kaney, 1989; Broomfield, Davies, MacMahon, Ali, & Cross, 2007; Peckham, McHugh, & Otto, 2010; Besnier et al., 2011) than healthy controls. These suggest that urban upbringing may also enhance emotional attention allocation to emotional, particularly negative stimuli.

In summary, despite numerous experiments investigating the effect of nature and urban exposures on visual attention, several avenues of research are still unexplored. For example, it is unclear whether nature and urban exposures modulate signalling to apply top-down processes, whether top-down processes are applied proactively or reactively or attention allocation towards emotional stimuli.

Behavioural adjustment

In everyday life, people often adjust their behaviour based on recent feedback or events in order to enhance success on a task or to avoid accidents. For example, stepping in front of a car after forgetting to check for oncoming traffic is likely to result in a pedestrian adjusting their behaviour by taking additional time to look for vehicles the next time they need to cross a road to ensure that they will not be stepping in front of a car again.

In the lab, behavioural adjustment is indexed by changes in reaction times. For example, on the Stroop task, participants' reaction times on incongruent trials gets faster a few trials into a block, indicating that participants adjusted their behaviour to cope with interference of word meaning on colour naming (Henik, Bibi, Yanai, & Tzelgov, 1997). Another common example of behavioural adjustment is slowing of responses after an erroneous versus correct response, called post-error slowing (PES; Rabbit, 1966; Laming, 1969). This slowing is thought to reflect additional time used to increase confidence in judgment in order to achieve greater success on the trial following an error (Dutilh et al., 2012; Valadez & Simons, 2017; Schroder et al., 2019).

Notably, while PES is present in a range of tasks, it is typically measured using the Go/No-Go task, where a series of stimuli are presented (see *Fig*. 1.6), and participants are asked to respond to all except for the target. When the target is presented, they are instead asked to withhold their response. Importantly, behavioural adjustment is underpinned by the medial frontal cortex, including the ACC (Cohen, Botvinick, & Carter, 2000; Carter & van Veen, 2007; Li et al., 2008; Mansouri et al., 2016).

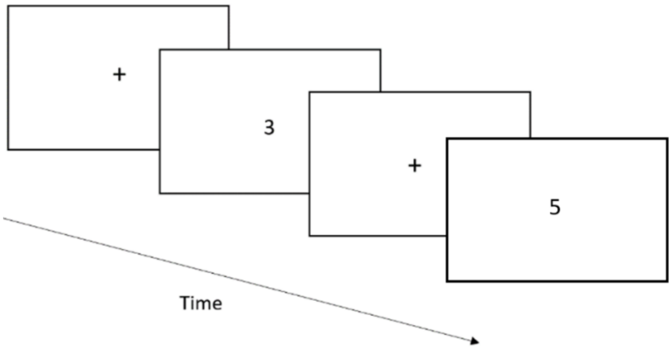

Figure 1.6. An illustration of an example trial of the Go/No-go task, where a series of stimuli (in this example digits) are presented. Participants are asked to respond to all digits except the target. When the target is presented, they are asked to withhold their response.

Behavioural adjustment and mood

Similar to selective attention, behavioural adjustment is also influenced by mood to some extent. For instance, anxious versus non-anxious participants display greater PES (Núñez-Peña, Tubau, & Suárez-Pellicioni, 2017; Voegler et al., 2018), indexing greater behavioural adjustment. Further support comes from EEG studies that investigated the error related negativity (ERN/Ne) ERP component that is not only elicited by errors (Luu, Tucker, & Makeig, 2004; Maier, Di Pellegrino, & Steinheuser, 2012) but is also indicates the generation of PES (Wang et al., 2015). These studies found that anxious versus non-anxious participants also show greater ERN/Ne amplitude (Hajcak, McDonald, & Simons, 2003, Pailing & Segalowitz, 2004; Olvet & Hajcak, 2008), suggesting the generation of greater PES and thus greater behavioural adjustment. In contrast with anxiety, general negative and positive moods do not modulate PES (Hajcak et al., 2004; Olvet & Hajcak, 2012; Paul et al., 2016), demonstrating that the above findings are specific to anxiety.

Behavioural adjustment and ego-depletion

In contrast with anxiety, ego-depletion diminishes behavioural adjustment. Indeed, PES has been shown to disappear with time on prolonged reaction time tasks, such as flanker and Simon tasks (Lorist, Boksem, & Ridderinkhof, 2005; Boksem, Meijman, & Lorist, 2006), indicating diminished behavioural adjustment. Furthermore, interference by incongruent distractors increased with time on a Simon task (Lorist et al., 2005), where participants are asked to respond using their left or right hand to targets presented on either the congruent or incongruent side of the screen (Simon & Small, 1969). This demonstrate that participants found it harder to adjust their behaviour in order to match the difficulty of the task as time passed, further supporting the notion that ego-depletion impairs behavioural adjustment. In line with this, amplitude of the ERN/Ne ERP component also diminishes with time on prolonged tasks (Lorist et al., 2005; Boksem et al., 2006), suggesting that ego-depletion diminishes generation of PES and reduces behavioural adjustment.

Behavioural adjustment and the environment

Unlike selective attention, no experiment to our knowledge has investigated the effect of urban and natural environments on behavioural adjustment. However, several neuroimaging studies have shown that these environments affect the function and structure of the frontal cortex including the ACC, regions that underpin behavioural adjustment (Cohen et al., 2000; Carter & van Veen, 2007; Li et al., 2008; Mansouri et al., 2016). For example, adult who were raised in urban versus non-urban areas have been found to have reduced grey matter volume of their frontal cortex (Haddad et al., 2015; Besteher, Gaser, Spalthoff, & Nenadić, 2017; Zhang et al.,

2018) and show enhanced activity in the ACC during social stress (Lederbogen et al., 2011). Although it is unclear how changes in the grey matter volume of the frontal cortex modulates PES, increased activity in the ACC has been linked to greater PES magnitude (Kerns et al., 2004; Chevier & Schachar, 2010), suggesting that chronic childhood exposure to urban versus rural environments may increase PES magnitude, indexing greater behavioural adjustment.

In contrast with these, the effect natural environments is slightly unclear. Some experiments found that nature exposures, such as listening to the sound of a forest (Jo et al., 2019) and viewing roses (Song, Igirashi, Ikei, & Miyazaki, 2017) or green foliage (Park et al., 2016), reduced activity in the frontal cortex. Igarashi, Song, Ikei and Miyazaki (2015), however, found that compared to viewing pictures of plants, physically looking at a foliage houseplant increase activity in the frontal cortex. Although greater activity in the frontal cortex has been linked to greater PES magnitude (Kerns et al., 2004; Klein et al., 2007; Chevier & Schachar, 2010), as nature exposure has an inconsistent effect on activity in this region, it is unclear how nature exposure may modulate behavioural adjustment.

Further support for the idea that urban and natural environments influence behavioural adjustment comes from mental disorders. Living in urban versus rural or less- versus more-green environments both as children and adults has been linked to an increased risk of schizophrenia, mood disorders, including depression and anxiety disorders (Lundberg et al., 2009; Peen et al., 2010; Sørensen et al., 2014; Engemann et al., 2018; 2019; 2020; Gascon et al., 2018; Liu et al., 2019; Perrino et al., 2019), that influence behavioural adjustment. Indeed, patients with depressive and anxiety disorders display greater PES (Compton et al., 2008; Núñez-Peña et al., 2017; Voegler et al., 2018), suggesting that urban versus natural environments may promote greater behavioural adjustment. However, patients with schizophrenia display reduced PES (Storchak, ehlis, & Fallgatter, 2021), indicating that the opposite pattern may be the case.

Theories

Similar to cognitive control, no theories have been developed to directly address the effect of urban and natural environments on behavioural adjustment. Nevertheless, ART (Kaplan & Kaplan, 1989; Kaplan, 1995; 2001) makes some important predictions that might be applicable to behavioural adjustment as well. ART argues that urban environments induce whereas natural environments resolve ego-depletion, that has been shown to impair behavioural adjustment (Lorist et al., 2005; Boksem et al., 2006). Although it is unclear whether urban exposures indeed induce while nature exposure resolve ego-depletion due to lack of baseline measurements, several experiments have shown that ego-depletion is indeed more severe after urban versus nature exposures (Taylor et al., 2002; van der Wal et al., 2013; Jenkin et al., 2018). Therefore, this implies that urban versus nature exposures may result in smaller PES magnitude, indicating smaller behavioural adjustment.

In contrast with this prediction, urban versus nature exposures have been shown to result in higher levels of anxiety (Song et al., 2014; Wang, Rodiek, Wu, Chen, & Li, 2016; Jo et al., 2019) that has been linked to greater PES (Núñez-Peña et al., 2017; Voegler et al., 2018). In contrast with ART, this suggests that urban exposures may result in greater PES magnitude than nature exposures, indexing greater behavioural adjustment.

Well-being

Well-being a broad construct that refers to positive indicators of psychological adjustment, such as positive emotions, in the absence of negative indicators of maladjustment, such as negative emotions, psychological symptoms or diagnoses (Houben, Van Den Noortgate, Kuppens, 2015). Typically, well-being is split into two categories; hedonic well-being that has been generally defined as the presence of positive and the absence of negative mood, and eudemonic well-being that focuses on satisfaction with and meaningfulness of life (Ryan, Huta, & Deci, 2008; McMahan & Estes, 2011).

Well-being is modulated by several factors. For example, people with lower socioeconomic status (SES) report lower overall well-being (Sainz et al., 2020) as well as greater distress symptoms (Huurre, Aro, & Rahkonen, 2003), indexing poorer well-being. Similarly, participants with higher body mass index (BMI), a measure of body weight, also report poorer overall well-being (Groessl, Kaplan, Barrett-Connor, & Ganiats, 2004; Zayed, Ahmed, Van Niekerk, & Ho, 2017), life satisfaction (Hawker, 2012; Zayed et al., 2017) as well as anxiety and depressive symptoms (Hawker, 2012), suggesting that greater body weight also results in poorer well-being.

Well-being and the environment

Methodology used in experiments investigating the effect of nature and urban exposures on well-being

Similar to SES and BMI, numerous experiments demonstrated that well-being is also affected by our environment (see McMahan & Estes, 2015 for review). Methodology used by these experiments has been very similar to that used by experiments investigating selective attention. For example, participants were exposed to a range of natural environments, including gardens, playing fields, footpaths, forests, parks, water scenes, and beaches, all of which were very natural with few human-built objects. In contrast, urban environments such as streets among various buildings such as offices or houses, predominantly containing traffic and people. Additionally, these occasionally included some form of vegetation, such as trees. Typically, physical exposures to and recordings of these environments occurred during summer, often on sunny days. Consequently, the effects of these environments on well-being during cold or wet days remains unclear. In addition to comparing natural versus urban environments, some experiments compared the effect of natural and indoor spaces, such as concrete parking garage, or the effect of several natural settings to each other. As these also contribute to our understanding of how natural environments modulates top-down processes, they will be discussed in this chapter too. Summarized methodology of the experiments included in the 'Effect of nature and urban exposures on well-being' section of this chapter is shown in *Table* 1.2.

Exposures to natural and urban environments were delivered in various ways including physical exposures, such as walking or viewing while sitting, as well as artificial exposures, such as listening to sound or viewing videos or pictures. The most popular exposure method was walking but viewing pictures was also common. Importantly, artificial methods limited participants' experience to visual and auditory aspects of these environments. Therefore, the effect of other features of natural and urban environments has been neglected.

Exposure lengths varied greatly from seventy-five milliseconds to three hours and ten minutes, with an average length of 21 minutes (s.d. = 38). Notably, physical exposures were longer (mean = 33 minutes, s.d. = 47) while artificial exposures were shorter (mean = 6 minutes, s.d. = 6) than this. Additionally, numerous experiments also investigated the effect of prolonged exposures that lasted for several days or the consequence of living in a relatively green versus urban area.

In several studies, well-being was measured using self-report questionnaires, such as the Positive and Negative Affect Scale or the Depression, Anxiety and Stress Scale, where participants needed to report some aspect of their well-being either at the present or over a certain period. While these are well validated, self-report questionnaires carry several disadvantages. For example, participants may remember certain events better than others (memory bias) or place a greater emphasis on the end versus beginning of the tested period (heuristic bias; Schwarz & Clore, 1983; Frederickson, 2000). To compensate for these, most experiments conducted a baseline measure and compared the difference between baseline and post-exposure measures after exposures to various environments. Notably, this also had the added advantage of seeing which direction various exposures modulated well-being. Additionally, avoiding the disadvantages of self-report questionnaires, several experiments used more objective physiological measures, such as skin conductance or heart rate or computed tasks, where participants were asked to either recognise expression of various emotions or evaluate the valence of Chinese pictographs. Notably, several experiments induced stress prior to exposures to various environments, allowing them to investigate how these environments modulate stress recovery.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Al-Barrack et al., 2017	40 people (mean age: 22 yrs).	No	No	Walk	Nature: quite green garden. Semi-nature: café with both in and outdoor seating. Urban: crowded supermarket.	5 minutes	EEG. Alpha levels indexed meditation levels.	Within	Higher meditation in Nature versus Urban condition.
Alvarsson et al., 2010	40 University student (mean age: 27 yrs).	Yes	Mental arithmetic (all subjects)	Sound	Nature: fountain and bird tweeting. Loud traffic noise. Quiet traffic noise. Ambient noise.	4 minutes	High frequency HRV, skin conductance	Between	Quicker skin conductance recovery in Nature condition. No heart rate effect.
Aspinall et al., XXX	12 University students (mean age: 30 yrs).	No	No	Walk	Nature: playing field with trees. Urban: shopping street with many people, commercial district with heavy traffic, pedestrians, and high noise levels.	25 minutes	EEG. Brain activity was classified as excitement, frustration, engagement, meditation.	Within	Lower frustration, engagement, arousal and higher meditation in Nature condition. Higher engagement when moving from Nature to Urban condition.
Bailey et al., 2018	10 University students (mean age: 20 yrs).	No	No	Walk	Nature: nature trail. Indoors: Aquating Recreational Centre.	30 minutes	EEG. Brain activity was classified as focused, interest, enjoyment, anxiety, relaxation, Or meditative state.	Within	Higher meditative state and relaxation in Nature condition.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Beil & Hanes, 2013	15 adults (mean age: 42 yrs).	Yes	Yes	View	Very natural, mostly natural, mostly built, very built.	20 minutes	Alpha-amylase, cortisol, PSS.	Between	Lower alpha-amylase and stress levels in Nature conditions.
Benfield et al., 2014	133 undergraduate students (age: 19 yrs).	Yes	Yes	Sound	Nature: birds and leaves rustling. Voice: birds, leaves rustling and voices. Motorized: birds, leaves rustling and motorised crafts.	3 minutes	BMIS	Between	Mood recovery in Nature condition. Mood did not change in Voices condition. Mood decreased in Motorized condition.
Berman et al., 2008	Study 1: 38 University students (mean age: 23 yrs). Study 2: 12 University students (mean age: 24 yrs).	Yes	No	Study 1: walk. Study 2: pictures	Study 1: Nature: arboretum. City: downtown. Study 2: Nature: Nova Scotia. City: Ann Arbor, Detriot, Chicago.	Study 1: 50-55 minutes. Study 2: 10 minutes	PANAS	Within	Mood improved in Nature condition.
Beukeboom and Tanja-Dijkstra, 2012	457 adolescents and adults (mean age: 53 yrs).	No	Subjects were patients awaiting radiology treatment.	Room	Room with plant, picture of plant or no plant.	N/A	POMS, STAI (scores combined into "stress" variable).	Between	Higher stress in No plant condition.
Cole & Hall, 2010	531 people	No	No	Walk	High vs low congestion areas	N/A	Self-reported stress.	Between	No effect.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Davudenko & Peetz, 2017	161 University students (mean age: 23 yrs).	Yes	No	Walk	Nature: along a river. City: campus.	10 minutes	Relaxation, sadness, self-rated happiness, stress.	Between	Greater stress reduction and positive mood improvement in Nature condition.
De Kort et al., 2006	80 Univeristy students (mean age: 24 yrs).	Yes	Yes	Video on large or small screen	Nature: vegetation, animals, water.	10 minutes	HR, PANAS, skin conductance, ZIPER.	Between	Lower skin conductance and qucker inter-beat-interval recovery in large screen condition. Negative mood decreased and positive mood increased in both conditions.
Gidlow et al., 2016	38 adults (mean age: 41 yrs).	Yes	No	Walk	Green: country park within city. Blue: footpath along canal with vegetation. City: quiet residential streets with low traffic.	30 minutes	Cortisol, HR, HRV, TMD.	Between	No effect.
Grassini et al., 2009	32 University students (mean age: 25 yrs).	No	No	Pictures	Nature: desert, forest, snow and water. City: without numbers, letters and faces.	1200 ms	EEG	Within	Lower power of delta, theta, high alpha (11-13Hz), beta activity and high power of low alpha (8-11hz) activity in Nature condition.
Hartig et al., 2003	112 University students (mean age: 21 yrs).	Yes	Stroop and binary classification tasks (half of subjects)	Viewing and walk	Nature group: sitting with view of trees then walking in wildlife reserve vs Urban condition: sitting with nedow view then walking among offices in a retail area.	50 minutes	Blood pressure, OHS, ZIPER.	Between	Steeper blood pressure decline after viewing trees, and walking in nature versus city. Positive mood increased in Nature and decreased in Urban condition. Anger and aggressiveness decreased in Nature and increased in Urban condition.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Hassan et al., 2018	60 University students (mean age: 20 yrs).	Yes	Yes	Walk	Nature: bamboo forest. City.	15 minutes	Blood pressure, POMS, STAI.	Within	Lower blood pressure and anxiety, higher positive mood in Nature condition.
Hedblom et al., 2019	154 adults (mean age: 27-28 yrs).	No	Mild electric shock (all subjects)	Pictures with auditory and olfactory stimulation	Unmanaged nature: forest. Managed nature: park. City.	3 minutes	Skin conductance	Between	Lower skin conductance in Nature conditions.
Heitanen et al., 2006	Study 1: 36 high school students (mean age: 17 yrs).	No	No	Pictures	Range between very natural and very urban.	300 and 1000 ms	Emotional facial expression recognition task.	Within	Study 1: faster recognition of happy versus disguist expressions in Nature condition at 300 ms presentation. No effect at 1000 ms presentation.
Holt et al., 2019	207 University students	No	No	Varied	Nature: area containing element of living systems including plants and animals across all degrees of human management.	One month	PSS. Time spent in natural spaces.	Between	Active green space use was associated with higher happinnes and lower stress. No association with passive green space use.
Jo et al., 2019	29 female Univeristy students (mean age: 22 yrs).	No	No	Sound	Nature: forest. City: traffic.	60 seconds	HR, HRV, POMS.	Within	Higher relaxation, comfort, overall mood as well as lower heart rate and ratio of low-frequency to high-frequency heart rate in Nature condition.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Joye et al., 2014 (Study 1)	95 University students (age: 18-25 yrs).	No	No	Pictures	Nature: vegetation. City: streetscapes.	75 milliseconds	Evaluating pleasantness of Chinese pictographs	Within	Pictographs were evaluated more positively in Nature condition.
Kobayashi et al., 2019	74 University students (age: 20-29 yrs).	Yes	No	Walk	Nature: forests. Urban: city centre, railway station.	15 minutes	Cortisol	Within	Lower cortisol in Nature condition.
Korpela et al., 2002	12 male adults (age: 37-55 yrs).	Yes	No	Pictures	Nature: garden in large park. City: concrete parking garage.	450 and 1450 milliseconds	Affective vocal expression recognition task.	Within	Faster recognition of happy versus angry expression in Nature condition.
Li et al., 2007	12 male adults (age: 37-55 yrs).	Yes	No	Trip	Nature: forest. Control: everyday environment.	3 days. Day 1: 2 hours. Day 2: 4 hours.	POMS	Between	Increased vigour, decreased anxiety, depression and anger in Nature condition.
Lohrn et al., 1995	96 adults (age: 18-46 yrs).	Yes	Simple reaction time task	Room	With or without houseplant.	Throughout session	Blood pressure, pulse, ZIPER.	Between	Lower blood pressure in Plant condition.
Lyu et al., 2019	60 male University students (age: 19-24 yrs).	Yes	No	Trip	Nature: bamboo forest. City.	3 days	Blood pressure, corticosterone, HR, POMS.	Between	Lower negative mood, HR, blood pressure, corticosterone levels, TMD and higher positive mood in Nature condition.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Marselle et al., 2019	1516 adults (age: most 55 yrs or older).	Yes	No	Walk	N/A	N/A	MDI, PANAS, PSS, WEMWS. Membership of nature walk group.	Between	Group walking was linked to greater psycologicalh resilience, positive mood, mental well-being and lower stress, depression, negative mood. Group walking frequency was linked to lower stress, depression, negative mood and greater resilience, positive mood, mental well-being.
Martens et al., 2011	96 people (mean age: 38 yrs).	Yes	No	Walk	Wild vs tended forest.	30 minutes	Well-being question-naire	Between	Greater improvement in mood in Tended Forest condition.
Mayer et al., 2009	Study 1: 76 University students. Study 2: 92 University students. Study 3: 64 Univeristy students.	No	No	Study 1: walking then sitting. Studies 2 and 3: walk and video.	Study 1: Nature: woods with creek. City: buildings and parking lot. Study 2 and 3: Nature: arboretum. City: busy metropolitan street.	Study 1: walk: 10 minutes, rest: 5 minutes. Study 2 and 3: 10 minutes.	PANAS	Between	Studies 1 and 2: more positive mood in Nature condition. Study 2: more negative mood in Virtual Urban than other conditions. Study 3: more positive mood after walking in versus viewing pictures of nature.
McFarland et al., 2008	373 University students.	No	No	Use	N/A	N/A	Frequency of green space use. Quality of life.	Between	Positive correlation between green space use and overall and affective (not cognitive) quality of life.
Park et al., 2010	12 male University students (mean age: 22 yrs).	Yes	No	Viewing and walk.	Nature: forest. City.	View: 14 minutes. Walk: 16 minutes.	Blood pressure, cortisol, POMS, pulse rate.	Within	Lower blood pressure, cortisol, pulse and negative POMS subscales scores, Higher vigor in Nature condition.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Parsons et al., 1998	150 University students (mean age: 20 yrs).	No	Yes	Stimulated driving	Nature: forest. Golf course. Built. Mixed.	20 minutes	Blood pressure, EMG, HR, skin conductance	Between	During driving: highest skin conductance in Built condition. After driving: quicker heart rate and pulse recover in Forest and Golf vs Built condition after passive stressor. Quicker heart rate and pulse recover in Built vs Golf condition after active stressor. Greatest skin conductance recovery in Golf condition. No EMG effect.
Saito et al., 2019	17 males (mean age: 40 yrs).	No	Static hand grip exercise.	Viewing	Unmanaged vs managed forest.	15 minutes	BDI, blood pressure, cortisol, HR, Neo Five-Factor Inventory.	Within	HR variability increased in Unmanaged condition and decreased in Managed condition.
Shanahan et al., 2016	1538 adults (age: 18-70 yrs).	No	No	Varied	N/A	Past week	DASS. Time spent in natural spaces.	Between	Spending at least 30 minutes in natural setting was linked to lower risk of depression and high blood pressure by 7% and 9% respectively.
Smyth et al., 2008	8890 people.	No	No	Dwelling	N/A	N/A	Life satisfaction. Neighbourhood greenness.	Between	Greater neighbourhood greenness was associated with greater life satisfaction.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Song et al., 2014	17 male University students (mean age: 21 yrs).	Yes	No	Walk	Nature: urban park. City.	15 minutes	HRV, POMS, STAI.	Within	Lower HR, HRV, anxiety and higher relaxation in Nature condition.
Sonntag-Öström et al., 2014	20 adults with exhaust disorder (mean age: 42 yrs).	Yes	No	Walk	Nature 1: lake. Nature 2: rock outcrop. Nature 3: spruce forest. City: busy urban street encompassed by birch trees.	10 minutes	Blood pressure, HR, heart rate recovery, POMS, ZIPER.	Within	Higher relaxation and happiness in Nature conditions.
Thompson et al., 2012	25 adults (mean age: 43 yrs).	No	No	Dwelling	Level of greenness	At least 12 months.	Cortisol, PSS, WEMWS.	Between	Steeper cortisol slope was associated with higher greenness level. Negative association between stress greenness level.
Triguero-Mas et al., 2017	26 adults (mean age: 44 yrs).	Yes	No	Walk	Nature: national park, beach. Urban.	30 minutes then 180 minutes	Blood pressure, cortisol, HR,	Within	Lower TMD in Nature conditions. Lower cortisol in Park versus Urban condition. Lower high frequency HRV
Tyrväinen et al., 2014	77 adults (mean age: 48 yrs).	Yes	No	Viewing and walk.	Nature: urban park, urban woodland. Urban: city centre.	30 minutes	Cortisol, PANAS.	Within	More positive and fewer negative mood in Nature conditions.

Reference	Subjects	Baseline	Stress induced	Exposure method	Exposure setting	Exposure length	Measure	Design	Results
Ulrich, 1981	17 adults (age: 20-27 yrs).	Yes	No	Picture	Nature: water, vegetation. City.	26 minutes	EEG, HR, ZIPER.	Within	Lower fear arousal in Water versus Urban condition. Highest alpha activity in Vegetation condition. Highest HR in Water condition. Highest sadness in Urban condition.
Wang et al., 2016	140 University students (mean age: 22 yrs).	Yes	Trier social tier test (all subjects)	Video	Nature 1: lawn without people. Nature 2: lawn with people. Nature 3: lake without people. Nature 4: walkway without people. Semi-urban 1: plaza without people. Semi-urban 2: plaza with people. Urban 1: roadway.	8 minutes	Heart beat, skin conductance, STAI.	Between	Lower skin conductance and state anxiety in Nature conditions. Lower heart beat in Nature 3, 4 versus Urban condition.
Wells & Evans, 2003	337 children (mean age: 9 yrs).	No	No	Dwelling	Naturalness of window view and yard, number of houseplants.	Varied	LSLES, RCBQ.	Between	Naturalness was negatively linked to psychological distress and stressful life event impact.
White et al., 2013	Life satisfaction analysis: 56,574 people. GHQ	No	No	Dwelling	N/A	N/A	Life satisfaction. GHQ.	Between	Greater neighbourhood greenness was associated with lower GHQ scores and greater life satisfaction.
White et al., 2019	20,264 people	No	No	Varied	N/A	Past week	Time spent in natural	Between	Spending less than 1 hour in nature was not associated with better outcomes than spending no time. Benefit emerged

Table 1.2. Summarized methodology of the experiments included in the 'Effect of nature and urban exposures on well-being' section of the chapter. (Notes: BMIS = Brief Mood Introspection Scale, DASS = Depression, Anxiety and Stress Scale, EEG = electroencephalography, EMG = electromyography, GHQ = General Health Questionnaire, HR = heart rate, HRV = heart rate variability, LSLES = Lewis Stressful Life Event Scale, MDI = Major Depressive Inventory, OHS = Overall Happiness Scale, PANAS = Positive and Negative Affect Scale, POMS = Profile of Mood States, PSS = Perceived Stress Scale, RCBQ = Rutter Child Behavioural Questionnaire, STAI = State/Trait Anxiety Inventory, TMD = Total Mood Disturbances, WEMWS = Warwick and Edinburgh Mental Wellbeing Scale, ZIPER = Zuckerman's Inventory of Personal Reactions).

Effect of nature and urban exposures on well-being

Focusing on overall well-being, longer and more frequent visits to natural environments have been associated with higher self-reported well-being (Lafortezza, Carrus, Sanesi, & Davies, 2009), suggesting that exposure to natural environments supports well-being. In line with this, people who spend three to five hours versus no time in natural settings also report greater well-being (White et al., 2019), further supporting the link between natural environments and well-being.

Similar to overall well-being, nature exposure has also been linked to enhanced life satisfaction, an index of eudemonic well-being. Indeed, participants who live in a relative green versus urban area report higher life satisfaction (Smyth, Mishra, & Qian, 2008; White et al., 2013). Furthermore, spending time in a natural environments positively correlates with self-reported life satisfaction (McFarland, Waliczek, & Zaijcek, 2008), demonstrating that nature exposure enhances eudemonic well-being.

Likewise, nature exposure has been shown to increase hedonic well-being. Indeed, nature exposures have also been consistently shown to increase positive mood (meta-analyses by Bowler Buyung-Ali, Knight, & Pullin, 2010; McMahan & Estes, 2015). Indeed, participants report more positive mood after viewing pictures (Berman et al., 2008; Mayer, Frantz, Bruehlman-Senecal, & Dolliver, 2009) or listening to the sounds (Jo et al., 2019) of natural versus urban environments. Likewise, positive mood is also higher after walking in a natural versus urban environment (Hartig et al., 2003; Berman et al., 2008; Mayer et al., 2009; Park et al., 2009; Sonntag- Öström et al., 2014; Davudenko & Peetz, 2017; Hassan et al., 2018). Moreover, more frequent visits to green spaces are associated with higher overall mood (Holt et al., 2019). Importantly, these results are supported by experiment that used more objective measures of mood. For example, artificial driving through a forest versus urban area led to reduced electrodermal activity over the eyebrows and increased activity over the cheeks, indicating positive mood (Parsons, et al., 1998). Furthermore, participants recognised both facial (Hietanen, Klemmetilä, Kettunen, & Korpela, 2006) and auditory (Korpela, Klemettilä, & Hietanen, 2002) expressions of happiness versus anger or disgust more quickly when these are preceded by pictures of natural versus urban environments, suggesting more positive mood after nature exposures. Moreover, due to misattribution, Chinese pictographs presented after a nature versus urban picture were evaluated more positively (Joye, Pas, Steg, & Lewis-Evans, 2014), further supporting that natural versus urban environments elicit more positive mood, indicating greater well-being.

Effects of nature and urban exposures on mood and therefore well-being have also been investigated using EEG. In these experiments, activity in a different frequency bands is used to index a specific mood. These consistently show that viewing pictures of (Ulrich, 1981; Grassini et al., 2019) or being in (Aspinall et al., 2013; Al-Barrack et al 2017; Ahmad et al 2018; Bailey et al 2018) natural versus urban environments increased power in the alpha band, that is typically interpreted as a sign of relaxation. However, alpha activity has also been linked to inward attention (Barry, Clarke, Johnstone, Magee, & Rushby, 2007; Wan et al., 2019), boredom (Miyauchi & Kawasaki, 2018; Yakobi, Boylan, & Dankert, 2021) as well as ego-depletion (Boksem et al., 2005; Lorist et al., 2009), making it difficult to draw firm conclusions from these findings. Nevertheless, experiment using self-report questionnaires, electrodermal activity or cognitive tasks to evaluate the effect of urban and natural exposures on mood consistently support the notion that natural environments promote positive mood and therefore, well-being.

In addition to higher levels of positive mood, nature versus urban exposure also reduce negative mood, another indicator of greater well-being. Indeed, participants reported feeling less anxious after exposure to natural versus urban sounds (Jo et al., 2019) or pictures (Grassini et al., 2009). Likewise, unlike urban walks, walking in a forests (Li et al., 2007; Ahmad et al., 2018; Lyu et al., 2019) or urban park (Song et al., 2014) has been shown to reduce anxiety levels compared to baseline. This indicates that differences in anxiety levels after urban versus nature exposures are due to nature exposures modulating anxiety levels.

Similar to anxiety, nature exposure also reduces stress levels. Supporting the link between the natural environments and reduced stress levels, Thomspon et al. (2012) found a close negative correlation between the amount of green space near participants' homes and their self-reported stress levels. Indeed, artificial nature versus urban exposures via videos (de Kort, Meijinders, Sponselee, & IJsselstejin, 2006; Wang, Rodiek, Wu, Chen, & Li, 2016), sound (Alvarsson, Wiens, & Nilsson, 2010; Benfield et al., 2014) or pictures combined with auditory and olfactory stimulation (Hedblom et al., 2019) led to lower stress levels. Likewise, spending time in a room with houseplants has been linked to lower stress levels (Lohrn, Pearson-Mims, & Goodwin, 1996; Beukeboom, Langeveld, & Tanja-dijkstra, 2012). In line with these, compared to walking in an urban environment, stress levels were lower after walking in various natural settings, such as wildlife preserve (Hartig et al., 2003), urban park (Beil & Hanes, 2013; Song et al., 2014; Tyrväinen et al., 2014; Gidlow et al., 2016), country side (Cole & Hall, 2010), or a forest (Park et al., 2009; ; Sonntag- Öström et al., 2011; Beil & Hanes, 2013; Triguero-Mas et al., 2017; Kobayashi et al., 2019). Importantly, numerous experiments have demonstrated that, similar to anxiety, differences are due to nature exposures reducing while urban exposures not modulating stress levels (Lohrn et al., 1995; Hartig et al., 2003; de Kort et a., 2006; Alvarsson et al., 2010; Sonntag- Öström et al., 2011; Beil & Hanes, 2013; Song et al., 2014; Tyrväinen et al., 2014; Gildow et al., 2016; Wang et al., 2016; Triguero-Mas et al., 2017). In line with this, viewing pictures of green settings reduce power of beta oscillations (13-30 Hz; Grassini et al., 2019), that has been associated with stress (Alonso, Romero, Ballester, Antonijoan, & Mañanas, 2015), and therefore further support the notion that nature exposure reduces stress levels, thus promoting well-being. Notably, spending at least thirty minutes per week in a natural environment leads to lower risk of high blood pressure by 9% (Shanahan et al., 2016), a marker of stress (Hortskov et al., 2004), highlighting that the benefits of brief nature exposures on well-being last for a relatively long time.

In addition to increasing positive and reducing negative mood, nature exposure may also enhance coping with negative life events, thus supporting future well-being. For example, children who live in a relatively green versus urban neighbourhood reported lower stress levels after stressful life events (Wells & Evans, 2003). Similarly, stressful life events had lower impact on perceived general health of people who live in areas with relatively high versus low levels of greenery (van den Berg, Maas, Verheij, & Groenewegen, 2010). However, Marselle, Warber and Irvine (2019) found no effect of walking in a natural environment on the extent to which stressful life events reduce mental well-being and mood, suggesting that brief nature exposures may not be sufficient to support future well-being.

In contrast with selective attention, majority of experiments found that water scenes also benefited well-being. Indeed, walking along a river or a lake has been found to reduce stress levels (Sonntag- Öström et al., 2014; Davudenko & Peetz, 2017; Triguero-Mas et al., 2017). Likewise, viewing pictures of water versus urban scenes resulted in lower power of beta oscillations, indexing reduced stress levels (Grassini et al., 2009). To my knowledge, only Gidlow et al. (2016) found no effect of resting and walking in natural environments that contained water features on stress levels. Therefore, overall these findings suggest that in contrast with selective attention, well-being benefits of natural settings are not limited to green environments.

Importantly, walking versus viewing pictures of the same natural environment have been found to increase positive mood to a greater extent (Mayer et al., 2009), demonstrating that physical versus artificial nature exposures have greater benefits for well-being. As suggested in the ‘Effect of nature and urban exposures on top-down processes’ section, this might be due to physical exposure allowing the effects of the different (i.e., visual and auditory) features of the natural environment to be combined.

Although the evidence is less consistent, some experiments found that urban exposures also modulate mood. Indeed, participants have been found to report more negative emotions after urban exposure compared to baseline, indexing diminished well-being (Hartig et al., 2003, meta-analysis by McMahan & Estes, 2015). In line with this, walking in an urban versus natural environment resulted in greater power of beta oscillations (Hassan et al., 2018), suggesting that urban exposures may increase stress levels, thus diminishing well-being. Overall, these provide some evidence that urban exposure can diminish well-being. However, why most experiments did not find such effect remains unclear.

Psycho-Evolutionary framework

To my knowledge, only the Psycho-Evolutionary Framework (PEF; also known as Stress Reduction Theory; Ulrich, 1983; 1993) has been developed to predict and explain the effect of urban versus natural environments on mood and thus well-being. It argues that certain features or “preferenda” of natural environments, such as presence of water and absence of threat, rapidly evoke positive mood that in turn reduces negative emotions, including stress. Notably, this predicts that stress levels are only reduced when mood is improved. In contrast with natural environments, urban environments do not improve mood because they lack such features.

In line with PEF, experiments discussed in the ‘Effect of nature and urban exposures on well-being’ section, consistently showed that nature exposure improve positive mood and reduce negative mood, including stress. As predicted by PEF, most experiments indeed found both improvement in mood and reduction in stress levels. Importantly, however, Greenwood and Gatersleben (2016) found that although participants’ mood improved after sitting on a grass field with a friend, their heart rate increased compared to baseline, indexing enhanced stress levels. This shows that mood and stress effects may be independent, suggesting that co-occurrence of improved mood and reduced stress levels in other studies may be a coincidence.

Further supporting PEF, absence of threat seems to contribute to the mood effects observed after nature exposures. Indeed, exposure to a natural environment with few versus numerous hiding places evokes more self-reported positive emotions (Gatersleben & Andrews, 2013). Furthermore, unmanaged forests, that are typically perceived as unsafe (van den Berg & Koniknendijk, 2012), enhance whereas managed forest reduce stress levels (Martens, Gutscher, & Bauer, 2011; Saito, Horiuchi, Takayama, & Fujiwara, 2019), further demonstrating that absence of threat may be an important aspect of natural environments for well-being. Although it is unclear whether absence or presence of threat also modulates the effect of urban environments, the lack of mood improvement after urban exposures suggests that either urban environments are always perceived as threatening or the absence of threat in these setting is insufficient to improve mood.

In contrast with absence of threat, there is little evidence to support the notion that presence of water indeed contributes to mood and thus well-being improvements after nature exposure. Although several experiments found that exposure to water scenes reduces stress levels

(Sonntag- Öström et al., 2014; Davudenko & Peetz, 2017; Triguero-Mas et al., 2017), to my knowledge, only Grassini et al. (2009) reported greater mood improvement after viewing pictures of water scenes versus other natural environments, such as forests (Grassini et al., 2009). Others found no difference in mood after resting and walking in a natural environment with versus without water features (Gidlow et al., 2016) or around a lake versus in a forest (Sonntag- Öström et al., 2014). This casts doubt on the idea that presence of water contributes to the benefits of natural environments on mood and thus well-being. Furthermore, as discussed in the 'Effect of nature and urban exposures on well-being' section, numerous environments found that nature exposures improved mood despite the absence of water, indicating that the presence of water may not be an important feature of natural environments for well-being.

Air pollution

Although PEF considers several differences between natural and urban environments to explain their distinct effect on well-being, it has also overlooked some, such as air pollution levels. Importantly, air pollution levels that are typically higher in urban versus natural environments (Hartig et al., 2014; Nowak et al., 2014; Hirabayashi & Nowak, 2016), have been shown to diminish well-being (see Li et al., 2018 for review). Indeed, participants who live in an area with relatively high versus low levels of air pollutants, such as $PM_{2.5}$, PM_{10}, nitrogen dioxide (NO_2) or black carbon, reported higher levels of stress (Mehta et al., 2015; Sass et al., 2017) and anxiety (Power et al., 2015; Pun, Manjourides, & Suh, 2017), suggesting lower well-being. Furthermore, participants who were interviewed on days with worse local levels of particulate matter reported lower happiness (Levison, 2012), further supporting the link between air pollution exposure and well-being. Notably, no experiment to my knowledge investigated the effect of brief air pollution exposures, therefore it is unclear whether brief air pollution exposures (similar to that used in experiments that investigate the effect of nature and urban exposures on selective attention) would also modulate well-being. Furthermore, due to the lack of experiments with baseline measures, it is unclear whether the above results are due to high air pollution levels diminishing or low air pollution levels increasing well-being. Finally, the period for which negative effect of high air pollution levels on well-being last is also unclear.

Conclusion

Overall, the effect of natural and urban environments on cognitive control and behavioural adjustment has been overlooked. While numerous experiments have investigated the effect of these environments on selective attention and well-being, these experiments tended to explore a narrow area of these. Therefore, this thesis aims to fill some of the gaps within the literature. The first aim was to investigate the effect of brief and chronic urban versus nature exposures on proactive and reactive cognitive control. This was addressed in Chapter 2, where participants were briefly exposed to these environments via videos (Experiment 1) or walks (Experiment 2) before completing a face attention task. Additionally, in a third experiment, young adult participants raised in urban versus rural and more- versus less-green neighbourhoods completed to same task to explore the long-term effects of chronic urban versus nature exposures on cognitive control. The second aim of the thesis was to test the effect of urban versus natural environments on attention allocation towards emotional face stimuli. This was also addressed in Chapter 2 using the same experiments. Furthermore, Chapter 3 also addressed this aim by measuring participants' brain activity using EEG during a different attention task with face stimuli after watching urban (both with and without faces) or nature videos. The third aim of the thesis was to explore the long-term effects of chronic urban versus nature exposures on behavioural adjustment. This was addressed in Chapter 4, where participants' childhood environments were categorised based on population size (indexing the extent to which an environment is urban), neighbourhood greenness (indexing the extent to which an environment is natural) and air pollution levels. Additionally, a combination of these were used to categorise childhood environments as worse versus better. Behavioural adjustment was indexed using PES on a Go/No-go task. The final aim of the thesis was to explore to long-term effect of chronic urban versus nature exposures on well-being. This was addressed in Chapter 5, where participants' childhood environments were categorised similarly to Chapter 4. To measure well-being, participants reported their depressive, anxiety, and stress symptoms.

Chapter 2. Threat bias and cognitive control after urban and nature exposures

Abstract

Findings that amygdala hyperactivity is associated with urban living raises the possibility that attention bias to threat-related stimuli, a cognitive response thought to be underpinned by amygdala hyperactivity, may be enhanced by exposure to urban environments. The link between attention bias to threat-related stimuli and reactive cognitive control suggests that urban environments may also modulate cognitive control. I investigated this in three experiments. To examine the effect of brief artificial and physical exposures to urban versus natural environments, adult participants watched a 25-minute video of (Experiment 1) or walked through (Experiment 2) urban streets or a nature reserve. To examine the long-term effects of chronic childhood exposures to urban and nature environments, adult participants raised in urban versus non-urban and more- versus less-green environments participated in Experiment 3. In all three experiments, participants completed a face attention task, in which they made speeded gender identification of spatially cued neutral target faces, ignoring a concurrent distractor that was either an emotional face or a scrambled meaningless image. I found that after brief artificial urban versus nature exposure, fearful faces specifically slowed responses, indexing increased attention bias to threat-related face stimuli. No such effect was observed after physical or chronic childhood exposure to urban environments. Interestingly, however, brief physical urban exposure promoted reactive control, whereas brief physical nature exposure promoted proactive control, demonstrating that these resulted in distinct styles of cognitive control. In contrast, neither brief artificial nor chronic childhood exposure to urban versus natural environments affected cognitive control. Overall, I demonstrated that artificial and physical urban exposures differentially influence threat bias and cognitive control. Furthermore, chronic urban and nature exposures during childhood do not have long-term effects on either of these that would last into young adulthood.

Humans preferentially orient their attention toward threatening or highly arousing negative stimuli. Indeed, numerous studies have shown that irrelevant fearful and angry faces are especially effective at interfering with performance on simple, speeded visual search tasks (Fox et al., 2000; Eastwood, Smilek & Merikle, 2001), including flanker (Grose-Fifer, Rodrigues, Hoover, & Zottoli, 2013) and dot-probe tasks (Pourtois, Grandjean, Sander & Vuilleumier, 2004; Fox, Derakshan & Shoker, 2008).

Importantly, numerous studies suggest that the neural basis for this bias involves the amygdala (see Vuilleumier, 2005 for review), a core midbrain structure that is part of a larger neural circuit involving the thalamus and orbital-frontal cortex. This is supported by neuroimaging studies demonstrating that anxious participants who show amygdala hyperactivity (Etkin et al., 2004; Carlson, Cha & Mujica-Parodi, 2013) also show threat biases (see Bar-Haim et al., 2007 for review). Further support comes from studies showing that selective serotonin reuptake inhibitors (SSRIs) that are known to suppress amygdala activity (Browning, Reid, Cowen, Goodwin, & Harmer, 2007) are also effective at reducing threat-related attention bias (Sheline et al., 2001). Additionally, amygdala damage is associated with reduced recognition of fear expressions in faces (Broks et al., 1998; Gamer, Schmitz, Tittgemeyer, & Schilbach, 2012), adding weight to the contention that amygdala plays an important role in attention to threat-related stimuli, especially threatening face stimuli.

Hyperactivity in the adult amygdala during social stress has been linked to living in urban environments both in the present as adults (Lederbogen et al., 2011) and in the past during childhood (Streit et al., 2014). These findings are consistent with a meta-analysis showing that urban versus rural dwelling increases the risk for anxiety by 21% (Peen, Schoevers, Beekman, & Dekker, 2010). Suggesting a specific role of the physical environment, Kim et al. (2010) reported greater amygdala activation when viewing urban versus rural scenes. Moreover, exposure to urban versus natural environments (Song et al., 2014; Wang, Rodiek, Wu, Chen, & Li, 2016) or sounds (Jo et al., 2019) has been causally linked to elevated anxiety levels. Considering the relationship between amygdala activity and anxiety and that between anxiety and threat-related attention bias, these findings suggest that exposure to urban environments may enhance threat-related attention bias.

Enhanced attention allocation to threat-related distractors may be underpinned by altering when attention is focused toward a target and away from distractors. According to the Dual Mechanism Model (Braver, Gray, & Burgess, 2007; Braver, 2012), attention can be focused either prior to stimulus presentation (proactive cognitive control) or afterwards if attention has been incorrectly captured by a distractor (reactive cognitive control). Notably, unlike reactive control, proactive control is effortful and therefore, can only be used when central cognitive resources are available (Braver et al., 2007; Braver 2012). Supporting the link between threat bias and reactive control, under high versus low working memory load that depletes central cognitive resources, participants show enhanced N2pc event related potential (ERP) component contralateral to angry versus neutral distractor faces (Holmes, Mogg, de Fockert, Nielsen, & Bradley, 2014). As this component indicates enhanced attention allocation to threat-related face stimuli (Luck & Hillyard, 1994) and only reactive control can be used when central cognitive resources are depleted, these finding suggests that reactive control may contribute to threat bias.

The Attention Restoration Theory (ART; Kaplan & Kaplan, 1989, Kaplan, 1995; 2001) argues that similarly to high working memory load, urban exposures also deplete central cognitive resources because cities provide a cognitively demanding environments where uninteresting objects often need to be effortfully attended while interesting ones need to be suppressed. This notion is supported by experiments using the Delay Gratification Task, where participants can either accept an immediate small reward or wait for a delayed larger reward (Rodriguez, Mischel, & Shoda, 1989). For example, Taylor, Kuo and Sullivan (2002) found that children who live in a relatively urban versus green area are less able to resist immediate small rewards, indexing lower levels of central cognitive resources. Suggesting that urban exposures causally deplete central cognitive resources, compared to baseline, participants are less able to resist immediate small rewards after watching a video of an urban versus natural environment (Jenkin, Frampton, White & Pahl, 2018). These suggest that central cognitive resources may not be available after urban exposures for proactive control to be applied, and therefore, urban exposures may result in an enhanced tendency to use reactive control. In contrast, results of Taylor et al. (2002) and Jenkin et al. (2018) indicate that central cognitive resources are available after exposure to natural environments. This suggests that nature exposure may lead to a tendency to use proactive control. Further supporting the idea that reactive control may be used after urban exposures and proactive control may be used after nature exposures is that anxiety, a state that is more prominent after urban than nature exposures (Song et al., 2014; Wang et al., 2016; Jo et al., 2019) lead to greater reliance on reactive than proactive control (Yang, Miskovich, & Larson, 2018).

Cognitive control is generally measured using tasks where a target is presented with either an identical (congruent) or non-identical (incongruent) distractor (Egner, 2007). Reaction times are typically faster on incongruent trials that were preceded by another incongruent trial (repeat trials) than on incongruent trials that were preceded by a congruent trial (novel trials; Egner & Hirsch, 2005; Egner, 2007). This is called the congruency sequence effect. Importantly, when proactive control is applied, this effect is small because attention is biased towards the target, reducing interference by the incongruent distractor on both types of trials. In contrast, the congruency sequence effect is relatively large when reactive control is applied because it requires retrieval of task goals as well as disengagement from the incorrectly attended incongruent distractor before a response can be made on novel trials (Braver, 2012). This means that reaction times are slowed on novel versus repeat trials, resulting in a large congruency sequence effect.

I conducted three experiments to investigate the effect of exposures to urban versus natural environments on both threat bias and cognitive control. Experiment 1 examined the effect of artificial exposures to these environments by asking participants to complete a face attention task before and after viewing an immersive 25-minute video of a walk through urban streets or a nature reserve. During the task, young adult participants were asked to report as quickly and accurately as possible the gender of a pre-cued target face that was presented simultaneously with another (distractor) image that was either a neutral or emotional (happy or fearful) face or scrambled meaningless images. Experiment 2 explored the effect of physical urban and nature exposures by asking a new group of young adult participants to complete the face attention task after going on a 25-minute walk through urban streets or a nature reserve. Finally, Experiment 3 tested whether chronic urban and nature exposures during childhood have long-term effects that last into young adulthood. To do so, another group of young adult participants completed the face attention task, and then I determined the extent to which their childhood environments were urban versus non-urban and naturally more- versus less-green. In all three experiments, differences in performance with fearful versus neutral face distractors were used to index threat bias. I predicted enhanced threat bias after the urban versus nature exposures in Experiments 1 and 2 as well as in young adults who were raised in urban versus non-urban or less- versus more-green environments in Experiment 3. Magnitude of the congruency sequence effect was used to index proactive and reactive control. I predicted greater congruency sequence effect, indexing reactive control, after the urban versus nature exposures in Experiments 1 and 2 as well as in young adults who were raised in urban versus non-urban or less- versus more-green environments in Experiment 3.

General methods

Participants

Number of participants in each experiment were determined based on Ter Huurne et al. (2015) experiment, in which twenty-four participants completed a similar task to ours, where neutral target faces were presented with either a distractor target face or a scrambled meaningless image. As our analysis was somewhat exploratory and I had more distractor conditions, I collected full datasets for thirty-five young university associated adults (23 females, mean age = 24.1 years, s.d. = 3.19) in Experiment 1. As Experiments 2 and 3 had a between-subject design that requires more participants, I collected full datasets from fifty-eight young university associated adults (41 females, mean age = 19.5 years, s.d. = 1.58) in Experiment 2 and from eighty (63 females, mean age = 19.4 years, s.d. = .97) in Experiment 3. All participated in exchange for course credit or cash. All participants were fluent in English, reported normal or corrected-to-normal vision and no history of neuropsychological or psychiatric disorders. Additionally, all participants in Experiment 3 spent their entire lives in England, United Kingdom, as the database used to categorise their childhood environment as more- versus less-green was only available for this region. Notably, all participants lived in Birmingham, United Kingdom, at the time of the experiment to ensure that the effect of childhood environments is not confounded by participants' current environments. All three experiments were approved by the University of Birmingham Ethics Committee.

Apparatus

A 17.5" Dell laptop (refresh rate, 59 Hz) in Experiment 1 and A 24" desktop monitor (refresh rate, 59 Hz) and Stone computer in Experiment 2 controlled the presentation of experimental stimuli and recorded data using Matlab (R207a, Mathworks, 2007) running Psychtoolbox. Participants were seated 50 cm away from the screen in a quiet, well lit room and entered responses using a Razer gaming keyboard in Experiment 1 and a traditional keyboard in Experiment 2.

In Experiment 3, experimental stimuli were presented, and data was recorded online using Gorilla Experiment Builder (gorilla.sc). Participants were asked to complete the experiment in a quiet, empty room. The experiment could only be completed on any computer or laptop. Responses were entered using a keyboard.

Stimuli

Face attention task. Size of stimuli in Experiment 1 and 2 were defined using visual angles. However, in Experiment 3, size of stimuli was defined using percentage of total screen pixels as participants used a range of devices with varied size to complete the task. Consequently, the exact size of the stimuli is unknown and varied between participants. Stimuli comprised a spatial cue, a centrally presented white fixation cross (0.5° or 4% in diameter), and two face images. The spatial cue was a small (1° x .7° or 10% x 14%), centrally presented white arrow pointing left or right. Each face in the stimulus array subtended 8.8° x 10.2° or 27% x 47% and was set into a 9.1° x 10.8° or 28% x 50% rectangle. The centre or each face was presented 6.8° or 23% laterally to the left and right of centre and 3.1° or 11% below the horizontal meridian. Colour photos of Caucasian adult faces with head hair but without glasses, make-up, or facial hair were used as stimuli (Karolinska Directed Emotional Faces dataset; Lundquvist, Flykt, & Öhman, 1998). Teeth were visible in all fearful and happy faces. Half the photos were of a female. In Experiment 1, photos of thirty-two individuals were selected, then split into four unique sets of photos showing eight individuals. The order of face set was counterbalanced across participants. Photos of eight individuals were selected in Experiments 2 and 3. In all experiments, photos of half of the individuals served as targets. These were always presented with a neutral expression. Photos of the remaining individuals served as distractors with each individual presented equally often having a neutral, fearful, or happy expression in Experiments 1 and 2 and with neutral or fearful expressions in Experiment 3. Photos that were presented as distractors were used to create the scrambled meaningless images (made by pixelating each image into 13,984 elements, then randomly repositioning every element).

Procedure

Face attention task. The procedure used in each trial in the face attention task is illustrated in *Figure* 2.1. Each trial in the face attention task began with a presentation of the fixation cross that after 400 ms was briefly replaced by a 100 ms central spatial cue. The cue always indicated the target's location. At the cue's offset, the fixation cross reappeared and remained visible until the end of the trial. The task was to report the target's gender as quickly and accurately as possible by pressing either the "Z" or "A" key using the index and middle finger, respectively, of the dominant hand. Response keys were counterbalanced. The trial ended with response or after 1500 ms. The correct answer was female on 50% of trials. No performance feedback was provided, and the next trial began immediately. The maximum length of each trial was 3.575s. Response time (RT; interval between stimulus array onset and response) and accuracy (proportion of correct trial) were recorded. Each combination of target location and gender was equally likely to occur. Target and distractor were 90% likely to be mismatched in gender in Experiments 1 and 2. (Gender-matched trials were used to detect strategies based on distractor selection and were not analysed.) Target and distractor were 100% likely to be mismatched in gender in Experiment 3. The distractor was 25% likely to be happy, fearful, neutral, or scrambled in Experiments 1 and 2, and were 33% likely to be fearful, neutral, or scrambled in Experiment 3. Participants completed twelve blocks (576 trials) for each pre- and post-video test episode in Experiment 1, six blocks (318 trials) in Experiment 2, and eight (200 trials) blocks in Experiment 3. Rest intervals between blocks were self-paced. In Experiment 3, breaks were limited to a maximum of five minutes. Participants were instructed not to talk to anyone, watch TV or use their phones during the breaks. Participants completed thirty practice trials in Experiments 1 and 2, and 15 practice trials in Experiment 3.

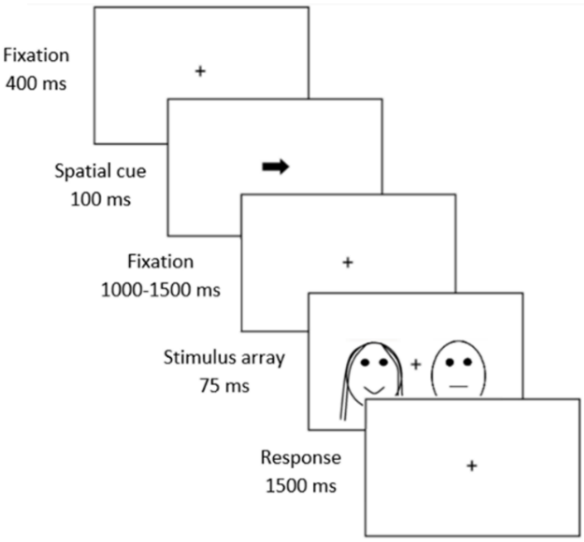

Figure 2.1. An illustration of an example trial in the face attention task. Faces are shows as cartoon for illustration purposes only. On each trial a fixation cross was visible throughout except when replaced by a brief 100% valid spatial cue (100 ms). This occurred 400 ms after trial onset. A stimulus array (75 ms) comprising target and distractor appeared between 1,000 and 1,500 ms after cue offset (randomly jittered interval), followed by a 1,500 ms response window. A speeded report of the target's gender was required. The correct response in this example was male.

Data analysis

RT data were excluded for all gender-match trials, all incorrect trials, anticipation errors (RTs < 200 ms) and when RTs exceeded the individual's condition mean by more than three s.d.'s.

To examine cognitive control, trials were categorised based on their stimulus array as either a one-face trial, where the target face image was presented with a scrambled distractor image, or a two-face trial, where the target face image was presented with a face distractor image (regardless of distractor expression). Two-face trials were then categorised as repeat trials if they were preceded by another two-face trial or as novel trials if they were preceded by a one-face trial. Congruency sequence effect was calculated by subtracting individual accuracy and RTs on repeat from novel trials.

Experiment 1

Experiment 1 aimed to investigate the effect of artificial nature and urban exposures on attention bias towards fearful faces as well as cognitive control. For this purpose, participants completed the face attention task where on each trials, a target neutral face was simultaneously presented with a face displaying either a neutral, happy, or fearful expression or a scrambled meaningless image. This task was completed before and after viewing a 25-minute video of an immersive walk through urban streets or a nature reserve. I was interested in the distraction cost of fearful faces to assess threat bias as well as in the magnitude of the congruency sequence effect to assess cognitive control.

Methods

Apparatus

Videos were presented using Windows Media Player (Microsoft).

Materials

Videos. A picture of each video is shown in *Figure* 2.2. Videos were sourced from the internet (Nature video, https://www.youtube.com/watch?v=b4AVn8mTuJw&t=2777s, starting at thirty seconds; Urban video, https://www.youtube.com/watch?v=LwYGxjdnZ84&t=1535s, starting at minute twenty-two). Both were 25-minutes long, presented without sound, and were filmed from a walker’s perspective at eye height. The nature video was filmed along a footpath, showing showed vegetation, a mountain and river, but no people or buildings. The urban video navigated busy streets in Vancouver, Canada, showing tall buildings, open urban spaces, signs in English, 335 neutral and three smiling faces (61% of all faces were male), and little vegetation.

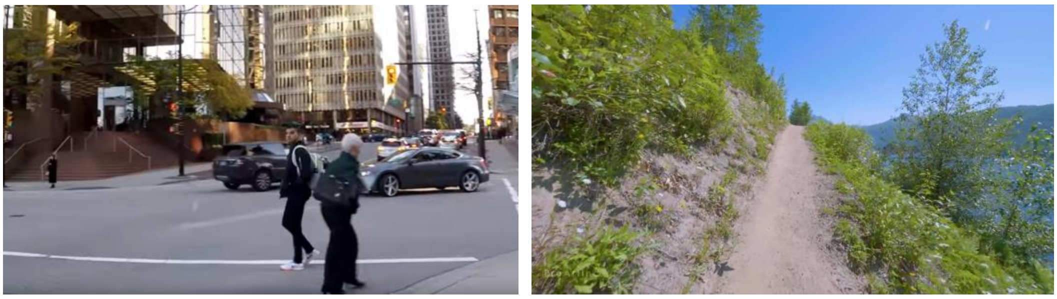

Figure 2.2. Environment shown in the urban (left) and nature (right) videos.

Procedure

The experiment consisted of two sessions conducted one week apart at the same time of day. In each session, participants completed two test phases: a pre-video and a post-video phase, each comprising twelve blocks of the face attention task. After completing the pre-video phase, participants completed the Positive and Negative Affect Scale (PANAS; Watson, Clarke, & Tellegan, 1988); rated relaxation levels using a 6-point Likert scale (1 = very stressed, 6 = very relaxed), then viewed the nature or urban video (alternate video on Day 2) with the instruction to imagine being present in the environment, following the route shown (De Kort, Meijenders, Sponselee, & IJsselsteijn, 2006). Order of the videos was counterbalanced. Immediately thereafter, PANAS and relaxation ratings were obtained again. Then, the post-video test phase was conducted. At the end of Session 2, participants also completed the Depression, Anxiety and Stress Scale (DASS-21; Lovibond & Lovibond, 1995; 21 items) to report feelings over the last week.

Data analysis

Face attention task. To investigate threat bias, individual accuracy and average RTs for each distractor condition (neutral, happy, fearful, scrambled), test phase (pre-video, post-video), video-type (urban, nature) and session order (Day 1 = urban, Day 1 = nature) were analysed using a 4 x 2 x 2 x 2 mixed-design ANOVAs with distractor-type, test phase, video-type as within-subjects factors and session order as a between group factor. As session order neither interacted with the other three factors (*p* = .445), nor had a significant main effect on RTs (*p* = .361) or accuracy (*p* = .108), it was excluded from all subsequent analyses. Separate repeated measures ANOVAs were conducted on pre-video and post-video data sets using distractor condition and video-types as factors. Mauchly's Test of Sphericity was used for all ANOVAs. Face distraction costs were calculated by subtracting RTs for scrambled distractors from RTs for neutral distractors; threat and happy distraction costs were calculated by subtracting RTs for neutral distractors from RTs for fearful and happy distractors, respectively. Mean comparisons used paired samples *t*-tests (2-tailed).

To investigate cognitive control, individual proportion correct trials (accuracy) and average RTs for each trial-type (novel, repeat), test phase, video-type and distractor-type were analysed using a 2 x 2 x 2 x 3 x 3 mixed-design ANOVAs with trial-type, test phase, video-type and distractor-type as within-subject factors and session order as a between group factor. Mauchly's Test of Sphericity was used for these ANOVAs. Follow-up analyses used independent and paired samples t-tests (2-tailed).

Ratings and scales. PANAS ratings for positive and negative items (10 each) were summed separately to produce two scores. Pre- and post-video relaxation ratings and PANAS subscale scores were analysed using Wilcoxon Sign Ranks Tests (2-tailed). DASS-21 scores for depression, anxiety, and stress items (7 each) were summed separately to produce three scores. Possible differences between those viewing the nature versus urban video on Day 1 on these subscales were assessed using Mann-Whitney U tests (2-tailed). Whether post-video relaxation ratings and post-video PANAS subscale scores were predictive of threat bias was analysed using linear regression.

For all other analyses, Bonferroni corrections applied where necessary and alpha levels were set at .05.

Results

Threat bias

Participants were less distracted by scrambled meaningless images than faces. Omnibus analysis of RTs showed a significant main effect of distractor-type, $F(3,99) = 34.876$, $p < .001$, $\eta^2_p = .514$. Follow-up analysis revealed faster RTs on scrambled (mean = 561 ms, s.d. = 89) versus face distractor trials (mean = 584 ms, s.d. = 96; $t(34) = -5.639$, $p < 0.001$), indicating that scrambled meaningless images interfered less with task performance than the other distractors. Furthermore, RTs were faster on neutral (mean = 578 ms, s.d. = 97) versus emotionally expressive face trials (happy and fearful trials combined; mean = 587 ms, s.d. = 97; $t(34) = -3.841$, $p = 0.001$), indicating that neutral distractors interfered less with task performance than emotionally expressive distractors. RTs on happy and fearful distractor trials did not differ ($p = 0.169$), showing that there was no overall attention bias specifically towards fearful faces.

Importantly, however, fearful distractor faces interfered more with task performance after the urban versus nature video. Omnibus analyses of RTs showed a significant interaction between test phase, video-type, and distractor-type ($\mathrm{F}_{3,99} = 3.121$, $p = 0.044$). Subsequent analyses of pre-video RTs found no interaction between upcoming video-type and distractor-type ($F_{3,102} = 0.670$, $p = 0.572$), indicating that distractor effects on performance were similar prior to the videos. To focus on post-video distractor effects, face distraction as well as threat and happy face biases were compared between video-types. Here, the group average threat bias (i.e., slowing of RTs when the distractor was a fearful versus neutral face) was significantly larger ($t(34) = -4.584$, $p < 0.001$; see *Fig.* 2.3) after viewing the urban (mean = 20 ms, s.d. = 21) versus nature (mean = 1 ms, s.d. = 21 ms) video. In contrast, the happy face bias was modest and unaffected by video-type (urban: mean = 12 ms, s.d. = 17; nature: mean = 4 ms, s.d. = 24; $t(34) = -1.464$, $p = 0.152$). Similarly, mean face distraction cost (i.e., slowing of RTs when distractor was a neutral face versus scrambled meaningless image) was only 4 ms larger after the urban (mean = 19 ms, s.d. = 36) than the nature video (mean = 15 ms, s.d. = 32; $t(34) = -0.668$, $p = 0.509$), suggesting that effects on attention were threat specific.

Although analysis of proportion correct (see *Table* 2.1) showed higher accuracy for scrambled (mean = 93%, s.d. = 4) versus face distractors (mean = 91%, s.d. = 5; $t(34) = 3.987$, $p < 0.001$; distractor main effect $F(3,99) = 8.085$, $p < 0.001$, $\eta^2_p = 0.197$), neither test phase nor distractor-type interacted with video-type (all p's > 0.273) to influence accuracy, indicating that threat bias effects reported here are not due to speed-accuracy trade-offs.

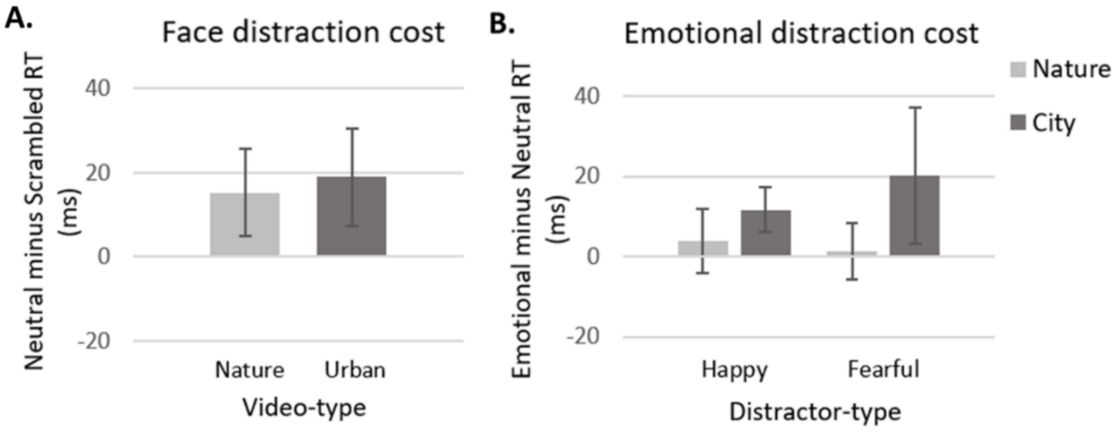

Figure 2.3. **A**. Group mean face distraction cost measured after each video-type. Face distraction cost is calculated as response time (RT) for neutral minus that for scrambled face distractors. **B**. Group mean emotional distraction cost after each video-type. Emotional distraction cost is calculated as RTs for happy or fearful distractors minus that for neutral distractors. Error bars show 95% confidence intervals.

		RT		Accuracy	
Video-type	Distractor-type	Pre-video	Post-video	Pre-video	Post-video
Urban	Scrambled	598 (118)	563 (94)	93 (0.05)	94 (0.04)
	Neutral	621 (126)	582 (100)	90 (0.06)	92 (0.06)
	Happy	622 (119)	584 (105)	91 (0.05)	92 (0.05)
	Fearful	619 (124)	602 (108)	91 (0.06)	93 (0.06)
Nature	Scrambled	601 (98)	559 (91)	92 (0.06)	93 (0.06)
	Neutral	615 (104)	574 (98)	90 (0.07)	92 (0.07)
	Happy	622 (102)	578 (94)	91 (0.05)	91 (0.08)
	Fearful	618 (99)	575 (93)	90 (0.06)	91 (0.08)

Table 2.1. Mean pre- and post-video RTs (ms) and accuracy (% correct) for each video- and distractor-type. S.d. are shown in parentheses.

Congruency Sequence Effect

In line with previous findings (Egner & Hirsch, 2005), omnibus analysis of RTs showed that participants responded more quickly on repeat (mean = 599 ms, s.d = 108) than novel trials (mean = 605 ms, s.d = 116; $F(1,33) = 11.825$, $p = 0.002$, $\eta^2_p = 0.264$). Importantly, however, I did not find a significant three-way interaction between trial-type, test phase and video-type ($p = 0.309$), demonstrating that neither the urban nor nature video modulate RTs congruency sequence effect. Furthermore, the interaction between these factors and distractor-type was also non-significant ($p = 0.635$), suggesting that distractor expression did not modulate the congruency sequence effect either.

Omnibus analysis of accuracy showed a main effect of test phase, $F(1,33) = 7.558$, $p = 0.01$, $\eta^2_p = 0.186$, revealing that accuracy was higher in post- (mean = 92%, s.d. = 0.5) versus pre-video test phase (mean = 90%, s.d. = 0.6), suggesting a practice effect1. Notably, this effect was marginally significantly modulated by trial-type and video-type, $F(1,33) = 3.948$, $p = 0.055$, $\eta^2_p = 0.107$. Consequent analysis showed similarly small congruency sequence effects in both the pre- and post-nature video test phase (pre-video: mean = 0.1%, s.d. = 0.026; post-video: mean = -0.09%, s.d. = 0.033; $p = 0.814$). In contrast, the congruency sequence effect was 1.5% higher in the post- (mean = 0.7%, s.d. = 0.36) versus pre-urban video test phase (mean = -0.8%, s.d. = 0.037; $t(34) = -1.781$, $p = 0.084$). This shows that during the pre-urban video test phase, accuracy was 8% lower on repeat versus novel trials, which is an unusual effect. In comparison, similar to previous studies (Egner, 2007), accuracy was 7% higher on repeat versus novel trials during the post-urban video test phase. Nevertheless, congruency sequence effect in the post-urban and post-nature video test phases did not significantly differ ($p = 0.2$). This suggests that although the urban video modulated cognitive control, urban and nature videos did not result in distinct style of cognitive control. Notably, these effects were not modulated by distractor-type ($p = 0.860$).

Relationship between threat bias and congruency sequence effect

In contrast with the implications of Holmes et al.'s (2014) results, there was not a significant relationship between threat bias and the congruency sequence effect after the urban video; $R^2_{adj} = -0.026$, $F(1, 34) = 0.131$, $p = 0.720$, showing that the use of reactive control is unlikely to account for threat bias induced by the urban video (see *Fig*. 2.4).

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[1] This effect was only marginally significant in ANOVA conducted to assess threat bias ($p = .058$).

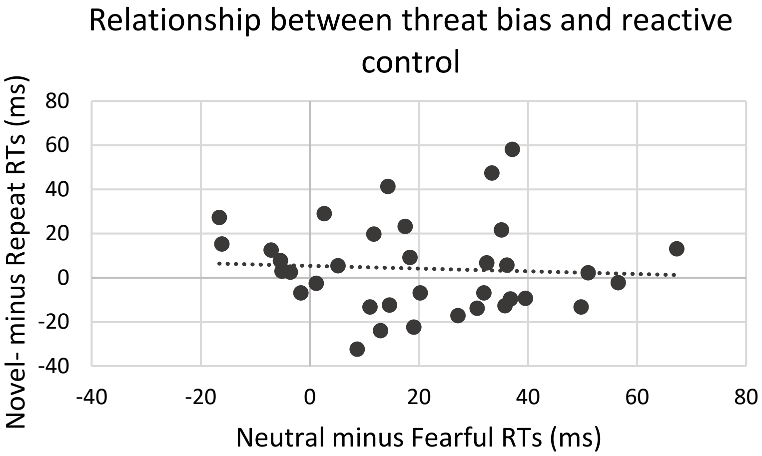

Figure 2.4. Relationship between threat bias and reactive control. Group mean threat bias was calculated as RTs for fearful distractors minus that for neutral distractors. Group mean reactive control was calculated as RTs for novel trials minus that for repeat trials.

Mood Effects

Participants reported lower levels of relaxation and high levels of positive mood after the urban than nature walk. Relaxation ratings and PANAS subscale scores before and after the urban and nature videos are shown in *Table* 2.2. Analysis of pre-video mood measures revealed no significant difference between the urban and nature videos (all *p*'s > 0.23). Subsequent analyses of the post-video mood measures revealed that relaxation ratings were significantly lower after the urban (mean = 4.7, s.d. = 1.1) versus nature video (mean = 5.3, s.d. = 0.9; Z = -2.457, *p* = 0.014). In comparison, post-video scores for the positive subscale of the PANAS were significantly higher after the urban (mean = 24.6, s.d. = 9.8) versus nature video (mean = 21.4, s.d. = 7.9; Z = -2.875, *p* = 0.004). PANAS negative subscale scores were unaffected by video-type (*p* = 0.075). Additionally, participants who watched the nature versus urban video on Day 1 did not differ on any of the DASS-21 subscales (all *p*'s > 0.351; see *Table* 2.3). Finally, post-urban video mood measures did not significantly predict post-urban-video threat bias (all *p*'s > 0.084), indicating that these measures did not contribute to threat bias.

Mood measure	Video-type	Test phase	Rating/score
Relaxation	Urban	Pre-video	4.3 (1.2)
		Post-video	4.7 (1.1)
	Nature	Pre-video	4.5 (1)
		Post-video	5.3 (0.9)
PANAS positive subscale	Urban	Pre-video	23.3 (8.3)
		Post-video	24.6 (9.8)
	Nature	Pre-video	21.4 (7.9)
		Post-video	20.9 (9.6)
PANAS negative subscale	Urban	Pre-video	12.2 (2.5)
		Post-video	12 (2.6)
	Nature	Pre-video	11.9 (2)
		Post-video	11.1 (1.6)

Table 2.2. Group mean relaxation ratings as well as PANAS positive and negative subscale scores before and after the urban and nature videos. S.d. are shown in parentheses.

DASS-21 subscale	First session	Score
Depression	Urban	2.8 (2.2)
	Nature	3.6 (5.3)
Anxiety	Urban	3.4 (5)
	Nature	4.5 (6)
Stress	Urban	6.2 (4.6)
	Nature	6.1 (5.3)

Table 2.3. Group mean scores for each subscale of the DASS-21 for participants who watched the urban or nature video first. S.d. are shown in parentheses.

Discussion

In summary, attention bias results showed that distraction RTs costs for neutral and happy face expressions were unaffected by video-type, suggesting that attention biases towards faces in general or towards faces with happy expressions were not influenced by artificial urban versus nature exposures. Importantly, however, distraction costs for fearful faces were greater after watching the urban versus nature video. This indicates that as predicted, artificial urban exposures clearly induced attention bias towards fearful facial expressions, while artificial nature exposure did not modulate threat bias.

Cognitive control results showed similarly small congruency sequence effects on response accuracy before and after the nature video, demonstrating that artificial nature exposure did not modulate cognitive control compared to baseline. In contrast, after the urban video, there was a trend towards higher accuracy on repeat than novel trials, an effect that was absent during baseline. Despite this, participants did not use distinct style of cognitive control after the urban and nature videos, contradicting my hypothesis.

Experiment 2

In contrast with the videos used in Experiment 1 that only captured the visual aspects of urban and natural environments, physically being in these settings allows people to experience multiple aspects of both environments, such as visual, auditory, and olfactory stimuli. Due to this key difference between artificial and physical exposures, effects seen in Experiment 1 may not generalise to physical exposures. To investigate the effect of physical urban and nature exposures on threat bias and cognitive control, I conducted a second experiment, where instead of watching videos, participants walked either through urban streets or in a nature reserve for twenty-five minutes then completed the face attention task. Similar to Experiment 1, I was interested in the distraction cost of fearful faces and the magnitude of the congruency sequence effect.

Methods

Procedure

The experiment consisted of a single session. First, participants completed the DASS-21 reporting feelings over the last week. Afterwards, participants went on a 25-minute (s.d. = .69) urban or nature walk. The urban walk was through urban streets along a busy road in Selly Oak, Birmingham, United Kingdom. The nature walk took place in a nature reserve called the Winterbourne Gardens, Birmingham, United Kingdom, where participants walked along a path among trees and bushes. Pictures of the urban and nature walks are shown in *Figure* 2.5. Participants walked in pairs and were accompanied by two researchers. They were restricted from talking to each other or using their phones. Participants were randomly assigned to the walks (urban: N = twenty-six; nature: N = thirty-two). The start of both walks was approximately two minutes away from the testing room where the face attention task was completed after the walks. As in Experiment 1, participants rated their relaxation levels and completed the PANAS before and after their walk.

Figure 2.5. Environment where the urban (left) and nature (right) walks took place.

Data analysis

To investigate threat bias, individual accuracy and average RTs for distractor-type (scrambled, neutral, happy, fearful) and walk-type (nature, urban) were analysed using 4 x 2 mixed-design ANOVAs with distractor-type as within-subject factor and walk-type as a between group factor. Mauchly's Test of Sphericity was used for these ANOVAs. Follow-up analyses used paired samples t-tests (2-tailed). Bonferroni corrections were applied where necessary and alpha levels were set at .0125.

To examine cognitive control, individual proportion of correct trials and average RTs for each trial-type (repeat, novel), distractor-type (neutral, happy, fearful) and walk-type were analysed using 2 x 3 x 2 mixed-design ANOVAs with trial-type and distractor-type as within-subject factors and walk-type as a between group factor. Mauchly's Test of Sphericity was used for these ANOVAs. Follow-up analyses used independent and paired samples t-tests (2-tailed). For all other analyses, Bonferroni corrections applied where necessary and alpha levels were set at .017.

Analysis of scales and ratings matched that in Experiment 1. However, instead of threat bias, I assessed whether post-video relaxation ratings and post-video PANAS subscale scores were predictive of cognitive control using linear regression.

Results

Threat bias

As in Experiment 1, participants were less distracted by scrambled meaningless images than faces. Omnibus analysis of RTs showed a significant main effect of distractor-type, $F(3,168) = 10.243$, $p < 0.001$, $\eta^2_p = 0.155$. Follow-up analysis revealed faster RTs on scrambled (mean = 554 ms, s.d. = 109) versus face distractor trials (mean = 580 ms, s.d. = 106; $t(57) = -4.607$, $p < 0.001$), indicating that scrambled meaningless images interfered less with task performance than the other distractors. RTs on neutral, happy, and fearful distractor trials did not differ (all *p*'s > 0.144), showing that there was no overall attention bias towards fearful faces. Threat bias was similarly absent after both the urban and nature walks as indicated by the lack of interaction between distractor-type and walk-type ($F(3,168) = 1.199$, $p < 0.312$, $\eta^2_p = 0.021$).

Omnibus analyses of accuracy showed no significant effects (all *p*'s > 0.692), indicating that the above effect is not due to a speed-accuracy trade-off.

Congruency sequence effect

Similar to Experiment 1, participants responded 15 ms more quickly on repeat (mean = 580 ms, s.d = 114) than novel trials (mean = 595 ms, s.d = 121; *F*(1,56) = 9.393, *p* = 0.003, η^2_p = 0.144). Notably, this effect was modulated by distractor-type; *F*(1,112) = 3.115 *p* = 0.048, η^2_p = 0.053. Subsequent analysis revealed that RTs were faster on repeat (mean = 576 ms, s.d. = 112) than novel trials (mean = 608 ms, s.d = 119) when the distractor was a happy face; *t*(57) = 3.284, *p* = 0.002). However, RTs did not differ between repeat and novel trials when the distractor was a neutral (repeat: mean = 583 ms, s.d. = 118; novel: mean = 588 ms, s.d. = 122; *p* = 0.431) or fearful face (repeat: mean = 581 ms, s.d. = 113; novel: mean = 588 ms, s.d. = 0.112; *p* = 0.399)

Finally, omnibus analysis of RTs showed a nearly significant interaction between trial-type and walk-type, *F*(1,56) = 3.519, *p* = 0.066, η^2_p = 0.059. Follow-up analysis revealed a 20 ms larger congruency sequence effect after the urban versus nature walk; *t*(56) = 2.247, *p* = 0.029, see *Fig*. 2.6). The minimal congruency sequence effect of -5 ms (s.d = 33) after the nature walk indicates proactive control whereas the relatively large group mean congruency sequence effect of 15 ms (s.d = 35) after the urban walk indicates reactive control. Importantly, this shows that participants used reactive control after the urban walk and used proactive control after the nature walk. Notably, distractor-type did not interact with any factors (*p* > 0.203).

Omnibus analyses of accuracy showed no significant effects (all *p*'s > 0.203), indicating that the above effects are not due to a speed-accuracy trade-off.

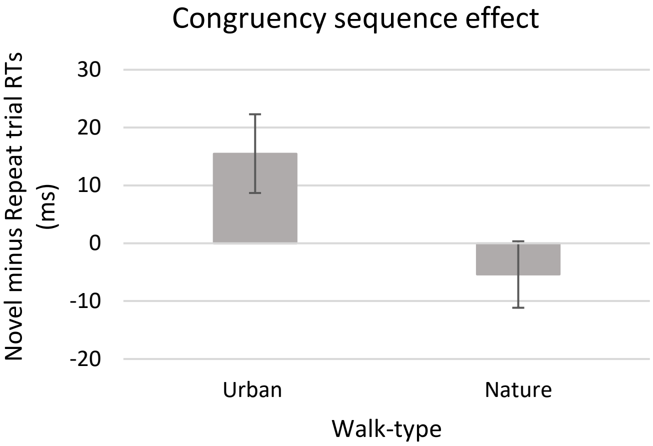

Figure 2.6. Group mean congruency sequence effect after walking in the urban (left) and nature (right) environments. Congruency sequence effect is calculated by subtracting reaction times (RTs) on repeat from novel trials. Error bars show standard error.

<u>Mood effects</u>

Participants reported lower relaxation levels after the urban than the nature walk. Relaxation ratings and PANAS subscale scores before and after the urban and nature videos are shown in *Table* 2.4. Analyses of pre-walk mood measures revealed no significant difference between the two walks (all *p*'s > 0.378). However, analysis of post-walk mood measures revealed lower relaxation levels after the urban (mean = 4.3, s.d. = 0.98) than nature walk (mean = 4.9, s.d. = .91; Z = -1.993, *p* = 0.046). In comparison, scores did not differ after the walk on either the positive (*p* = 0.651) or negative PANAS subscales (*p* = 0.940). Additionally, participants who completed the urban versus nature walk did not differ on any of the DASS-21 subscales (all *p*'s > 0.393; see *Table* 2.5). Finally, post-urban video mood measures did not significantly predict the magnitude of congruency sequence effect (all *p*'s > 0.492), indicating that these measures did not contribute to cognitive control.

Mood measure	Walk-type	Test phase	Rating/score
Relaxation	Urban	Pre-video	4.5 (0.8)
		Post-video	4.4 (1)
	Nature	Pre-video	4.6 (0.9)
		Post-video	4.9 (0.9)
PANAS positive subscale	Urban	Pre-video	26.5 (6.6)
		Post-video	27.9 (9.2)
	Nature	Pre-video	25.1 (6.8)
		Post-video	26.4 (8.7)
PANAS negative subscale	Urban	Pre-video	12.1 (2)
		Post-video	11.4 (2.1)
	Nature	Pre-video	12.4 (3.1)
		Post-video	11.6 (2.1)

Table 2.4. Group mean relaxation ratings as well as PANAS positive and negative subscale scores before and after the urban and nature walks. S.d. are shown in parentheses.

DASS-21 subscale	First session	Score
Depression	Urban	4.3 (3.1)
	Nature	4.2 (3.7)
Anxiety	Urban	4.8 (3.5)
	Nature	4.4 (4.5)
Stress	Urban	7.3 (4.3)
	Nature	7.3 (4.5)

Table 2.5. Group mean scores for the depression, anxiety, and stress subscales of the DASS-21 for participants who walked in an urban or natural environment. S.d. are shown in parentheses.

Discussion

Attention bias results showed that distraction cost for fearful face distractors was unaffected by walk-type, suggesting that unlike artificial exposure, physical urban exposure did not lead to enhanced attention allocation to threat-related face stimuli.

Cognitive control results showed that in line with our hypothesis, RTs congruency sequence effect was relatively large after the urban walk, indexing reactive control, and was relatively small after the nature walk, indexing proactive control. Overall, these effects highlight that artificial and physical exposures to natural and urban environments clearly have distinct effects on both threat bias and cognitive control.

Experiment 3

Similar to brief exposures in the present, chronic urban and nature exposures during childhood may affect threat bias and cognitive control in young adulthood. Supporting this, neuroimaging studies demonstrated that urban upbringing resulted in elevated activity in the adult amygdala (Streit et al., 2014), the region that is thought to underpin threat bias (see Vuilleumier, 2005 for review). Furthermore, urban upbringing has been linked with reduced grey matter volume in the adult prefrontal cortex (PFC; Haddad, 2015; Besteher, Gaser, Spalthoff, & Nenadić, 2017; Zhang et al., 2018), an area that is involved in cognitive control (Braver, 2012). Yet, direct investigation of the effect of childhood environment on threat bias and cognitive control in adulthood is currently lacking. Therefore, to examine the effect of chronic childhood exposure to urban and natural environment on threat bias and cognitive control in young adulthood, I conducted a third experiment where participants also completed the face attention task. I measured distraction cost of fearful faces to index threat bias and the magnitude of the congruency sequence effect to index the use of proactive and reactive control. Additionally, I determined the extent to which each participants' childhood environment was urban versus non-urban and naturally more- versus less-green to index chronic childhood urban and nature exposures.

Methods

Procedure

The experiment consisted of a single online session. First, participants completed a questionnaire that queried home postcode for each year of life from birth to present. Afterwards, they completed the face attention task.

Data analysis

Scales. In line with previous studies (Mortensen et al., 1999; Lederbogen et al., 2011; Lundberg, Cantor-Graae, Rukundo, Ashaba, & Östergren, 2009), environments were categorised using home postcodes for the childhood period of the first fifteen years of life.

Childhood environments were categorised as urban versus non-urban using a conventional urbanicity metric that uses population size of each place of residence during childhood (Mortensen et al., 1999). Population size of each place of residence was determined based on the 2011 Census data (https://www.ons.gov.uk/census/2011census/2011censusdata). Each place of residence was assigned a score based on population size (1 – <10,000, 2 – 10,000-100,000, 3 – >100,000), then multiplied by years dwelt there. Products were then summed over the childhood period to determine the final urbanicity score (values range from fifteen to forty-five). Urbanicity score of forty-five indicates urban childhoods (Mortenen et al., 1999; Lederbogen et al., 2011). Typically, urbanicity scores below forty-five are split to represent childhoods in towns (score of thirty) versus rural areas (score of fifteen). As only seven participants grew up in a rural area, participants who spent their childhood in a town or rural area were grouped together. Therefore, all urbanicity scores below forty-five indicated non-urban childhoods. Based on this, thirty-six participants had urban childhoods and forty-four participants had non-urban childhoods (see *Table* 2.6).

Childhood environments were categorised as more- versus less-green based on neighbourhood greenness that was defined as a combination of land cover by private and public green spaces (White, Alcock, Wheeler, & Depledge, 2013; Martin et al., 2020; Mueller & Flouri, 2020), using the Generalised Land Use Database Statistics for England (Office of the Deputy Prime Minister, 2005). In this database, land use for 32,482 neighbourhoods (called lower-layer super output areas; LSOAs) was defined. Neighbourhoods encompass similar areas (average size of four km^2) with an average population size of 1,500 residents. To calculate neighbourhood greenness for each place of residence, land cover by private gardens and public green space was summed then divided by the total land cover for each neighbourhood. This score was multiplied by the number of years dwelt there. Products were then summed over the childhood period to determine the final neighbourhood greenness score. Based on the final scores, forty participants' childhood environment was categorised as more-green and another forty's as less-green using median split (see *Table* 2.6). On average, participants in the less-green group had a neighbourhood score of 846 (s.d. = 173) that is 294 lower than the national average over the childhood period (1140). In contrast, participants in the more-green group had a neighbourhood greenness score of 1269 (s.d. = 135) that is 129 higher than the national average over the childhood period. Distribution of neighbourhood greenness scores in the less- versus more-green groups is shown in Figure 2.7.

Notably, urbanicity and neighbourhood greenness scores were strongly correlated ($r_s = -.589$, $N = 80$, $p < .001$; see *Fig*. 2.8), showing that higher urbanicity scores were associated with lower neighbourhood greenness scores. Scores for these scales were combined to quantify participants' overall childhood environment. To do this, first, scores for each scale were turned into Z-scores by the following formula: individual score minus group mean divided by group standard deviation. Neighbourhood greenness Z-scores were then reversed so that positive values became negative and vice versa, so that higher Z-scores represented less green environments. Z-scores for each scale were then summed to create a single score, called overall childhood environment. High scores for this new scale represented childhood environments that had high population size and low levels of neighbourhood greenness, characteristics that have been linked to negative outcomes, such as poorer mental health (Lundberg et al., 2009; Peen et al., 2010; Engemann et al., 2018; 2019; 2020) or poorer cognition (Tennessen & Cimprich, 1995; de Fockert, Caparos, Linnell, & Davidoff, 2011; Linnell, Caparos, de Fockert, & Davidoff, 2013). Applying median split to final overall childhood environment scores, forty participants' childhood environments were categorised as 'better childhood environment' and another forty's a 'worse childhood environment' (see *Table* 2.6).

Distribution of overall childhood environment scores in the worse versus better childhood environment groups is shown in Figure 2.7.

	Urban		Non-urban	
	More-green	Less-green	More-green	Less-green
Worse childhood environment	8	27	1	4
Better childhood environment	1	0	30	9

Table 2.6. Number of participants in urban versus non-urban and more- versus less-green groups within the worse and better childhood environment groups.

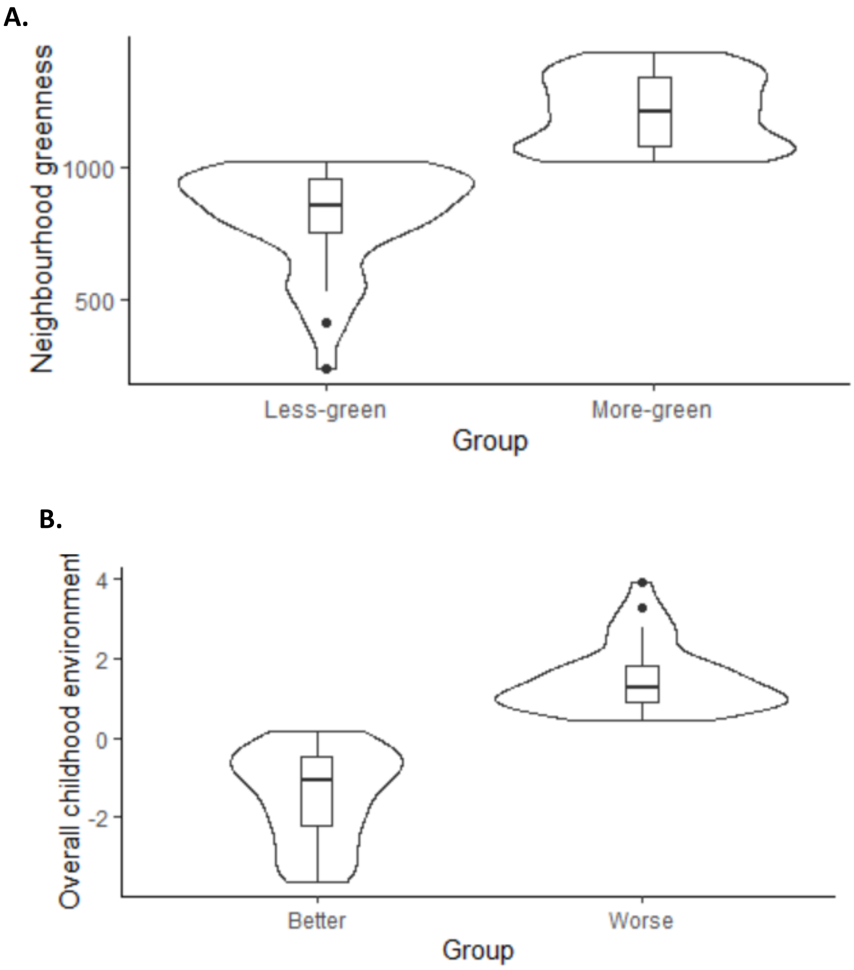

Figure 2.7. **A.** Distribution of neighbourhood greenness scores in the more- (left) versus less-green groups (right). **B.** Distribution of overall childhood environment scores in the better- (left) versus worse childhood environment groups (right).

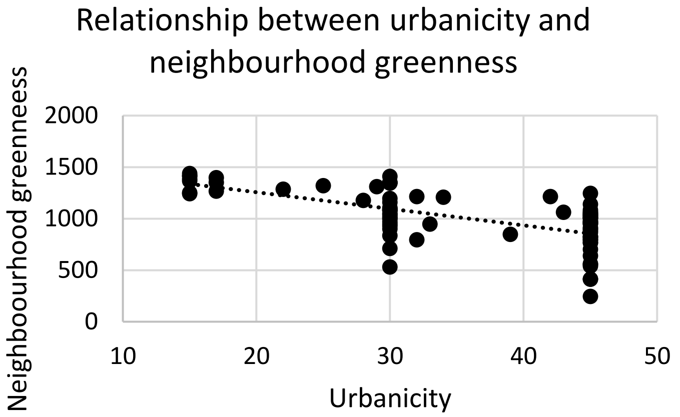

Figure 2.8. Relationship between urbanicity and neighbourhood greenness scores. Urbanicity scores were calculated using population size whereas neighbourhood greenness scores were calculated using the amount of the neighbourhood covered by private and public green spaces.

Face attention task. To investigate the effect of childhood environment on threat bias, individual accuracy and average RTs for each distractor-type (scrambled, neutral, fearful) were analysed using 3 x 2 mixed-design ANOVAs with distractor-type as within-subject factors and overall childhood environment (worse childhood environment, better childhood environment) as between group factor. To investigate the effect of specific features of childhood environment, these ANOVAs were then replicated with urbanicity (urban, non-urban) or neighbourhood greenness (more-green, less-green) as the between group factor instead.

To investigate the effect of childhood environment on cognitive control, individual accuracy and average RTs for each trial-type (novel, repeat) and distractor-type (neutral, fearful) were analysed using 2 x 2 x 2 mixed-design ANOVAs with trial-type and distractor-type as within-subject factors and overall childhood environment (worse childhood environment, better childhood environment) as between group factor. To investigate the effect of specific features of childhood environment, these ANOVAs were then replicated with urbanicity (urban, non-urban) or neighbourhood greenness (more-green, less-green) as the between group factor instead.

Mauchly’s Test of Sphericity was used for all ANOVAs. Follow-up analyses used paired samples t-tests (2-tailed). Bonferroni corrections were applied were necessary and alpha levels were set at .017.

In addition to these ANOVAs, I also investigated whether childhood environment predicted either threat bias or cognitive control. Therefore, I conducted linear regressions with distraction cost for fearful faces or congruency sequence effect as dependent variable and overall childhood environment, urbanicity or neighbourhood greenness as predictor. Alpha levels were set at .05.

Results[2]

Threat bias

In line with Experiments 1 and 2, participants responded more quickly and accurately on scrambled versus face distractor trials. Omnibus analysis of RTs revealed a significant main effect of distractor-type, $F(2,156) = 11.883$, $p < 0.001$, $\eta^2_p = 0.132$. Subsequent analysis showed faster RTs on scrambled (mean = 609 ms, s.d. = 60) versus face distractor trials (mean = 622 ms, s.d. = 63; $t(78) = 4.750$, $p < 0.001$), indicating that scrambled meaningless images interfered less with task performance than face distractors. RTs on neutral and fearful distractor trials did not differ ($p = 0.562$), demonstrating that there was no overall threat bias. Notably, this was not

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[2] Unless stated otherwise, values describing all effects were taken from the ANOVAs with overall childhood environment as a between group factor, and similar size effects were also present in the ANOVAs with urbanicity or neighbourhood greenness groups as a between group factor. Furthermore, effects remained the same when 1) childhood length was reduced to 10 years (Engemann et al., 2018; 2019; 2020), 2) neighbourhood greenness was defined using public green space only (Ord, Mitchell, & Pearce, 2013; Weeland, Lacuelle, Nederhof, Overbeek, & Reijneveld, 2019), and 3) neighbourhood greenness groups were defined using the national average instead of median split.

modulated by overall childhood environment (p = 0.608), suggesting that childhood environment did not affect threat bias in young adulthood. Focusing on specific features of childhood environment, the extent to which each distractor interfered with task performance was not modulated by either urbanicity (p = 0.777) or neighbourhood greenness (p = 0.856), showing that childhood environments did not modulate threat bias in young adulthood.

Omnibus analysis of accuracy also showed a significant main effect of distractor-type, $F(2,156) = 11.628$, $p < 0.001$, $\eta^2_p = 0.130$. Follow-up analysis showed higher accuracy on scrambled (mean = 89%, s.d. = 7) versus face distractor trials (mean = 86%, s.d. = 7; $t(78) = 4.780$, $p < 0.001$). Accuracy on neutral and fearful distractor trials did not differ (p = 0.458). As both RTs and accuracy were better on scrambled distractor trials, these effects are not due to speed-accuracy trade-off. This effect was not modulated overall childhood environment (p = 0.1). Notably, however, the effect of distractor-type was modulated by urbanicity; $F(2,156) = 3.215$, $p = 0.043$, $\eta^2_p = 0.04$. Subsequent analysis revealed that distraction accuracy cost for face distractors (difference between scrambled versus face distractor trials regardless of emotional expression) was 2.8% higher in the non-urban (mean = 3.9%, s.d. = 4.4) than urban group (mean = 1.1%; s.d. = 5; $t(78) = 2.646$, $p = 0.01$), indexing greater attention allocation to faces compared to meaningless scrambled images. However, distraction accuracy cost for fearful faces (difference between neutral versus fearful face trials) did not differ between the non-urban (mean = -1%, s.d. = 7.5) and urban groups (mean = -0.5%, s.d. = 4.4; $p = 0.730$), further supporting that chronic childhood exposure to urban environment did not modulate threat bias in young adulthood. Furthermore, effect of distractor-type was not modulated by neighbourhood greenness (p = 0.219), further supporting that chronic childhood exposure to natural environments did not modulate threat bias in young adulthood either.

Congruency sequence effect

In line with Experiment 1 and 2, participants responded more quickly on repeat (mean = 622ms, s.d. = 62) than novel trials (mean = 630 ms, s.d = 72; $F(1,78) = 3.240$, $p = 0.076$, $\eta^2_p = 0.040$). Notably, this effect was not modulated by childhood environment (p = 0.944). Focusing on features of childhood environments, congruency sequence effect was not modulated by urbanicity ($p = 0.992$) or neighbourhood greenness ($p = 0.756$) either, demonstrating that neither feature of childhood environment modulated cognitive control in young adulthood.

In line with previous findings (Egner, 2007), omnibus analysis of accuracy revealed a main effect of trial-type; $F(1,78) = 3.946$, $p = 0.051$, $\eta^2_p = 0.048$, indicating that accuracy was higher on repeat (mean = 87%, s.d. = 7.5) than novel trials (mean = 85%, s.d. = 10). Additionally, omnibus analysis of accuracy also revealed a marginally significant main effect of distractor-type, $F(1,78) = 3.566$, $p = 0.063$, $\eta^2_p = 0.044$, indicating that accuracy was higher on fearful (mean = 85%, s.d. = 9.1) than neutral distractor trials (mean = 87% s.d. = 8.9).3 Notably, neither of these effects were modulated by childhood environment ($p > 0.1$). In line with this, congruency sequence effect in accuracy was not affected by urbanicity ($p > 0.1$) nor neighbourhood greenness ($p > 0.480$), further demonstrating that childhood environment did not modulate cognitive control in young adulthood.

Regressions

There was no significant relationship between distraction cost for fearful faces in young adulthood and overall childhood environment ($R^2_{adj} = -0.013$, $F(1, 78) = 0.001$, $p = 0.972$), urbanicity ($R^2_{adj} = -0.011$, $F(1, 78) = 0.121$, $p = 0.729$) or neighbourhood greenness ($R^2_{adj} = -0.01$,

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[3] ANOVA with neighbourhood greenness as a between group factor shows no significant main effects of trial-type ($p = 0.378$) and distractor-type ($p = 0.668$).

F(1, 78) = 0.118, *p* = 0.666). These support the conclusion that threat bias in young adulthood was not influenced by childhood environments.

Similarly, there was no significant relationship between the magnitude of the congruency sequence effect in young adulthood and overall childhood environment (R^2_{adj} = -0.003, *F*(1, 78) = 0.223, *p* = 0.638), urbanicity (R^2_{adj} = -0.011, *F*(1, 78) = 0.120, *p* = 0.730) or neighbourhood greenness (R^2_{adj} = 0.04, *F*(1, 78) = 1.330, *p* = 0.252). These support the conclusion that cognitive control was not influenced by childhood environment.

Discussion

Overall, I found that adults who were raised in non-urban versus urban environment showed a greater distraction accuracy cost for all face stimuli regardless of emotional expression, illustrating that chronic childhood exposure to non-urban environments led to greater attention allocation to all faces. Importantly, however, in contrast with my hypothesis, neither distraction cost for fearful faces nor the magnitude of the congruency sequence effect were modulated by childhood environment. This demonstrates that unlike brief exposures, chronic urban and nature exposures during childhood did not modulate threat bias nor cognitive control in young adulthood. This is further supported by the lack of relationship between childhood environment and threat bias or cognitive control.

General discussion

In three experiments, I contrasted the effects of urban and nature exposures on threat bias and cognitive control. To assess these, participants in all three experiments engaged in a visuospatial attention task in which a neutral target face was flanked by a scrambled meaningless image or a face displaying either a neutral, happy, or fearful expression. Experiment 1 examined the effect of artificial exposures to these environments by asking participants to view an immersive 25-minute video of a walk through urban streets or a nature reserve before and after completing the task. Experiment 2 explored the effect of physical urban and nature exposures by asking participants to go on a 25-minute walk through urban streets or a nature reserve before completing the task. Finally, Experiment 3 tested whether chronic exposures to urban and natural environments during childhood have long-term effects that last into young adulthood. For this purpose, I determined the extent to which each participants' childhood environment was urban versus non-urban as well as naturally more- versus less-green.

Focusing on threat bias results, distraction cost for fearful face expressions were greater after artificial urban versus nature exposure, indicating that artificial urban exposure induced attention bias towards fearful facial expressions. In contrast, I found no evidence for threat bias after either physical or chronic childhood exposures to urban or natural environments. Moving on to cognitive control results, I found minimal congruency sequence effects after physical nature exposure and a relatively large congruency sequence effects after physical urban exposure. This demonstrates that physically spending time in a natural environment promoted proactive control, whereas physically spending time in an urban environment promoted reactive control. Although the congruency sequence effect was modulated by artificial urban exposures compared to baseline, artificial urban versus nature exposures did not lead to distinct style of cognitive control. Similarly, chronic childhood exposure to urban and natural environments did not modulate the magnitude of the congruency sequence effect, suggesting that similar to threat bias, childhood environments did not have long-term effect on cognitive control that lasted into young adulthood.

Threat bias

Interestingly, artificial urban exposure induced threat bias. This may be due to the urban video increasing anxiety levels, a state associated with enhanced vigilance towards threat-related stimuli (see Bar-Haim et al., 2007 for review). Arguing against this possibility is that despite relaxation levels indicating lower anxiety levels after versus before the videos, no threat-related attention bias was detected before video viewing. Furthermore, comparable relaxation levels after the urban walk in Experiment 2 did not result in threat bias. Finally, there was no relationship between relaxation ratings or PANAS subscale scores and distraction cost for fearful faces after the urban video, casting doubt on the idea that anxiety levels could account for threat bias after artificial urban exposure.

An alternative explanation for this effect may be that the urban video presented many faces whereas the nature video had none. As faces seen in the video were never fearful (largely neutral), some form of priming by fearful faces cannot account for threat bias after stimulated urban exposure. However, the urban video showed crowds of people in close proximity to the camera (participant’s viewpoint), creating a stimulus configuration known to activate the amygdala (Kennedy, Gläscher, & Adolphs, 2009), a region closely linked to threat-related attention bias (see Vuilleumier, 2005 for review). This highlights that crowds may be an important feature of urban environments that contributes to subsequent threat bias.

In contrast with artificial exposure, physical urban exposure did not result in threat bias. This suggests that artificial and physical urban exposures differentially affected attention functioning. This is particularly interesting as stimulated and physical nature exposures have been shown to have similar effects on attention functioning (Gatersleben & Andrews, 2013), suggesting that differences in the effect of artificial versus physical exposures may be specific to urban environments. Importantly, however, unlike in Gatersleben and Andrews’ experiment, participants during the artificial and physical exposures were exposed to different urban environments. Therefore, distinct effect of these exposures may be due to differences in the environments instead of the exposure methods themselves. For example, as the walks were not recorded, it is possible that participants have seen too few faces during the urban walk to increase activity in the amygdala and thus to induce threat bias. If so, this further supports the notion that crowds of strangers are critical urban features for heightened threat bias and urban environment without lots of people might not elicit threat bias.

Similar to physical urban exposure, urban upbringing did not result in threat bias. This is surprising as urban upbringing has been shown to increase activity in the amygdala (Streit et al., 2014), a region that is thought to underpin threat bias (see Vuilleumier, 2005 for review). This lack of effect may be explained by the non-associative fear acquisition account that argues that although people are born with a fear of certain stimuli, such as fearful faces, repeatedly experiencing these stimuli as harmless allows habituations (see Hoehl & Pauen, 2017 for review). This suggests that participants who were raised in urban environments did not show enhanced allocation to fearful faces because they were regularly exposed to a large number of fear-related faces during childhood, leading to habituation and therefore reduced attention allocation to such stimuli. Supporting this, participants who were raised in an urban versus non-urban environment that are abundant with faces (Abbott, 2012; Hartig & Kahn, 2016) allocated less attention to all faces compared to meaningless scrambled images. Notably, if the lack of effect is indeed due to habituation to faces, urban upbringing may still result in enhanced attention allocation to threatening non-face stimuli that also activate the amygdala, such as snakes (Carlsson et al., 2004; Almeida, Soares, Castelo-Branco, 2015). However, this remains untested.

In summary, I found that only brief artificial and not brief physical or chronic childhood exposure to urban environments induced attention bias toward fearful facial expressions. This highlights that the effects of artificial urban exposures may not generalise to physical exposures. Furthermore, it shows that despite long-term changes in the amygdala that last into young adulthood, childhood environments did not have a long-term effect on threat bias.

Cognitive control

Importantly, brief physical urban exposure promoted reactive control and brief physical nature exposure promoted proactive control, indicating that these differentially influenced when attention was focused towards the target and away from distractors. As proactive control decreases whereas reactive control increases distractibility (Grimshaw, Kranz, Carmel, Moody, & Devue, 2018), these results might explain why nature versus urban exposures result in superior distractor suppression (Berman, Jones & Kaplan, 2008; Gamble, Howard, & Howard, 2014; Bailey, Allen, Herdon, & Demastus, 2018).

As suggested by the ART as well as Taylor et al. (2002) and Jenkin et al. (2018), greater reliance on reactive control after physical urban versus nature exposures may be due to urban exposures depleting central cognitive resources, thus reducing the ability to apply proactive instead of reactive control. Alternatively, differences in cognitive control after these exposures may be underpinned by nature exposure improving the ability to apply cognitive resources (Kaplan & Kaplan, 1989, Kaplan, 1995; 2001) and thus proactive control. Supporting this, Van der Wal, Schade, Krabbendam and van Vugt (2013) found that viewing pictures of natural environments improves participants' ability to resist immediate small reward on a Delay Gratification Task, indexing the availability of central cognitive resources after nature exposure.

In contrast with ART, the 'shifting' notion (Linnell & Caparos, 2020) argues that instead of causing an impairment, physical urban and nature exposures merely alter the mode of attention. According to this notion, urban environments shift attention towards an exploratory mode that is comparable to reactive control as they both allow all stimuli to capture attention. In contrast, natural environments shift attention towards a focused mode that is comparable to proactive control as they both bias processing towards task-relevant stimuli thus reducing distractibility. Therefore, the 'shifting' notion suggests that urban exposures did not impair proactive control, but instead they shifted cognitive control towards reactive control thus reducing the likelihood of proactive control being applied. As participants were already applying proactive control at baseline, it is unclear whether nature exposures indeed increased the likelihood of proactive control being used. Interestingly, urban environments are thought to shift attention towards an exploratory mode and therefore reactive control because these are more beneficial in cities that are abundant with unexpected events (Atchley, Strayer, & Atchley, 2012; White & Shah, 2019; Linnell & Caparos, 2020) that would not be noticed if proactive control were applied.

Unlike physical exposure, brief artificial urban and nature exposures did not result in distinct style of cognitive control, despite the larger congruency sequence effect after the urban versus nature exposure. This lack of effect may be due to physical versus artificial exposures differentially modulating central cognitive resources. Despite Jenkin et al. (2018) showing that watching an urban video reduced resistance to immediate small reward, suggesting depleted central cognitive resources, Van der Wal, Schade, Krabbendam and van Vugt (2013) found no evidence for this. This suggests that urban videos do not reliably deplete central cognitive resources. Moreover, ART argues that urban environments deplete central cognitive resources because they provide a cognitively demanding environment where people need to effortfully attend to uninteresting stimuli while ignoring interesting ones in order to successfully function in cities (Kaplan & Kaplan, 1989, Kaplan, 1995; 2001). In contrast with this, participants could attend to anything in the video, meaning that the video was not cognitive demanding and therefore it is possible that they did not deplete central cognitive resources.

Similar to physical exposures, childhood environments did not modulate cognitive control. This is surprising as urban upbringing has been shown to modulate the PFC (Haddad, 2015; Besteher et al., 2017; Zhang et al., 2018), a region that is thought to be involved in cognitive control (Braver, 2012). As all participants lived in Birmingham, United Kingdom, at the time of the experiment, this as well as the lack of threat bias effects might be due to participants' current environment counteracting and effect of that their childhood environment might have had. An alternative explanation may be that residence is a crude way of categorising childhood environments. Although children and teenagers spend a lot of time near their homes, they often go to school or spend recreational time in different towns to where they live. As England has numerous cities that are close to rural areas, participants whose childhood environments were categorised as non-urban could have spent a lot of time in cities, thus regularly exposing themselves to large crowds. Arguing against this explanation, neuroimaging experiments that found that urban upbringing modulates the PFC also categorised childhood environments as urban versus non-urban based on population size of residence, therefore these studies would have also been affected by this, casting doubt on this explanation.

The lack of effect of childhood environment on cognitive control in young adulthood contradicts the long-term implications of the 'shifting' notion. Although numerous experiments demonstrated that during childhood, urban living results in exploratory mode of attention whereas living in natural environments results in focused mode of attention (Davidoff, Foneneau, & Fagot, 2008; de Fockert, Caparos, Linnell, & Davidoff, 2011; Caparos et al., 2012; Linnell, Caparos, de Fockert, & Davidoff, 2013; Bremner et al., 2016), this is the first experiment to show that these effects do not last into young adulthood.

In summary, I found strong evidence that brief urban exposures promote reactive control, whereas brief nature exposures promote proactive control, perhaps as an adaptation to enhance success in these environments. In contrast with brief exposures, chronic childhood exposure to urban and natural environments did not modulate cognitive control in young adulthood, demonstrating that despite long-term changes in the PFC, childhood environments did not have long-term effect on cognitive control that lasts into young adulthood.

Wider implications

Holmes et al. (2014) demonstrated that threat bias may at least in part be underpinned by reactive control. However, I found no relationship between congruency sequence effect and threat bias in Experiment 1. Furthermore, despite that both artificial and physical urban exposures promoted reactive control, only the artificial exposure induced threat bias, casting doubt on the notion that reactive control contributes to threat bias.

Numerous experiments demonstrated that urban versus non-urban dwellers have an elevated risk of developing mental disorders, such as schizophrenia as well as mood and anxiety disorders (Krabbendam & Van Os, 2005; Peen, Schoevers, Beekman, & Dekker, 2010; Engemann et al., 2020). Interestingly, similar to participants after physical urban exposures, patients with these disorders display greater reliance on reactive than proactive control (Krug & Carter, 2012; Lesh et al., 2013; Vanderhasselt et al., 2014). This suggests that the enhanced tendency to apply reactive control after physical urban exposure may contribute to the link between urban living and mental health disorders. In contrast, although threat bias has been suggested to contribute to anxiety disorders (Mathews & MacLeod, 2002), as physical urban exposures did not reliably induce threat bias, it is unlikely that threat bias could contribute to the association between urban living and anxiety disorders.

Similarly, urban versus non-urban upbringing is also associated with an elevated risk of schizophrenia and major depressive disorder (MDD; Marcelis, Navarro-Mateu, Murray, Selten, & van Os, 1998; Laursen, Munk-Olsen, Nordentoft, & Bo Mortensen, 2007; Lundberg et al., 2009), that result in greater reliance on reactive than proactive control. However, as childhood environment did not modulate cognitive control, it is unlikely that altered styles of cognitive control contributes to the relationship between urban upbringing and elevated risk of mental disorders.

Overall, I found that brief artificial urban versus nature exposure enhanced attention allocation to fearful facial expression but did not modulate cognitive control. In contrast, brief physical exposures did not affect threat bias. Instead, brief physical urban exposure promoted reactive control whereas brief physical nature exposure promoted proactive control, demonstrating that these had distinct short-term effects on cognitive control. Notably, unlike brief exposures, chronic childhood exposure to urban versus natural environments had no long-term effect on either threat bias or cognitive control that lasted into young adulthood.

Chapter 3. Differential brain responses to face stimuli after exposure to urban versus natural environments

Abstract

Despite numerous experiment investigating the effects of urban and natural environments on attention functioning, neurobiological evidence is lacking. Furthermore, it is unclear whether exposure to faces, a key feature of urban environments, contributes to the distinct effect of these environments on attention functioning. Therefore, I investigated how urban versus nature exposures affect neural substrates of attention, and whether the effect of urban exposure is underpinned by exposure to faces. I focused on the P1 event related potential component to measure early bottom-up attention allocation as well as theta oscillations to measure later top-down attention allocation. In two separate experiments, participants brain activity was measured while viewing a series of neutral and emotional (happy, fearful, and angry) faces in a gender discrimination task. Importantly, prior to this task, participants watched a 25-minute video of either an urban or nature walk from the observer's perspective. In Experiment 1, the urban video contained several hundred faces whereas the nature video contained none. To resolve this, in Experiment 2, all faces in the urban video were blurred beyond recognition so that neither the urban nor nature video contained any faces. For the first time, I showed that compared to the nature video, the urban video with faces resulted in greater bottom-up attention allocation to all faces as well as greater selective top-down attention allocation to angry faces (Experiment 1). Interestingly, these effects disappeared when the number of faces in the videos were controlled for (Experiment 2), suggesting that exposure to faces underpinned the effects seen in Experiment 1.

We are a species that is moving away from open skies and natural landscapes to an urbanized habitat that is mostly human-made, crowded, noisy, and lacking green space. This change is seemingly not without consequence. Numerous previous investigations found urbanisation to increase risk factors for mental health disorders that involve ‘selective attention’ (Krabbendam & Van Os, 2005; Kelly et al., 2010; Engmann et al., 2020), a fundamental cognitive process that affords us the ability to focus on relevant aspects of our environment while suppressing the irrelevant (Posner & Rothbart, 2007). This suggests that urban environments may impair attention functioning.

In comparison, several recent studies found that the amount of vegetation surrounding a school area significantly predicts standardized test scores and graduate rates (Matsuoka, 2010; Wu et al., 2014; McCormick 2017), illustrating that natural landscapes may support cognition. Specifically, previous work has observed that natural environments improve attention. For example, exposure to green environments decreased some of the attention deficits observed in children with attention deficit hyperactivity disorder (Kuo & Taylor, 2004). Moreover, watching a nature video led to more similar reaction times to targets presented at a cued versus uncued location (Laumann, Gärling, & Stormark, 2003), suggesting that natural settings improved the ability to disengage attention from distractors, an important aspect of attention functioning. Similarly, after viewing nature pictures, reaction times to targets presented with congruent versus incongruent distractors became more similar (Berman, Jones, & Kaplan, 2008; Gamble, Howard, & Howard, 2014), indicating that natural environments improved selective attention.

Despite evidence that exposure to urban versus natural environments can affect attention performance, there is an absence of neurobiological data on how exposures to these environments impact cognition. Furthermore, it is unclear why urban versus natural settings have distinct effects on attention functioning. One possible explanation is that urban versus natural environments are typically more crowded (Abbott, 2012; Hartig & Kahn, 2016) and therefore contain more faces. In support of this notion, numerous experiments demonstrated that exposure to faces affects subsequent cognition. For example, repeated exposure to distorted face images shifts the idea of an ‘average’ face towards that distortion (Rhodes, Jeffery, Watson, Clifford, & Nakayama, 2003). Moreover, exposure to faces results in faster and more accurate recognition of similar faces (Ellis, Young, Flude, & Hay, 1987; Walther, Schweinberger, Kaiser, & Kovács, 2013). Therefore, the objective of this chapter was to investigate how artificial exposure to urban versus natural environments modulate the brain’s processing of human faces and whether this is altered by changing the number of faces in the urban environment.

Attention is often conceptualised to consist of bottom-up and top-down processes (Lang, 1995; Itti & Koch, 2000; Corbetta & Shulman, 2002). Bottom-up processes capture attention automatically by the onset of a novel or salient stimulus in an otherwise homogenous display (Jonides & Yantis, 1988; Theeuwes, 1992; 1994). In comparison, top-down processes use mental templates of goal-relevant information or expected target features to bias attention allocation towards the target (Posner, Snyder & Davidson, 1980; Yantis & Johnston, 1990; Desimone & Duncan, 1995).

Brain activity underlying these attention processes can be measured non-invasively using electroencephalography (EEG), a method with excellent time resolution (1ms; da Silva, 2013; Cohen, 2017). EEG data contains at least two types of brain activity; slow stimulus evoked voltage changes called event related potentials (ERPs; Kapperman & Luck, 2011) as well as stimulus induced synchronous neuronal activity called oscillations (Thut, Miniussi, & Gross, 2012).

Bottom-up attention allocation is reflected by the P1 ERP component (Eason, 1981; Hillyard & Münte, 1984), that peaks around 100 ms at occipito-parietal locations (Luck & Kappenman, 2011). Larger P1 amplitude to attended versus unattended stimuli is believed to reflect facilitation of early stimulus processing (Mangun & Hillyard, 1988; Heinze et al., 1990; Gonzalez, Clark, Fan, Luck & Hillyard, 1994). Importantly, this is separate from later top-down attention processes (Luck, Heinze, Mangun, & Hillyard, 1990), that are reflected by theta, an oscillatory activity between 3-5 Hz with maximum power at mid-frontal channels (Phillips, Vinck, Everling, & Womelsdorf, 2014; Bastos et al., 2015).

In the current study, I conducted two separate experiments to investigate whether artificial urban versus nature exposures modulate bottom-up (indexed by P1 component) and top-down (indexed by theta activity) neural substrates of attention. Furthermore, I investigated whether the effect of urban environments on these substrates of attention is underpinned by exposure to faces. Therefore, in Experiment 1, participants' brain activity was measured while viewing a series of neutral and emotional faces as part of a gender discrimination task after watching a video that showed an urban or nature walk from the observer's perspective in two separate sessions. Importantly, the urban but not nature video contained several hundred faces. To foreshadow our findings, watching the urban video led to greater early bottom-up attention allocation to all faces as well as greater top-down attention allocation to angry faces. To investigate whether these effects are due to the urban video containing faces, in Experiment 2, all faces in this video were blurred beyond recognition so that neither the urban nor nature video contained any faces. Interestingly, this led to both effects seen in Experiment 1 disappearing.

General methods

Participants

24 young adults (17 females, mean age = 24.6 years, s.d. = 4.24) participated in the Experiment 1 and a new group of 24 young adults (21 females, mean age = 18.84 years, s.d. = .8) participated in the Experiment 2. Participants received course credit or cash in return for their participation. All participants were fluent English speakers, had normal or corrected-to-normal vision and were right-handed. They reported no history of psychiatric or neuropsychological disorders. Participants were recruited through the University's research participation scheme and posters. The study was approved by the University of Birmingham Ethics Committee.

Apparatus

A 24" desktop monitor (refresh rate, 59 Hz) and Dell computer controlled the presentation of experimental stimulus and recorded data using MatLab (R207a, Mathworks, 2007) running Psychtoolbox. Participants were seated 50 cm away from the screen in a quiet, dark, sound-proof room. They entered their responses using a traditional mouse.

Stimuli

Gender discrimination task. Stimuli consisted of a white fixation cross (0.5^o in diameter), and a single face image. Both were presented centrally on the screen. The face image subtended 10.5^o x 14^o and was set into a 10.9^o x 14.8^o rectangle. Forty colour photos of Caucasian adult faces (twenty-eight neutral, four fearful, four happy, and four angry) from the Karolinska Directed Emotional Faces dataset were used as stimuli (Lundqvist, Flykt, & Öhman, 1998). These were split into two equal but unique sets of photos. Half of the faces were female. All faces were shown with head hair, but without glasses, make-up, or facial hair. Teeth were visible in all fearful and happy faces.

Procedure

The experiment consisted of two sessions conducted one week apart at the same time of day. On both days, after the EEG setup, participants completed the Positive and Negative Affect Scale (PANAS; Watson, Clarke, & Tellegan, 1988) and rated their relaxation levels using a 6-point Likert scale (1 = very stressed, 6 = very relaxed). Afterwards, they watched one of the 25-minute videos without sound in a soundproof booth. The order of the videos was counterbalanced. De Kort, Meijenders, Sponselee and IJsselsteijn (2006) highlighted the importance of feeling present to benefit from nature exposure, therefore, participants were instructed to imagine that they are following the route shown in the videos. Afterwards, participants completed the PANAS and rated their relaxation levels again, before performing the gender discrimination task. Different sets of pictures were used in the two sessions and the order of these was counterbalanced.

Gender discrimination task. The procedure used in each trial in the gender discrimination task is illustrated in *Figure* 3.1. All trials started with a fixation cross being presented for 1000-1200 ms in the middle of a black screen. This was replaced by a face stimulus for 200 ms. Participants were asked to report the face's gender as quickly and accurately as possible using mouse click via the dominant hand. Response clicks were counterbalanced. The correct response was female on 50% of trials. The next trial started after the participant responded or when the response time (1000 ms) has elapsed. The next trial began immediately without any feedback. The maximum length of each trial was 2400 seconds. Response time (RT; interval between stimulus array onset and response) and accuracy (proportion of correct trials) were recorded. Neutral faces were shown on 70% of trials, and happy, angry, and fearful faces on 10% each. Stimuli were presented in a semi-random order so that 1) only neutral faces were presented on the first five trials of each block, 2) no more than six neutral faces were presented in a row, 3) emotional faces were not presented on two consecutive trials, and 4) two faces expressing the same emotion were not presented without another emotional expression in between. The task consisted of 1200 trials split into 20 blocks. Rest intervals between blocks were self-paced.

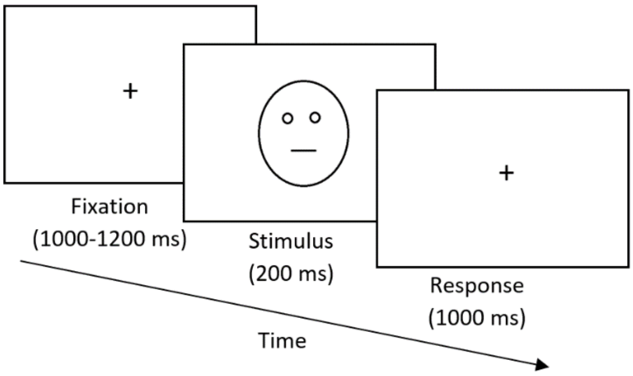

Figure 3.1. An illustration of an example trial in the gender discrimination task. The face is shown as cartoon for illustration purposes only. On each trial, a fixation cross was presented for 1000-1200 ms prior to the stimulus (200 ms). This was then followed by a 1000 ms response window. A speeded report of the target's gender was required.

Behavioural data analysis

RTs data were excluded for all incorrect trials, anticipations errors (RTs < 200 ms) and when RTs exceeded the individual's condition mean by more than three s.d.'s. All participants performed with at least 60% accuracy. One participant's behavioural data was lost due to computer failure in one of the sessions, therefore, only twenty-three datasets were included in the behavioural analysis.

Individual accuracy and average RTs for each video environment (urban, nature) and stimulus expression (neutral, happy, fearful, angry) were analysed using 2 x 4 repeated measures ANOVAs with video-type and stimulus expression as within-subject factors. Mauchly's Test of Sphericity was used for this ANOVA. Follow-up analyses used repeated measures *t*-tests (2-tailed).

Ratings and scales. PANAS ratings for positive and negative items (10 each) were summed separately to produce two scores. Pre- and post-video PANAS subscale scores and relaxation ratings were analysed using Wilcoxon Sign Ranks Test (2-tailed).

For all other analyses, Bonferroni corrections applied where necessary and alpha levels were set at .05.

EEG recording

EEG data was acquired using a 64-channel Ag/AgCl electrode 10-10 WaveGuard cap and eego^{TM} sports amplifier from ANT (http://www.ant-neuro.com). Eye movements were recorded with four electrodes placed on either side of the face as well as below and above the right eye. Impedences were below 20 kΩ**.** The data was recorded with Cpz as the reference and converted to an average reference montage offline (with the exclusion of the mastoid and bipolar electrodes). The data was acquired at a sampling rate of 500 Hz, using 80 Hz low pass and a 0.05 Hz high pass filters. Non-biological artefacts were rejected manually. Eye blinks and eye movements were rejected using the runica algorithm of Independent Component Analysis in EEGLAB (version 14; Delorme & Makeig, 2004).

EEG pre processing

Pre-processing of the EEG data was done EEGLAB and Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011). The data was epoched to face onset (-500 1000 ms). An average reference was used with the exclusion of the mastoid and bipolar electrodes. Biological artefacts were rejected manually. The average number of trials rejected was 75 (s.d. = 80.5) in Experiment 1 and 100 (s.d. = 94.95) in Experiment 2. Ocular artefacts were rejected based on scalp distribution using independent component analysis in EEGLAB. A 30 Hz low pass filter was applied. Trials with incorrect responses were rejected from further analysis.

ERP data analysis

For the ERP analysis, the data was baseline corrected to 100 ms before stimulus presentation. An ERP waveform averaged across all conditions was used to select the time window of 100-150 ms for the P1 component. The regions of interest (ROI) were defined as PO7 and PO8 based on previous literature (Kuefner et al., 2010).

Mean P1 amplitude and frequency for each video-type, stimulus expression and channel (PO7, PO8) were analysed using 2 x 4 x 2 repeated measures ANOVAs with all of these being within-subject factors. Mauchly's Test of Sphericity was used for this ANOVA. Follow-up analyses used repeated measures *t*-tests (2-tailed). Bonferroni corrections applied where necessary and alpha levels were set at 0.025 in Experiment 1 and 0.016 in Experiment 2.

Time-frequency representations of power analysis

The length of each epoch was increased to -1500 and 2000 ms using zero padding. The data was then baseline corrected to 500-200 ms before stimulus presentation. Time-frequency representations (TFR) of power for frequencies between 1 and 30 Hz were calculated using sliding Hanning tapers with an adaptive time window of three cycles of each frequency.

To assess the effects of the video environments on theta (3-5 Hz) power in response to different stimulus expressions, first, theta power change (relative to baseline) was averaged across facial expressions for the urban and nature conditions separately. I focused on theta band activity 200 ms after stimulus onset to avoid contamination from sensory evoked responses. Difference between the urban and nature conditions was assessed using cluster-based permutation procedure (Maris & Oosteveld, 2007) in FieldTrip. This method controls the Type I error rate involving multiple comparisons. A probability value was calculated through the Monte Carlo estimate of permutation p value of the channel cluster by randomly shuffling group labels (urban, nature) within participants 1000 times and calculating the maximum cluster level test statistics. Each cluster consisted of at least two adjacent electrodes.

However, the above analysis yielded no significant results presumably because the difference in brain activity may be bigger for stimulus expression than for the urban and nature conditions. Therefore, this analysis was not replicated in Experiment 2. Instead, in both Experiments 1 and 2, theta power change was averaged across video conditions for each stimulus expression separately. Using the analysis described above, I compared theta change in response to the neutral expression with each emotional expression (happy, fearful, angry) separately.

For each significant cluster, theta band change was averaged across the significant channels and time points for the urban and nature conditions separately. Theta band change for each video-type and stimulus expression (emotional, neutral) were analysed using 2 x 2 ANOVAs with these being within-subject factors. Notably separate ANOVAs were conducted for happy fearful, and angry expressions. Mauchly's Test of Sphericity was used for this ANOVA. Follow-up analyses used repeated measures *t*-tests (2-tailed). Bonferroni corrections applied where necessary and alpha levels were set at 0.0125.

Experiment 1

Methods

<u>Materials</u>

Videos. A picture of each video is shown in *Figure* 3.2. Videos were sourced from the internet. (Nature video, https://www.youtube.com/watch?v=oSmUI3m2kLk&t=1335s, starting at minute twenty-three; Urban video, (https://www.youtube.com/watch?v=OFLn-S049ZY&t=1167s, starting at five seconds). Both videos were twenty-five minutes long and were presented without sound. Both were filmed from a walker's perspective at eye height. The nature video was filmed in Snoqualmi, Washington, USA, along a footpath amongst high trees and ferns along the middle fork trail. It contained no people or human-built objects. The urban video was filmed in Mexico City, Mexico, along busy, narrow streets filled with cars and people among high buildings as well as in open spaces with few people. This video contained little vegetation and showed 642 neutral, ten smiling and two frowning faces (67% of all faces were male). Fifteen people looked directly at the camera.

Figure 3.2. Environments shown in the urban (left) and nature (right) videos.

Data analysis

Whether post-video relation ratings or PANAS subscale scores were predictive of significant ERP or oscillatory effects of the videos was analysed using linear regression. Bonferroni corrections applied where necessary and alpha levels were set at .017.

Results

Behavioural results

On average, participants reported the faces' gender 509 ms (s.d. = 94.4) after stimulus onset with 90% (s.d. = 7.4) accuracy. Notably, RTs were faster after the urban (mean = 499 ms, s.d. = 97.8) than the nature video (mean = 519 ms, s.d. = 92; *F*(1,22) = 5.376, $p = 0.03$, $\eta_p^2 = 0.196$). No accuracy effects were found.

Participants reported lower relaxation scores after the urban than nature video. Relaxation ratings and PANAS subscale scores before and after the urban and nature videos are shown in *Table* 3.1. Analysis of pre-video mood measures showed no significant difference between the two videos (all *p*'s > 0.47). However, subsequent analyses of post-video mood measures revealed that relaxation ratings were significantly lower after the urban (mean = 4.5, s.d. = 0.7) versus nature video (mean = 5, s.d. = 0.8; Z = -2.164, $p = 0.03$). No such differences were found on the PANAS subscales (all *p*'s > 0.474).

Mood measure	Video-type	Test phase	Rating/score
Relaxation	Urban	Pre-video	4.6 (0.8)
		Post-video	4.5 (0.7)
	Nature	Pre-video	4.7 (1)
		Post-video	5 (0.8)
PANAS positive subscale	Urban	Pre-video	26.4 (8.3)
		Post-video	23.3 (10)
	Nature	Pre-video	26.4 (7.5)
		Post-video	22.7 (7.9)
PANAS negative subscale	Urban	Pre-video	11.6 (2)
		Post-video	11.8 (2.2)
	Nature	Pre-video	12 (3)
		Post-video	11.5 (2)

Table 3.1. Group mean relaxation ratings as well as PANAS positive and negative subscale scores before and after the urban and nature videos. S.d. are shown in parentheses.

ERP results

In line with previous studies (Mueller et al., 2009; Mühlberger et al., 2009), visual inspection revealed a typically larger P1 amplitude over the right compared to the left hemisphere. Importantly, this was influenced by video-type, *F*(1,23) = 5.827, $p = 0.024$, $\eta_p^2 = 0.202$. While P1 amplitude over the left hemisphere did not differ between the urban (mean =

4.61 µV, s.d. = 3.1) and nature videos (mean = 4.53 µV, s.d. = 3; *p* = 0.814), over the right hemisphere, P1 amplitude was larger after the urban (mean = 5.64 µV, s.d. = 3.7) than nature video (mean = 4.97 µV, s.d. = 3.8; *t*(24) = -2.231, *p* = 0.035; See *Fig*. 3.3). No latency effects were found.

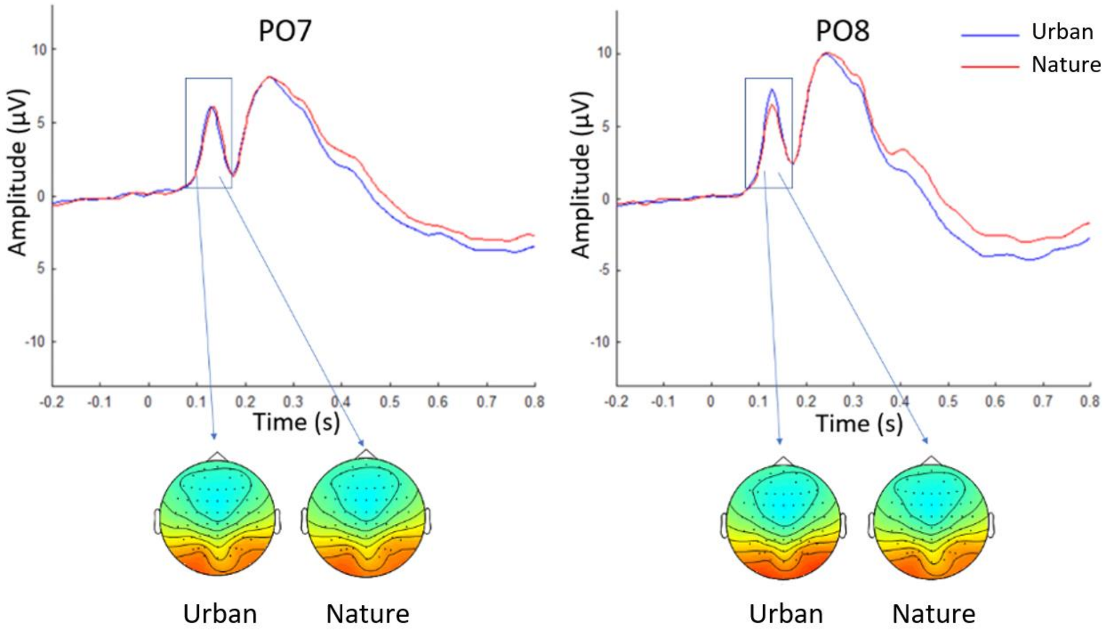

Figure 3.3. P1 amplitude over the left (PO7) and right hemispheres (PO8) after the urban (blue) and nature videos (red) with the topographies.

Interestingly, linear regression revealed a trend towards a relationship between post-video scores for the positive PANAS subscale and P1 amplitude after the urban video; R^2_{adj} = 0.178, *F*(1, 22) = 5.780, *p* = 0.026, showing that positive mood accounts for 17.8% of variance in P1 amplitude. Notably, neither the negative PANAS subscale (*p* = 0.308) nor relaxation scores (*p* = 0.426) predicted P1 amplitude after the urban video. In contrast, linear regression did not reveal any significant relationship between post-video mood measures and P1 amplitude after the nature video (all *p*'s > 0.007).

Time-frequency representation of power results

Visual inspection revealed an increase in theta band power (relative to baseline) for all stimulus expressions. This started around 100 ms, peaking at around 400 ms, after stimulus onset and was maximal over the Cz electrode.

Happy versus neutral faces evoked greater increase in theta power. The cluster-based permutation test revealed greater theta power increase between 200 and 450 ms in response to happy (mean = 0.41 yV, s.d. = 0.35) versus neutral expressions (mean = 0.29 yV, s.d. = 0.31; $p = 0.018$, Monte Carlo estimated). This difference between happy versus neutral expressions was confirmed by omnibus analysis, $F_{1,23} = 15.180$, $p = 0.001$. Importantly, however, this was not modulated by video-type ($p = 0.541$).

Relative to neutral faces, angry faces evoked greater increase in theta power after the urban versus nature video. The second cluster-based permutation analysis also revealed a greater theta power increase between 200 and 800 ms in response to angry (mean = 0.36 yV, s.d. = 0.32) than neutral expressions (mean = 0.26 yV, s.d. = 0.27; $p = 0.002$, Monte Carlo estimated), an effect that was confirmed by the omnibus analysis ($F_{1,23} = 15.664$, $p = 0.001$). Importantly, this effect was modulated by video-type, $F(1,23) = 4.942$, $p = .036$, $\eta_p^2 = 0.177$ (see *Fig*. 3.4). Subsequent analysis revealed that theta power increased more to angry (mean = 0.42 yV, s.d. = 0.45) versus neutral expressions (mean = 0.27 yV, s.d. = 0.38; $t(23) = -3.586$, $p = 0.002$) after viewing the urban video. In contrast, after the nature video, theta power increased to a similar degree in response to both angry (mean = 0.31 yV, s.d. = 0.29) versus neutral expressions (mean = 0.26 yV, s.d. = 0.22; $t(23) = -1.869$, $p = 0.074$). I found no significant clusters for the neutral versus fearful expression.

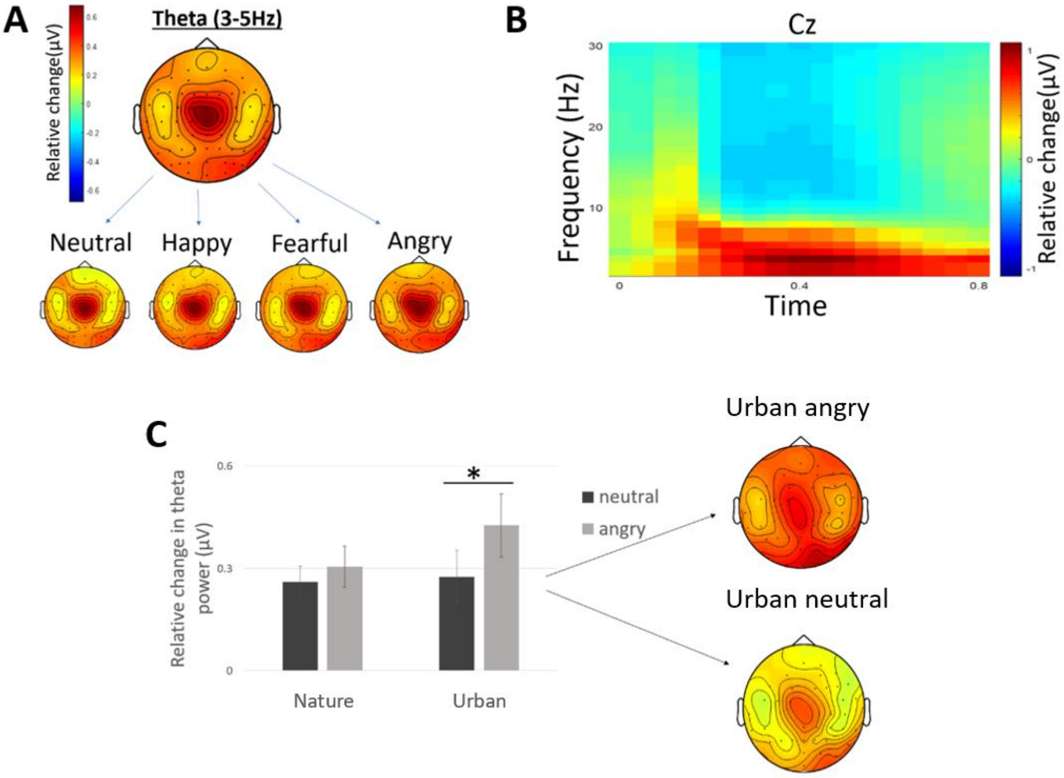

Figure 3.4. **A**. Topography of theta modulation averaged across all stimulus expressions (top) and for each stimulus expression separately (bottom). **B**. Time-frequency activity averaged across all stimulus expressions. **C**. Increase in theta power (relative to baseline) between .2 and .8 seconds in response to neutral (black) and angry expressions (grey) after the nature (left) and urban videos (right). Topographies and channels of interest for the urban condition are shown on the right. The error bars represent standard error.

Linear regression revealed no significant relationship between mood measures and theta power increase in response to angry faces after the urban video (all *p*'s > 0.07). In contrast, there was a trend towards a relationship between relaxation scores and theta power after the nature video, $R^2_{adj} = 0.196$, $F(1, 22) = 6.357$, $p = 0.02$, showing that positive mood accounts for 19.6% of variance in theta power. Notably, linear regression did not reveal any significant relationship between either the positive ($p = 0.679$) or negative ($p = 0.967$) PANAS subscales and theta power after the nature video.

Experiment 2

Methods

Materials

Videos. A picture of each video is shown in *Figure* 3.5*.* Videos were sourced from the internet (Nature video, https://www.youtube.com/watch?v=b4AVn8mTuJw, starting at minute 1; Urban video, https://www.youtube.com/watch?v=LwYGxjdnZ84&t=1722s, starting at minute 22). Similar to Experiment 1, both videos were twenty-five minutes long, presented without sound and filmed from a walker's perspective at eye height. The nature video was filmed along a foot path among trees, flowers and bushes with a river and a mountain in the background. It contained no people or man-built objects. The urban video was filmed in Vancouver, Canada, along busy roads filled with cars and people. This video showed little vegetation. All faces in this video were blurred beyond recognition using Wondershare Filmora9 software.

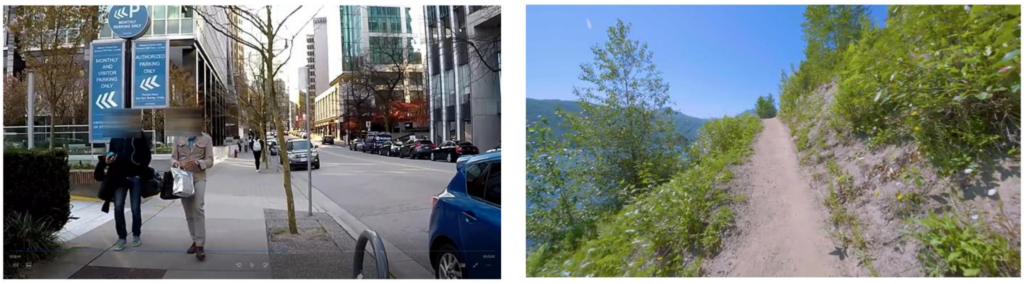

Figure 3.5. Environments shown in the urban (left) and nature (right) videos.

Results

Behavioural results

Participants' average response time was 538 ms (s.d. = 94.5) with an average accuracy of 91% (s.d. = 0.06). Unlike in Experiment 1, omnibus analyses of these revealed no significant effects.

Similarly, no significant differences were found on relaxation ratings (all *p*'s > .132) or PANAS subscales (all *p*'s > .083) between the urban nature videos. Relaxation ratings and PANAS subscale scores before and after the urban and nature videos are shown in *Table* 3.2.

Mood measure	Video-type	Test phase	Rating/score
Relaxation	Urban	Pre-video	4.7 (1)
		Post-video	4.8 (0.9)
	Nature	Pre-video	4.7 (0.9)
		Post-video	5.1 (0.7)
PANAS positive subscale	Urban	Pre-video	26.3 (6.9)
		Post-video	20.9 (7.4)
	Nature	Pre-video	26 (7.5)
		Post-video	20.8 (6.5)
PANAS negative subscale	Urban	Pre-video	11.6 (2.1)
		Post-video	11.2 (2.4)
	Nature	Pre-video	12.3 (2.8)
		Post-video	11.5 (2.5)

Table 3.2. Group mean relaxation ratings as well as PANAS positive and negative subscale scores before and after the urban and nature videos. S.d. are shown in parentheses.

ERP results

In line with the literature (Mühlberger et al., 2009; Mueller et al., 2009) and Experiment 1, P1 amplitude was larger over the right (mean = 7.44 µV, s.d. = 2.94) than the left hemisphere (mean = 5.76 µV, s.d. = 2.96; $F(1,23) = 5.199$, $p = 0.032$, $\eta_p^2 = .184$). However, unlike in Experiment 1, this was not modulated by video-type ($p = .484$; see *Fig*. 3.6).

Omnibus analysis of P1 latency showed a significant main effect of stimulus expression ($F(3,69) = 3.394$, $p = 0.023$, $\eta_p^2 = .129$). Subsequent analysis revealed an earlier P1 latency in response to fearful (mean = 131.9 ms, s.d. = 0.87) versus angry expressions (mean = 133.7 ms, s.d. = 0.86; $t(23) = 2.834$, $p = 0.009$). Similarly there was a trend towards an earlier P1 latency in response to fearful versus happy (mean = 133.3 ms, s.d. = 0.81; $t(23) = 1.787$, $p = 0.087$) and neutral expressions (mean = 133.1 ms, s.d. = 0.82; $t(23) = -2.478$, $p = 0.021$).

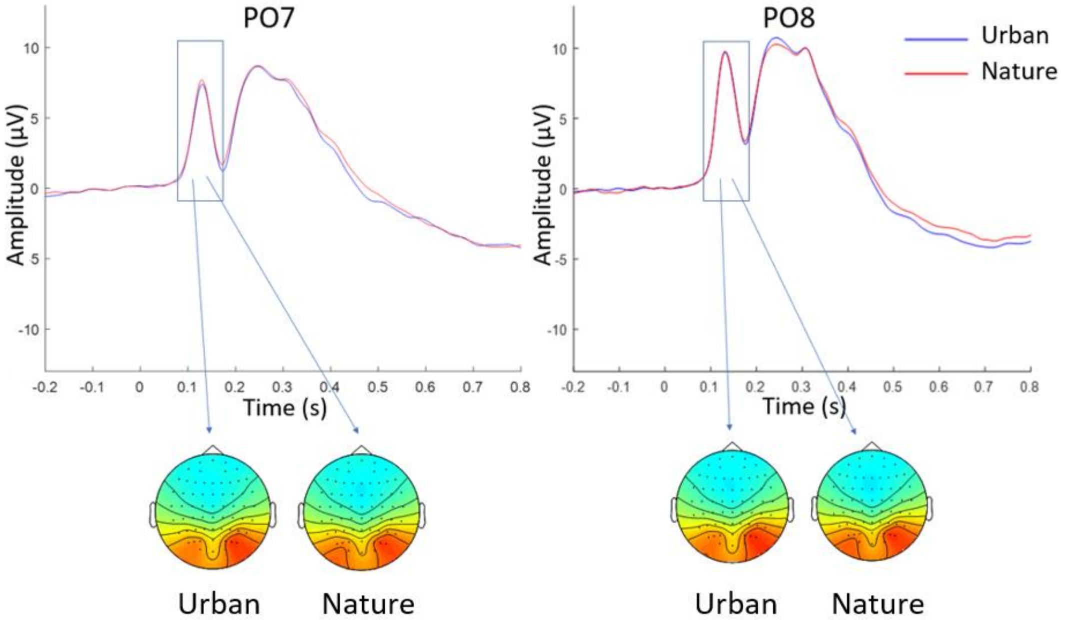

Figure 3.6. P1 amplitude over the left (PO7) and right hemispheres (PO8) after the urban (blue) and nature videos with topographies (red).

Time-frequency representation of power results

Visual inspection revealed increased theta power for all expressions starting around 150 ms, peaking at approximately 400 ms, after face onset. This effect was maximal over the Cz electrode.

Similar to Experiment 1, happy versus neutral expressions evoked greater increase in theta power. The cluster-based permutation test revealed greater theta power increase between 200 and 800 ms in response to happy (mean = 0.2 yV, s.d. = 0.19) versus neutral expression (mean = 0.13 yV, s.d. = 0.18; *p* = .0009, Monte Carlo estimated), an effect that was confirmed by omnibus analysis ($F_{1,23}$ = 29,029, *p* < 0.001). However, this was not modulated by video-type (*p* = .839). Furthermore, unlike in Experiment 1, no significant clusters were found for neutral versus fearful or angry expressions. The lack of effect of urban and nature videos on theta power increase in response to angry versus neutral expressions is shown in *Figure* 3.7.

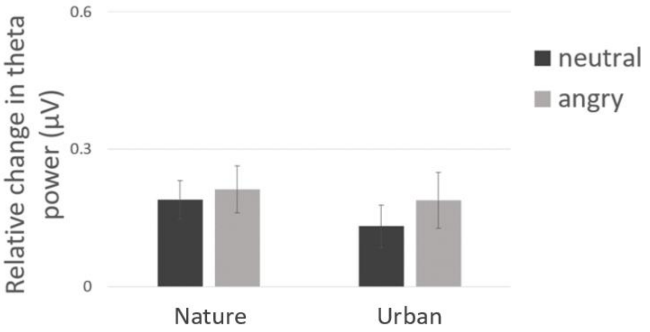

Figure 3.7. Theta power (relative to baseline) between .2 and .8 seconds in response to neutral (black) and angry expressions (grey) after the nature (left) and urban videos (right). The error bars represent standard error.

Discussion

In two separate experiments, I investigated the effects of artificial urban versus nature exposures on bottom-up (indexed by P1 component) and top-down (indexed by theta activity) neural substrates of attention. To assess these, participants' brain activity was measured while viewing a series of faces with neutral and emotional (happy, fearful, and angry) expressions in a gender discrimination task in two separate sessions. Importantly, before this task, participants watched a 25-minute video showing an urban or natural walk. In Experiment 1, the urban video contained hundreds of faces whereas the nature video contained none. To resolve this, in Experiment 2, all faces in the urban video were blurred beyond recognition so that neither the urban nor nature video contained any faces. Importantly, in Experiment 1, all facial expressions evoked a larger P1 amplitude over the right hemisphere after the urban versus nature video, indexing greater bottom-up attention allocation to all faces. Moreover, the urban versus nature video led to a greater theta power increase in response to angry (relative to neutral) expressions, indicating greater top-down attention allocation to angry faces. Interestingly, however, in Experiment 2, where neither videos contained any faces, both bottom-up and top-down effects disappeared, demonstrating that the attention effects observed in Experiment 1 may be underpinned by exposure to faces in the urban video.

One explanation for greater bottom-up attention allocation to all facial expressions after the urban video may be that this video enhanced anxiety levels (indexed by relaxation score), a state associated with a greater P1 response to faces (Holmes et al., 2008; Rossignol, Campanella, Bissot, & Philippot, 2013; Morel, George, Foucher, Chammat, & Dubal, 2014). In line with this, greater bottom-up processing of faces disappeared in Experiment 2 where relaxation scores no longer indicated higher anxiety levels after the urban versus nature video. However, regression analysis showed no significant relationship between relaxation scores and P1 amplitude, suggesting that anxiety levels are unlikely to explain the P1 effect seen in Experiment 1.

An alternative explanation for greater bottom-up attention allocation to faces may be that exposure to faces in the urban video activated the amygdala, the region that is thought to underpin attention allocation to face stimuli (see Vuilleumier, 2005 for review). Indeed, numerous experiments have shown that faces (Thomas et al., 2001; Canli, 2002; Öhman, 2002; Wright & Liu, 2006; Wright, Wedig, Williams, Rauch, & Albert, 2006) as well as urban (versus rural) scenes with faces (Kim et al., 2010), enhance activity in the amygdala. Furthermore, greater P1 response to faces disappeared when the urban video contained no faces, and therefore, it may have been unable to enhance amygdala activity. Notably, however, while the amygdala is thought to contribute to attention allocation to all emotional faces, it has been specifically linked to enhanced attention allocation to negative faces (see Vuilleumier, 2005 for review). Therefore, if greater bottom-up attention allocation to faces is indeed underpinned by the amygdala, it is unclear why the urban video did not result in greater bottom-up attention allocation to specifically negative faces, similar to Chapter 2.

Despite greater bottom-up attention allocation to all facial expressions, only angry faces captured more attention via top-down processes after the urban video in Experiment 1. One explanation for this may be enhanced stress levels (indexed by relaxation scores) that have been shown to increase selective attention to angry faces (Roelofs et al., 2007). Supporting this notion, greater top-down processing of angry faces disappeared in Experiment 2 where relaxation scores no longer differed after the two videos. Importantly, the disappearance of stress effects in Experiment 2 may be underpinned by the removal of faces from the urban video as crowding is thought to be a key contributor towards enhanced stress levels after urban exposures (Abbott, 2012). This suggests that exposure to faces in the urban video may indirectly underpin greater theta response to angry faces by increasing stress levels. However, regression analysis showed that relaxation scores were not associated with theta response, suggesting that stress levels are unlikely to explain this effect.

An alternative explanation for greater theta response to angry faces after the urban video may be enhanced rejection sensitivity. Similar to everyday life where people in urban settings pay little attention to one another, very few people looked at the camera in the urban video used in Experiment 1, making it seem like the participant was ignored by others. This may have enhanced participants' feelings of social rejection, thus increasing their rejection sensitivity (Romero-Canyas, Downey, Berenson, Ayduk, & Kang, 2010). Importantly, in response to disapproving faces, such as angry faces, participants with high versus low rejection sensitivity show a greater activity in the anterior cingulate cortex (ACC; Burklund, Eisenberger, & Leibenman, 2007; Masten et al., 2009), the brain regions that generates theta activity (Nigbur, Ivanova, & Stürmer, 2011). This demonstrates that rejection sensitivity could contribute to greater top-down attention allocation to angry faces after urban exposures that contains faces.

Interestingly, anxiety disorder that urban versus rural dwellers are more likely to develop (Peen, Schoevers, Beekman, & Dekker, 2010) lead to similar attention effects as seen in Experiment 1 (Holmes, Nielsen, & Green, 2008; Knyazev, Bocharov, Levin, Savostyanov, & Slobodskoj-Plusnin, 2008; Mühlberger, Wieser, Herrmann, Weyers, Tröger, & Pauli, 2009). This suggests that greater bottom-up and top-down attention allocation to faces may contribute to the link between urban living and anxiety disorders. Notably, while crowding has been suggested to underpin the link between urban living and mental disorders via enhanced stress levels (Lederbogen et al., 2011; Lederbogen, Haddad, & Meyer-Lindenberg, 2013), to my knowledge, this is the first evidence to suggest that crowding may contribute to this link via altered attention allocation to faces.

Overall, for the first time, I showed that artificial exposure to urban versus natural environments result in greater bottom-up attention allocation to all faces as well as greater top-down attention allocation to angry faces specifically. Importantly these effects disappear when faces in the urban video are blurred beyond recognition, demonstrating that exposure to faces is likely to underpin these attention effects.

Chapter 4. Effect of childhood environment on behavioural adjustment in young adulthood

Abstract

Recent evidence shows that various aspects of urban versus non-urban upbringing results in lower grey matter volume in the adult prefrontal cortex, a region that has been implicated in behavioural adjustment. This suggests that childhood environments may affect behavioural adjustment in young adulthood. To investigate, young adults completed a Go/No-Go task in which they were asked to respond to all except for one stimulus. Behavioural adjustment was indexed by RTs differences on trials after correct versus erroneous responses, called post-error slowing. I combined population size, neighbourhood greenness and air pollution levels of participants' childhood residence to categorise overall childhood environment as better versus worse. Additionally, I categorised childhood environments as urban versus non-urban using population size, as more- versus less-polluted using air pollution levels, and as more- versus less-green using neighbourhood greenness for each place of residence. I found a marginal relationship between neighbourhood greenness and PES, revealing that lower childhood neighbourhood greenness was associated with greater behavioural adjustment in young adulthood. In contrast, overall childhood environment, urbanicity and air pollution levels did not affect PES. Instead, there was a relationship between post-error accuracy change and overall childhood environment as well as urbanicity, showing that worse versus better as well as urban versus non-urban childhood environments resulted in greater probability of making another error after an erroneous response in young adulthood. Finally, while there was a relationship between air pollution levels of childhood residence and post-error accuracy change in young adulthood, post-error accuracy change did not significantly differ between participants who were raised in a more- versus less-polluted area. Overall, these results highlight that childhood environments have long-term effects on cognition that last into young adulthood.

Over the last century, humans have moved from open skies and natural landscapes to urbanised, human-made habitats that provide a complex, fast-paced environment abundant with crowds, traffic, and trip-hazards. Such environments require the ability to adjust behaviour in order to avoid accidents. For example, stepping in front of a car after forgetting to check for oncoming traffic is likely to lead to a pedestrian adjusting their behaviour by taking additional time to look for vehicles the next time they need to cross a road to ensure that they will not be stepping in front of a car again.

In the lab, behavioural adjustment to achieve greater confidence in decisions is thought to be reflected by the extent to which reaction times slow after an erroneous versus correct response (Dutilh et al., 2012; Valadez & Simons, 2017; Schroder et al., 2019), called post-error slowing (PES; Rabbit, 1966; Laming, 1969). Importantly, numerous neuroimaging studies have shown that PES is underpinned by the medial frontal cortex, including the anterior cingulate cortex (ACC; Cohen, Botvinick, & Carter, 2000; Carter & van Veen, 2007; Li et al., 2008; Mansouri et al., 2016), brain regions that are affected by childhood environments. Indeed, adults who were raised in urban versus non-urban areas have reduced grey matter volume in their frontal cortex (Haddad et al., 2015; Besteher, Gaser, Spalthoff, & Nenadić, 2017; Zhang et al., 2018) and show enhanced activity in the ACC during social stress (Lederbogen et al., 2011), suggesting that urban versus non-urban childhoods may differentially modulate PES in adulthood. In line with this, urban versus rural upbringing and dwelling increases the risk of several mental disorders in adulthood, such as schizophrenia, major depressive and anxiety disorders (Lundberg, Cantor-Graae, Rukundo, Ashaba, & Östergren, 2009; Peen, Schroevers, Beekman, & Dekker, 2010). Notably, all of these has been shown to modulate behavioural adjustment and PES (Compton et al., 2008; Núñez-Peña, Tubau, & Suárez-Pellicioni, 2017; Voegler et al., 2018; Storchak, Ehlis, & Fallgatter, 2021), further supporting the notion that urban versus non-urban childhoods may differentially affect behavioural adjustment in adulthood.

Importantly, the above studies categorised environments as urban versus non-urban based on population size of childhood residence. While this is a conventional metric that has been used in numerous experiments (Mortensen et al., 1999; Lundberg et al., 2009; Lederbogen et al., 2011; Hirts et al., 2021), it has several disadvantages. Most importantly, considering only population size means that other differences between urban and non-urban environments are overlooked.

One such difference is that unlike non-urban areas, urban environments often lack natural green spaces (Nieuwenhuijsen, Khreis, Triguero-Mas, Gascon, & Dadvand, 2017), resulting in lower levels of neighbourhood greenness. Similar to high population size, low levels of neighbourhood greenness have also been linked to elevated risk of schizophrenia, major depressive disorder and anxiety (Gascon et al., 2018; Liu et al., 2019; Engemann et al., 2020). As these have been linked to altered PES and behavioural adjustment (Compton et al., 2008; Núñez-Peña et al., 2017; Voegler et al., 2018; Storchak et al., 2021), this suggests that childhood neighbourhood greenness may also modulate behavioural adjustment in adulthood.

Additionally, urban environments also have higher levels of air pollution than non-urban areas (Hewitt, Ashwroth, & MacKenzie, 2020). Air pollution refers to a complex mixture of chemicals, volatile organic compounds, metals, and particulate matter (Schauer et al., 2006; Block et al., 2012; Genc, Zadeoglulari, Fuss, & Genc, 2012). Similar to population size, chronic exposure to higher levels of air pollution (particulate matter, nitrogen oxides and ozone) have also been associated with reduced grey matter volume in the frontal cortex (Power et al., 2018; Gale et al., 2020) as well as elevated risk of schizophrenia, major depressive disorder and anxiety (Power et al., 2015; Kioumourtzoglou et al., 2017; Antonsen et al., 2020). As both findings have been linked with altered PES and behavioural adjustment, this suggests that exposure to higher air pollution levels during childhood may also modulate behavioural adjustment in adulthood.

To investigate the effect of childhood environment as well as its various aspects on behavioural adjustment in adulthood, young adults completed the Go/No-Go task in which they were presented with a series of digits between 1 and 9. Participants were asked to respond to all digits except for the digit 5. When the digit 5 was presented, they were asked to withhold their response. RTs differences on trials after correct versus erroneous responses were used to index PES and therefore behavioural adjustment. A combination of population size, neighbourhood greenness and air pollution levels of participants' childhood residence was used to categorise overall childhood environment as better versus worse. Additionally, childhood environments were categorised as urban versus non-urban using population size, as more-polluted versus less-polluted using air pollution levels, and as more-green versus less-green using neighbourhood greenness for each place of residence. I predicted adults who were raised in worse versus better, urban versus non-urban, more-polluted versus less-polluted, and more-green versus less-green environments to show distinct PES, indexing divergent behavioural adjustment.

Methods

Participants

Complete data sets were collected from ninety-three undergraduate students (eighty-two female, mean age = 19.85 years, s.d. = .92) in exchange for course credit. All spoke fluent English, reported normal or corrected-to-normal vision and no history of neuropsychological or psychiatric disorders. Furthermore, all participants spent their entire lives in England, United Kingdom, as the database used to categorise their childhood environment as more- versus less-green was only available for this region. Notably, all participants lived in Birmingham, United Kingdom, at the time of the experiment to ensure that the effect of childhood environments is not confounded by participants' current environments. The study was approved by the University of Birmingham Ethics Committee.

Apparatus

Stimuli were presented, and data was recorded online using Gorilla Experiment Builder (gorilla.sc) on either a laptop or a computer. The size, type and refresh rate of each participants' monitor are unknown. Responses were entered using a keyboard.

Stimuli

Go/No-go task. Stimuli consisted of a centrally presented black fixation cross and a single digit between 1 and 9. Stimuli (8% of total screen pixels) were presented centrally between 46% and 54% of the screen (both horizontally and vertically). As the experiment was completed online using their personal computers, the exact size of the stimuli is unknown and varied between participants.

Procedure

The experiment consisted of one session. First, participants reported their weight and height as well as their current family income using a 11-point scale (1 = '<£15,000', 11 = '>£60,000'). Afterwards, they reported their home postcode for each year of life from birth to present. Finally, participants completed the Go/No-go task.

Go/No-go task. The procedure used in each trial of the Go/No-go task is shown in *Figure* 4.1. Each trial began with the fixation cross being presented for 200 ms before being replaced by a single digit between 1-9 for 200 ms. At stimulus offset, the fixation cross reappeared. Participants were asked to respond to digits 1-4 and 6-9 ('go' trials) by pressing the "b" key using the index finger on their dominant hand and to withhold their response when the digit 5 was presented ('no-go' trials). Each trials ended once a response was made, or the response time has elapsed (1,500 ms). The next trial began immediately. No feedback was provided. Each trial lasted for 1,900 ms. Response time (interval between stimulus onset and response) and accuracy (proportion of correct trial) were recorded. The task consisted of 1812 trials split into 12 blocks. 40% (725) of all trials were No-go trials. Breaks between blocks were self-paced with a maximum length of five minutes. Participants were instructed not to talk to anyone, watch TV or use their phones during the breaks.

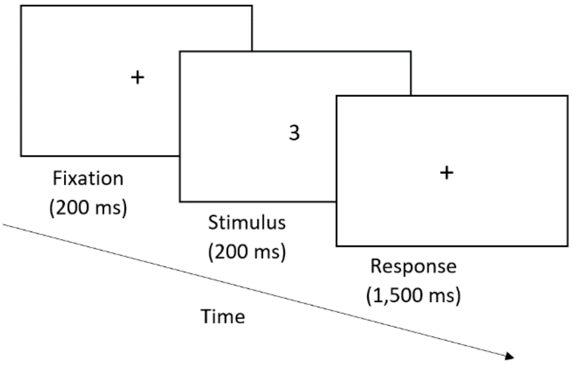

Figure 4.1. An illustration of an example trial in the Go/No-go task. The fixation cross was shown for 200 ms. This was then replaced for 200 ms by the stimulus that was a single digit between 1-9. At stimulus offset, the fixation cross reappeared for the 1,500 ms long response window. Participants were asked to respond if the digits 1-4 and 6-9 were presented but withhold their response if the digit 5 was shown. This example trials is a go trials, therefore, the participant would have had to press the response button.

Data analysis

Scales. For each participant, weight (kilograms) was divided by the square of height (meters) to calculate Body Mass Index (BMI). Current family income was used to index socio-economic status (SES).

In line with Chapter 2 and previous studies (Mortensen et al., 1999; Lundberg et al., 2009; Lederbogen et al., 2011), environments were categorised using home postcodes for the childhood period of the first fifteen years of life.

Childhood urbanicity was determined based on population size using a conventional metric (Mortensen et al., 1999). Population size of each place of residence was determined based on the 2011 Census data (https://www.ons.gov.uk/census/2011census/2011censusdata). Based on population size, each place of residence was assigned a score (1 – <10,000, 2 – 10,000-100,000, 3 – >100,000), that was then multiplied by years dwelt there. Products were then summed over the childhood period to determine the final score (values ranging from fifteen to forty-five). Urbanicity score of forty-five indexed urban childhoods. Typically, urbanicity scores below forty-five are split to represent childhoods in towns (score of thirty) versus rural areas (score of fifteen). However, as only nineteen participants grew up in a rural area, participants who spent their childhood in a town or rural area were grouped together. Therefore, all urbanicity scores below forty-five indicated non-urban childhoods. Based on this, childhood environments of forty-four participants were categorised as urban and childhood environments of forty-nine participants as non-urban (see *Table* 4.1).

Childhood environments were categorised as more-green versus less-green based on neighbourhood greenness that was defined as a combination of land cover by private and public green spaces (White, Alcock, Wheeler, & Depledge, 2013; Martin et al., 2020; Mueller & Flouri, 2020), using the Generalised Land Use Database Statistics for England (Office of the Deputy Prime Minister, 2005). This database defined land use for 32,482 neighbourhoods (called lower-layer super output areas; LSOAs) within England, United Kingdom. Each neighbourhood encompasses an area with the average size of four km^2 and an average population size of 1,500 residents. To calculate neighbourhood greenness for each place of residence, land cover by private gardens and public green space was summed then divided by the total land cover for each neighbourhood. This score was multiplied by the number of years dwelt there. Products were then summed over the childhood period to determine the final neighbourhood greenness score. Using median split on final scores, childhood environments of forty-seven participants were categorised as more-green and childhood environments of forty-six participants as less-green (see *Table* 4.1). Distribution of neighbourhood greenness scores in the more- versus less-green groups is shown in Figure 4.2.

Childhood environments were categorised as more- versus less-polluted based on air pollution levels that were determined using the Defra UK-AIR GIS Tool (https://uk-air.defra.gov.uk/data/gis-mapping). This tool determines the average annual levels of numerous air pollutants for each postcode in the United Kingdom. Here, I focused on four pollutants; nitrogen oxides (NOx), particulate matter 10 (PM_{10}), particulate matter 2.5 ($PM_{2.5}$) and ozone (O_3) as these have been shown to modulate cognition (see Schikowski & Altuğ, 2020, for review), the PFC (Power et al., 2018; Gale et al., 2020) as well as mental health (Power et al., 2015; Kioumourtzoglou et al., 2017; Antonsen et al., 2020). Level of each pollutant was determined for each year dwelt at each place of residence. Data was available for NOx and PM_{10} since 2001, for $PM_{2.5}$ since 2002, and for O_3 since 2003. For earlier years, level of each pollutant was calculated by averaging available data for the childhood period. The scores were then summed over the childhood period to determine the final score. Using median split on the final scores, childhood environment of thirty-nine participants were categorised as more-polluted and childhood environment of forty-one participants as less-polluted (see *Table* 4.1). Distribution of air pollution scores in the more- versus less-green groups is shown in Figure 4.2.

Notably, urbanicity, neighbourhood greenness and air pollution scores were strongly correlated ($r_s > 0.613$, N = 93, $p < 0.001$; see *Fig*. 4.3). Higher neighbourhood greenness was associated with lower population size and air pollution levels while higher population size was associated with higher air pollution levels. Scores for these scales were combined to quantify participants' overall childhood environment. Similar to Chapter 2, first, I turned scores for each scale into Z-scores by subtracting the group's mean from each participant's score then dividing it by the group’s standard deviation. Neighbourhood greenness Z-scores were then reversed so that positive values became negative and vice versa, thus higher Z-scores represented less green environments. Z-scores for each scale were then summed to create a single score, called overall childhood environment. High scores for this scale represented childhood environments that had high population size and air pollution levels as well as low levels of neighbourhood greenness, characteristics that have been linked to negative outcomes, such as poorer mental health (Lundberg et al., 2009; Peen et al., 2010; Engemann et al., 2018; 2019; 2020) or poorer cognition (Tennessen & Cimprich, 1995; de Fockert, Caparos, Linnell, & Davidoff, 2011; Linnell, Caparos, de Fockert, & Davidoff, 2013). Based on the final scores, fifty-one participants’ childhood environments were categorised as better childhood environment’ and forty-two participants’ a ‘worse childhood environment’ using median split (see *Table* 4.1). On average, participants in the less-green group had a neighbourhood score of 828 (s.d. = 198) that is 312 lower than the national average over the childhood period (1140). In contrast, participants in the more-green group had a neighbourhood greenness score of 1299 (s.d. = 126) that is 159 higher than the national average over the childhood period. Distribution of overall childhood environment scores in the more- versus less-green groups is shown in Figure 3.

	Urban				Non-urban			
	More-green		Less-green		More-green		Less-green	
	More-polluted	Less-polluted	More-polluted	Less-polluted	More-polluted	Less-polluted	More-polluted	Less-polluted
Worse childhood environment	6	0	27	7	2	0	6	3
Better childhood environment	0	4	0	0	7	28	0	3

Table 4.1. Number of participants in each urbanicity (urban, non-urban), neighbourhood greenness (more-green, less-green) and air pollution groups (more-polluted, less-polluted) within the worse and better childhood environment groups.

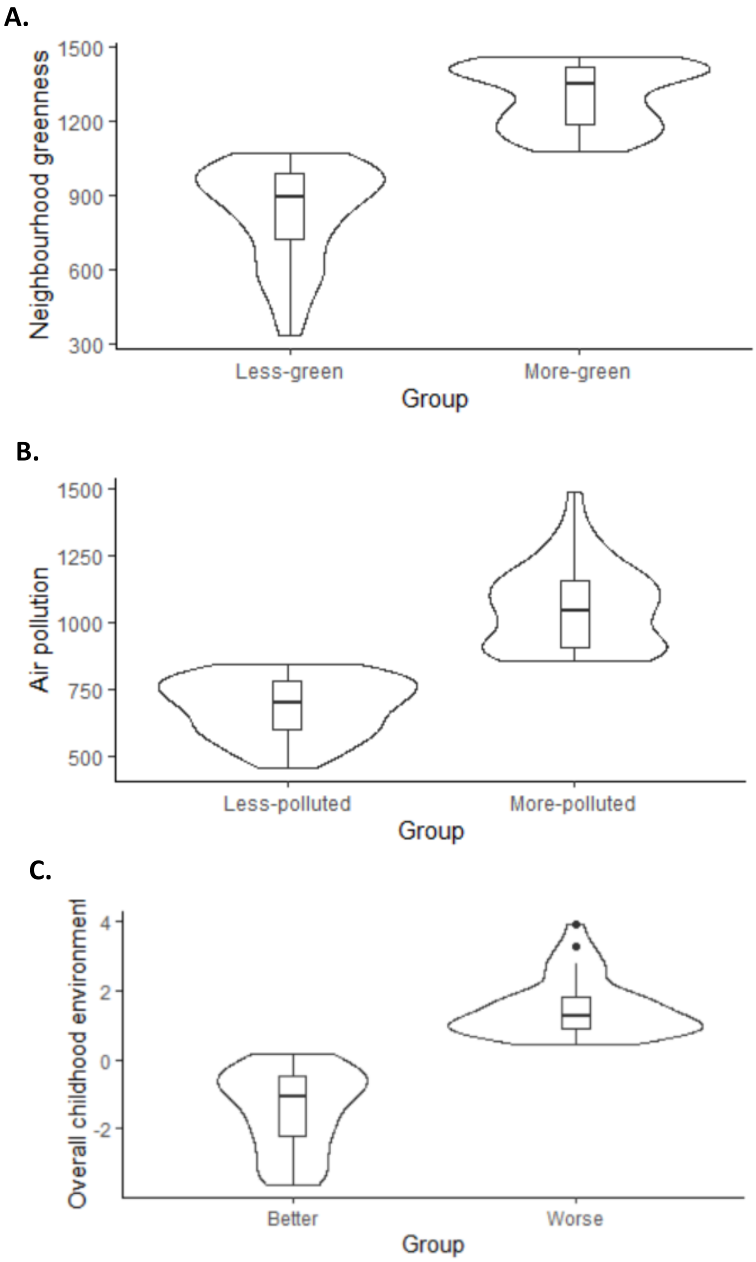

Figure 4.2. **A.** Distribution of neighbourhood greenness scores in the more- (left) versus less-green groups (right). **B.** Distribution of air pollution scores in the more- (left) versus less-polluted groups (right). **C.** Distribution of overall childhood environment scores in the better- (left) versus worse childhood environment groups (right).

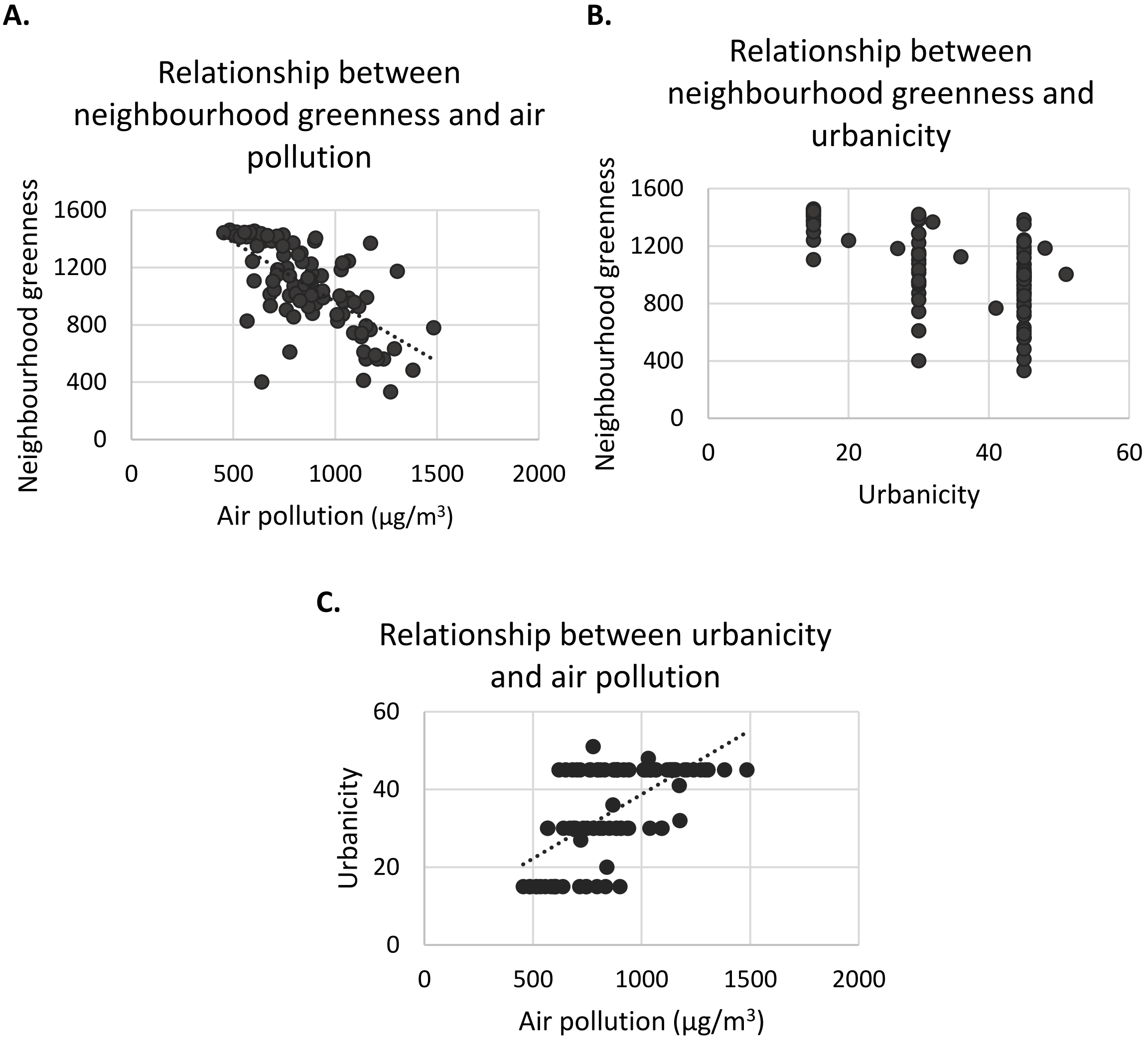

Figure 4.3. **A**. Relationship between neighbourhood greenness and air pollution scores of childhood residence. **B**. Relationship between neighbourhood greenness and urbanicity of childhood residence. **C**. Relationship between urbanicity and air pollution levels of childhood residence.

Individual BMI and SES scores were compared between the overall childhood environment (worse childhood environment, better childhood environment), urbanicity (urban, non-urban) neighbourhood greenness (more-green, less-green) and air pollution groups (more-polluted, less-polluted) separately using Mann-Whitney U tests (2-tailed). Furthermore, the relationship between each measure of childhood environment (overall childhood environment, urbanicity, neighbourhood greenness, and air pollution) as well as BMI and SES was examined using linear regression. Here, SES and BMI were the dependent variables, and each measure of childhood environment was the predictor.

Go/No-go task. Response times (RT) were excluded when they were slower than 200 ms (anticipation errors) or exceeded the individual's condition mean by more than three s.d.'s. All participants performed the task with 60% accuracy or higher. Importantly, trials where participants correctly responded to go trials were categorised as 'Hits' and trials where participants mistakenly responded to no-go trials were categorised as 'False Alarms' (FAs). Furthermore, trials where participants correctly withheld a response to no-go trials were categorised as 'Correct Misses' and trials where participants mistakenly withheld a response to go trials were categorised as 'False Misses'.

Possible differences in proportion of Hit and FA trials between worse versus better, urban versus non-urban, more-green versus less-green and more-polluted versus less-polluted groups was tested using independent samples t-tests (2-tailed). Bonferroni corrections were applied, and alpha levels were set at .0125.

For each participant, average accuracy was calculated using all trials (both go and no-go trials). In contrast, average RTs were calculated using Hit trials only, as there were no RTs for Correct Miss trials and both FAs and False Miss trials were incorrect. To investigate the effect of childhood environment, individual accuracy and average RTs for trial-type (after Hits, after FAs) were analysed using 2 x 2 mixed-design ANOVAs with trial-type was within-subject factor and childhood environment (better childhood environment, worse childhood environment) as a between group factor. To investigate the effect of a single feature of childhood environments, these ANOVAs were replicated three times, with urbanicity (urban, non-urban), neighbourhood greenness (more-green, less-green) or air pollution (more-polluted, less-polluted) as a between group factor. Mauchly's Test of Sphericity was used for all ANOVAs. Follow-up analyses used independent and paired samples t-tests (2-tailed). For follow-up analyses, PES was calculated by subtracting RTs on trials after FAs from RTs on trials after CH. Post-error accuracy change was calculated by subtracting accuracy on trials after FAs from accuracy on trials after CH. Follow-up analyses used independent samples *t*-tests (2-tailed). For all other analyses, Bonferroni corrections applied where necessary and alpha levels were set at .017.

I also investigated the relationship between task performance and overall childhood environment or its features (urbanicity, neighbourhood greenness, air pollution level). Therefore, I conducted linear regressions with PES or post-error accuracy change as the dependent variable and overall childhood environment, population size, neighbourhood greenness or air pollution level as a predictor. Alpha levels were set at .0125.

Results[4]

BMI and SES

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[4] Unless stated otherwise, values describing all effects were taken from the ANOVA with overall childhood environment as between group factors and similar effects were also present in the ANOVAs with urbanicity, neighbourhood greenness or air pollution groups as a between group factor. Effects remained the same when 1) childhood length was reduced to 10 years (Engemann et al., 2018; 2019; 2020), 2) neighbourhood greenness was defined using public green space only (Ord, Mitchell, & Pearce, 2013; Weeland, Lacuelle, Nederhof, Overbeek, & Reijneveld, 2019). However, the RTs effects of neighbourhood greenness disappeared when neighbourhood greenness groups were defined using the national average instead of median split.

Linear regression showed no significant relationship between BMI and any measure of childhood environment (all *p*'s > 0.630). Furthermore, BMI did not differ across any measure of childhood environment (all *p*'s > 0.224), suggesting that adulthood BMI is unlikely to contribute to the effects of childhood environment on behavioural adjustment in young adulthood.

Similarly, there was no significant relationship between SES and any measure of childhood environment (all *p*'s > 0. 231). Furthermore, SES did not differ across any measure of childhood environment (all *p*'s > 0.148), suggesting that similar to BMI, adulthood SES is also unlikely to contribute to the effects of childhood environment on behavioural adjustment in young adulthood. Average BMI and SES for each group of each feature of childhood environment are shown in *Table* 4.2.

Feature of childhood environment	Group	BMI	SES
Overall childhood environment	Worse	22.4 (2.8)	6.8 (3.5)
	Better	22.8 (3.2)	6.5 (3.2)
Urbanicity	Urban	22.8 (3.3)	6.5 (3.1)
	Non-urban	22.4 (2.8)	6.8 (3.5)
Neighbourhood greenness	More-green	22.2 (2.7)	7.1 (3.5)
	Less-green	23 (3.4)	6.1 (3)
Air pollution	More-polluted	22.6 (3.1)	6.8 (3.2)
	Less-polluted	22.5 (2.9)	6.5 (3.4)

Table 4.2. Average BMI and SES in each group of overall childhood environment (worse, better), urbanicity (urban, non-urban), neighbourhood greenness (more-green, less-green) and air pollution (more-polluted, less-polluted). S.d. are shown in parentheses.

Post-error slowing

On average, participants made a FAs on 21% (s.d. = 11) and made Hits on 92% (s.d. = 9). Importantly, this did not differ across each measure of childhood environment (all *p*'s > 0.290). Similarly, proportion of Hits did not differ across each measure of childhood environment either (all p's > 0.083). Average proportions of FAs and Hits for each group of each feature of childhood environment are shown in *Table* 4.3.

Feature of childhood environment	Group	% of Hits	% of FAs
Overall childhood environment	Worse	91 (10)	23 (12)
	Better	93 (9)	19 (9)
Urbanicity	Urban	91 (10)	22 (10)
	Non-urban	93 (9)	20 (12)
Neighbourhood greenness	More-green	92 (9)	21 (12)
	Less-green	92 (10)	21 (9)
Air pollution	More-polluted	91 (10)	22 (12)
	Less-polluted	93 (9)	20 (10)

Table 4.3. Average proportions of FAs (False Alarms) and Hits in each group of overall childhood environment (worse, better), urbanicity (urban, non-urban), neighbourhood greenness (more-green, less-green) and air pollution (more-polluted, less-polluted). S.d. are shown in parentheses.

In line with previous findings (Rabbit, 1966; Laming, 1969; Mazaheri, Nieuwenhuis, Van Dijk, & Jensen, 2009), omnibus analysis of RTs revealed a main effect of trial-type ($F(1,91) = 82.708$, $p < 0.001$, $\eta_p^2 = 0.4.76$). This showed that RTs were slower on trials after FAs (mean = 504 ms; s.d. = 71) versus after Hits (mean = 450 ms, s.d. = 51; see *Fig*. 4.4), indicating that RTs slowed after erroneous go responses.

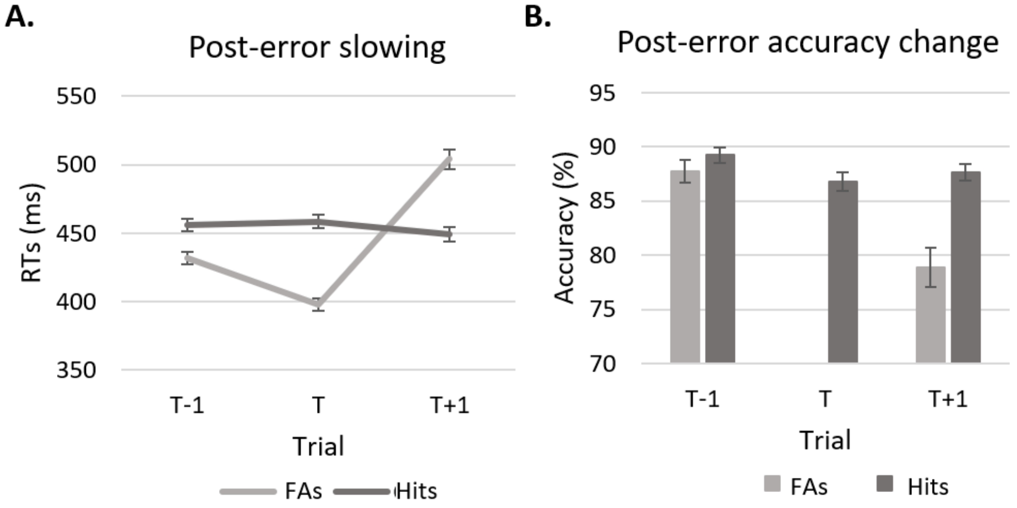

Figure 4.4. **A.** Mean reaction times (RTs) on trials before (T-1) during (T) and after (T+1) false alarms (FAs; light grey) and Hits (dark grey). **B.** Mean accuracy trials before (T-1) during (T) and after (T+1) false alarms (light grey) and Hits (dark grey). Error bars show 95% standard error.

Notably, this effect was not modulated by overall childhood environment (p = 0.110). Importantly, however, adults who were raised in areas with lower versus higher levels of neighbourhood greenness showed somewhat greater PES in young adulthood. Omnibus analysis of RTs showed a significant interaction between trial-type and neighbourhood greenness, $F(1,91) = 5.159$, $p = 0.025$, $\eta_p^2 = 0.054$. Consequent analysis revealed that groups of neighbourhood greenness did not differ on trials after either Hits (less-green: mean = 448 ms, s.d. = 49; more-green: mean = 450 ms, s.d. = 53; p = 0.845) or FAs (less-green: mean = 516 ms, s.d. = 70; more-green: mean = 492 ms, s.d. = 71; p = 0.099). Nevertheless, PES was marginally greater in the less- (mean = 68 ms, s.d. = 60) than more-green group (mean = 42 ms, s.d. = 52; $t(91) = 2.271$, p = 0.025; see *Fig*. 4.5). Notably, there was no significant interaction between trial-type and air pollution (p = 0.444) or urbanicity (p = 0.229), indicating that these did not modulate PES in young adulthood.

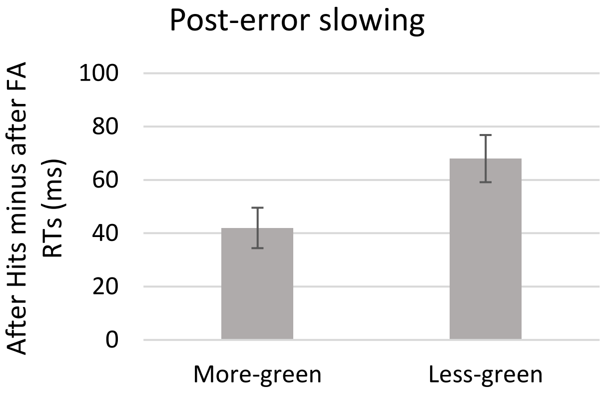

Figure 4.5. Group mean post-error slowing (PES) in the more-green (left) versus less-green (right) groups. PES was calculated by subtracting reaction times (RTs) on trails after Hits from RTs on trials after false alarms (FAs). Error bars show standard error.

Post-error accuracy

Similar to previous studies that used short response stimulus intervals (Jentzsch & Dudschig, 2009; Sellaro et al., 2015), accuracy was lower on trials after FAs (mean = 79%, s.d. = 17) versus after Hits (mean = 88%, s.d. = 7; $F(1,91) = 34.791$, $p < 0.001$, $\eta_p^2 = 0.277$, see *Fig*. 4.4). Furthermore, there was a trend towards lower accuracy in the worse (mean = 86%, s.d. = 11) versus better childhood environment group (mean = 81%, s.d. = 11; $F(1,91) = 4.136$, $p < 0.045$, $\eta_p^2 = 0.043$). Analysis of each feature of childhood environments revealed that this effect is driven by a trend towards lower overall accuracy in the urban (mean = 81%, s.d. = 11) versus non-urban group (mean = 85%, s.d. = 15; $F(1,91) = 3.039$, $p = 0.085$, $\eta_p^2 = 0.032$) as well as in the more- (mean = 81%, s.d. = 11) versus less-polluted group (mean = 85%, s.d. = 11; $F(1,91) = 2.959$, $p = 0.089$, $\eta_p^2 = 0.031$). Notably, childhood neighbourhood greenness did not affect overall accuracy ($p = 0.910$).

Importantly, adults who were raised in worse versus better childhood were more likely to make another error after an erroneous response. Omnibus analysis of accuracy revealed a significant interaction between trial-type and overall childhood environment, $F(1,91) = 4.136$, p

= 0.045, η_p^2 = 0.043. Follow-up analysis showed that while accuracy of the worse and better childhood environment groups were similar on trials after Hits (*p* = 0.270), on trials after FAs, there was a trend towards lower accuracy in the worse (mean = 75%, s.d. = 18) versus better childhood environment group (mean = 83%, s.d. = 16, *t*(91) = 2.152, *p* = 0.034). Consequently, magnitude of post-error accuracy reduction was marginally greater in the worse (mean = -11%, s.d. = 16) than better childhood environment group (mean = -6%, s.d. = 11, *t*(91) = 2.034, *p* = 0.045; see *Fig*. 4.6). Similarly, adults who were raised in urban versus non-urban environments showed a trend towards greater reduction in post-error accuracy, indicating that they were more likely to make another error after an erroneous response. Omnibus analysis of accuracy revealed a significant interaction between trial-type and urbanicity, *F*(1,91) = 4.717, *p* = 0.032, η_p^2 = 0.049. Follow-up analysis showed that while accuracy of the urban and non-urban groups were similar on trials after Hits (*p* = .554), on trials after FAs, there was a trend towards lower accuracy in the urban (mean = 75%, s.d. = 17) versus non-urban group (mean = 82%, s.d. = 16, *t*(91) = 2.028, *p* = 0.045). Consequently, magnitude of post-error accuracy reduction was marginally greater in the urban (mean = -12%, s.d. = 15) than non-urban group (mean = -6%, s.d. = 12, *t*(91) = 2.172, *p* = 0.032; see *Fig*. 4.6). Notably, trial-type did not interaction with neighbourhood greenness (*p* = 0.609) or air pollution (*p* = 0.172). As neighbourhood greenness only affected PES and overall childhood environment as well as urbanicity only influenced post-error accuracy change, none of these effects are due to a speed-accuracy trade-off.

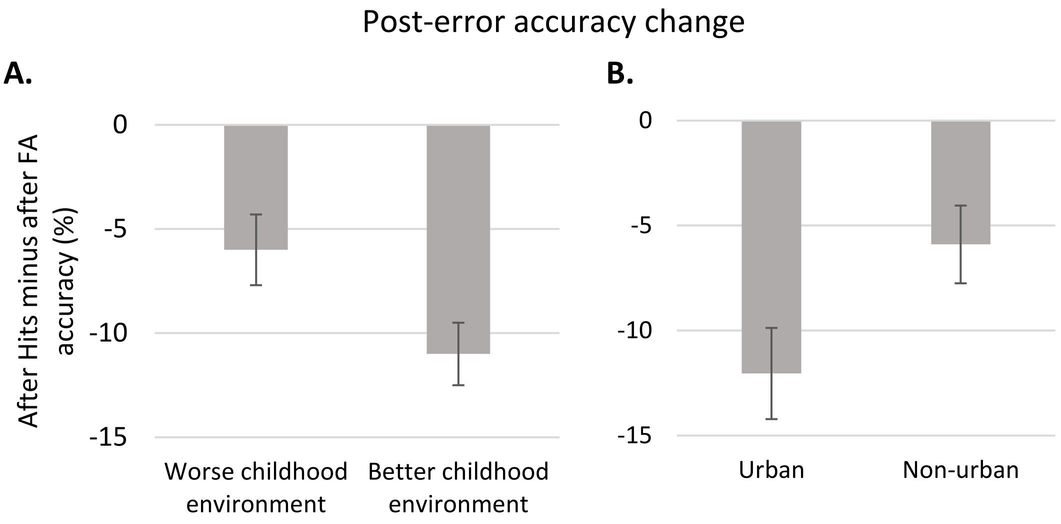

Figure 4.6. **A**. Group mean post-error accuracy change in the worse (left) versus better (right) childhood environment groups. **B**. Group mean post-error accuracy change in the urban (left) versus non-urban (right) groups. Post-error accuracy change was calculated by subtracting accuracy on trails after Hits from accuracy on trials after false alarms (FAs). Error bars show standard error.

Regressions

PES in young adulthood was not significantly associated with overall childhood environment (p = .096), urbanicity (p = 0.611) or air pollution level (p = 0.109) of childhood residence. Importantly, however, there was a marginal relationship between PES and neighbourhood greenness; R^2_{adj} = .026, $F(1, 91)$ = 3.481, p = 0.065, showing that 2.6% of the variance in PES in young adulthood can be accounted for by neighbourhood greenness of childhood residence (see *Fig*. 4.7).

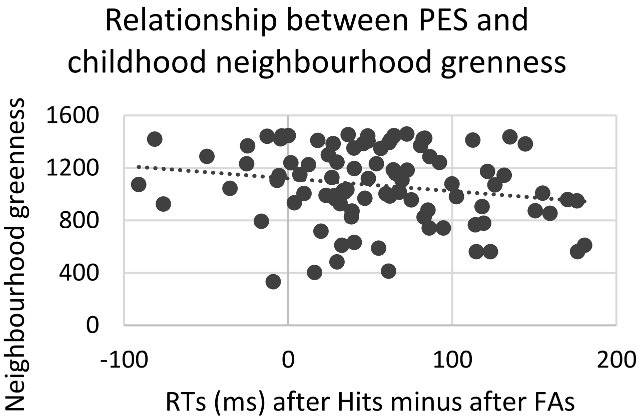

Figure 4.7. Relationship between post-error slowing (PES) and neighbourhood greenness of childhood residence. PES was calculated by subtracting reaction time (RTs) on trails after Hits from RTs on trials after false alarms (FAs).

Furthermore, there was a significant relationship between post-error accuracy change and overall childhood environment; R^2_{adj} = .084, $F(1, 91) = 9.442$, $p = 0.003$, showing that 8.4% of the variance in post-error accuracy change in young adulthood can be explained by overall childhood environment (see *Fig.* 4.8). This association was most likely driven by urbanicity and air pollution levels. Indeed, there was also a significant relationship between post-error accuracy change and urbanicity, R^2_{adj} = .09, $F(1, 91) = 10.112$, $p = 0.002$, showing that 9% of the variance in post-error accuracy in young adulthood change can be explained by urbanicity of childhood residence (see *Fig*. 4.8). Additionally, there was a significant relationship between post-error accuracy change and air pollution scores, R^2_{adj} = 0.103, $F(1, 91) = 11.607$, $p = 0.001$, showing that 10.3% of the variance in post-error accuracy change in young adulthood can be accounted for by air pollution scores of childhood residence (see *Fig*. 4.8). Notably, there was no significant relationship between post-error accuracy change and neighbourhood greenness ($p = 0.108$).

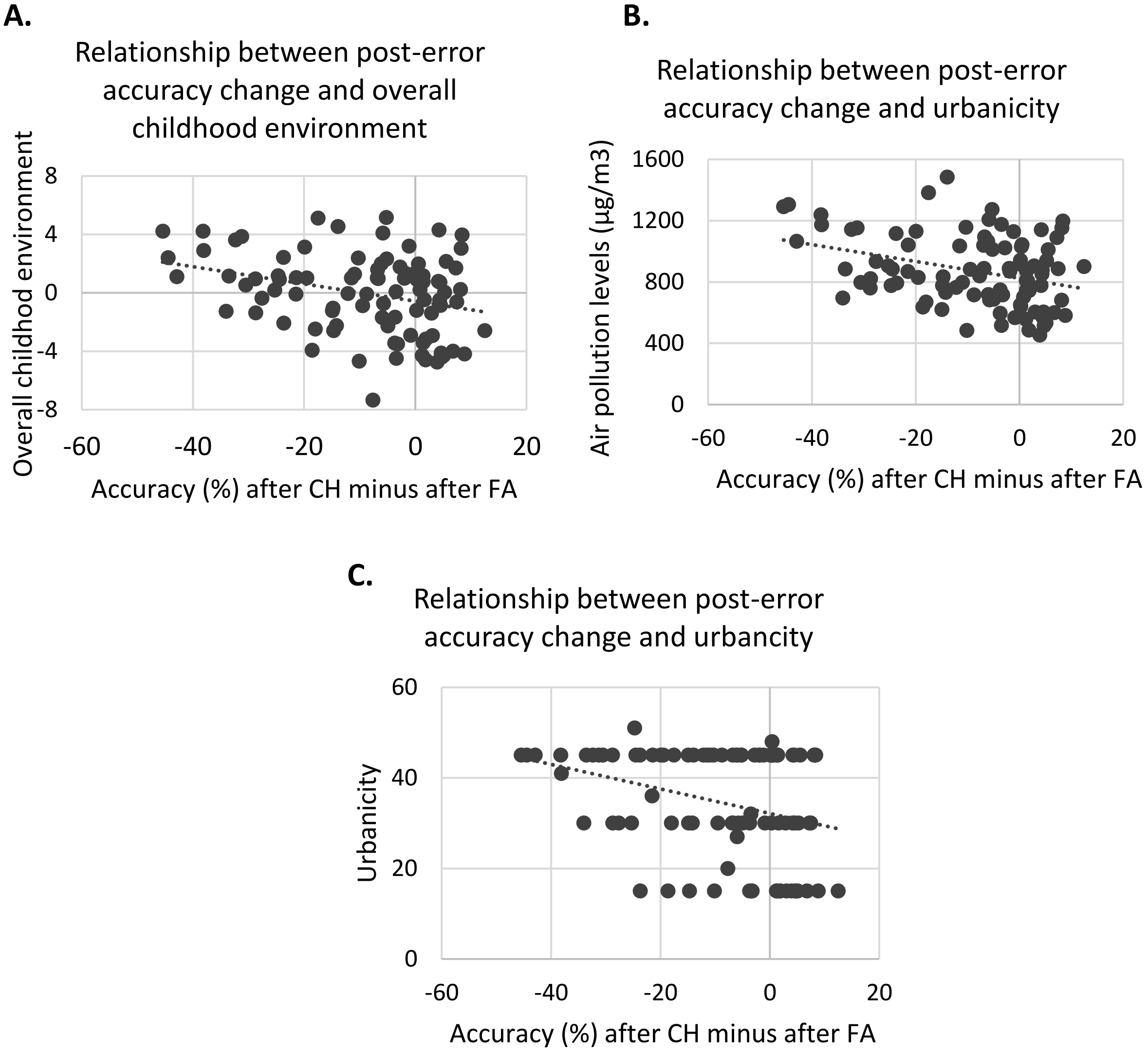

Figure 4.8. **A.** Relationship between post-error accuracy change and overall childhood environment. **B.** Relationship between post-error accuracy change and urbanicity of childhood residence. **C.** Relationship between post-error accuracy change and air pollution scores of childhood residence. Post-error accuracy change was calculated by subtracting accuracy on trails after correct hit (CH) from accuracy on trials after false alarms (FAs).

Discussion

I examined the effect of childhood environment as well as its various aspects on behavioural adjustment in young adulthood. To do this, participants were asked to complete the Go/No-go task in which they needed to respond to all except for one stimulus. PES was used to index behavioural adjustment. A combination of urbanicity, neighbourhood greenness and air pollution levels of childhood residence were used to categorise overall childhood environments as worse versus better. Additionally, childhood environments were categorised as urban versus non-urban using population size, as more-polluted versus less-polluted using air pollution levels and as more-green versus less-green using neighbourhood greenness for each place of residence. Importantly, participants who were raised in less- versus more-green environments showed greater PES, indicating that childhood exposure to less-green areas led to marginally greater behavioural adjustment in adulthood, a finding that was confirmed by linear regression. In contrast, overall childhood environment, urbanicity and air pollution levels did not affect PES. Instead, worse versus better childhood environments as well as urban versus non-urban childhood resulted in marginally greater post-error accuracy reduction, indicating that childhood exposure to worse as well as urban environments resulted in a greater tendency to make another error after an erroneous response in young adulthood, findings that were also confirmed by linear regression. Finally, despite no difference between adults who were raised in areas with low versus high air pollution levels, there was a relationship between air pollution levels and post-error accuracy change. This indicates that childhood exposure to greater air pollution levels also resulted in a greater tendency to make another error after an erroneous response in young adulthood.

Importantly, adults who were raised in areas with lower versus higher levels of neighbourhood greenness had somewhat greater PES, illustrating that they adjusted their behaviour to a greater extent. As PES is diminished in several mental disorders, such as schizophrenia and major depressive disorders (Compton et al., 2008; Storchak et al., 2021), greater PES is often considered to be a marker of better cognitive abilities. In line with this, greater PES has been linked to better distractor suppression (Wessel, 2016), suggesting that adults who were raised in areas with little versus lots of greenery may be better able to ignore distractors. Notably, it has recently been suggested that natural environments influence cognition to promote success there (Atchley, Strayer, & Atchley, 2012; White & Shah, 2019; Linnell & Caparos, 2020). As areas with little green space are often found in cities (Nieuwenhuijsen et al., 2017), taking longer to gain confidence in one's decision, indexed by greater PES, may be beneficial as errors that may have serious consequences, e.g., stepping in front of a car, are more likely to happen in urban versus non-urban environments.

Despite the link between greater PES and superior distractor suppression (Wessel, 2016) and that between greater PES and lower neighbourhood greenness, several experiments have demonstrated that living in an area with lower versus higher levels of neighbourhood greenness results in poorer distractor suppression (de Fockert, Caparos, Linnell, & Davidoff, 2011; Linnell, Caparos, de Fockert, & Davidoff, 2013). This suggests that greater PES may not be a marker of superior cognition. Supporting this notion, despite greater PES, participants raised in less- versus more-green neighbourhoods did not achieve greater accuracy, suggesting that these participants needed to adjust their behaviour to a greater extent to achieve similar task performance to those raised in more-green neighbourhoods. Further support comes from findings that anxious versus non-anxious participants display larger PES (Núñez-Peña et al., 2017; Voegler et al., 2018), demonstrating that greater PES can be maladaptive. For example, while taking time to look for oncoming traffic is important to avoid accidents, if, after stepping in front of a car, a pedestrian takes too much additional time to look for vehicles, they may miss many opportunities to cross the road, resulting in longer road crossing time.

Importantly, regardless of whether somewhat greater PES reflects superior or inferior cognition, these results suggests that in addition to causing adaptation (Linnell, Caparos, de Fockert, & Davidoff, 2013), our environment also affects the ability to adapt behaviour to some extent.

In contrast with neighbourhood greenness, overall childhood environment, urbanicity and air pollution levels of childhood residence did not affect PES, suggesting that these did not affect behavioural adjustment in young adulthood. This is surprising as childhood exposure to both urban versus non-urban environments as well as areas with higher versus lower air pollution levels have been shown to affect the frontal cortex (Haddad et al., 2015; Besteher et al, 2017; Power et al., 2018; Zhang et al., 2018; Gale et al., 2020), the brain region that is thought to underpin PES (Cohen et al., 2000; Carter & van Veen, 2007; Li et al., 2008; Mansouri et al., 2016). As all participants lived in Birmingham, United Kingdom, at the time of the experiment, the lack of effect of these measure of childhood environment might be due to participants' current environment counteracting any effect that their childhood environment might have had. An alternative explanation may be that residence is a crude way of categorising childhood environments. Although children and teenagers spend a lot of time near their homes, they often go to school or spend recreational time in different towns to where they live. As England has numerous cities that are close to rural areas, participants whose childhood environments were categorised as non-urban could have spent a lot of time in cities, thus regularly exposing themselves to large crowds. Arguing against this explanation, previous neuroimaging experiments that found that urban upbringing modulates the PFC also categorised childhood environments based on population size, therefore these studies would have also been affected by this.

In addition to our PES results, I found that adults who were raised in worse versus better as well as urban versus non-urban environments were marginally more likely to make another error after an erroneous response. Similarly, higher air pollution levels were associated with greater tendency to make another error after an erroneous response. According to the orienting account of PES (Notebaert et al., 2009), erroneous responses briefly interfere with task performance by causing distraction thus resulting in another error on the following trial. This suggests that adults who were raised in worse versus better, urban versus non-urban or more-versus less-polluted environments may have been more distracted by their errors. Supporting this view, participants who live in urban versus green environments (de Fockert et al., 2011; Linnell et al., 2013) as well as areas with higher versus lower air pollution levels (Sunyer et al., 2017; Rivas et al., 2019) are indeed less able to ignore task-irrelevant distractors.

Although outside of the focus of this chapter, I found that no measure of childhood environment modulated the proportion of FAs that indexes response inhibition, a measure of impulsivity (Horn, Dolan, Elliott, Deakin, & Woodruff, 2003; Nolan, D'Angelo, & Hoptman, 2011). This is interesting, as urbanicity (Haddad et al., 2015; Besteher et al., 2017; Zhang et al., 2018) and air pollution levels (Power et al., 2018; Gale et al., 2020) have been shown to modulate PFC that is thought to underpin impulsivity (Kim & Lee, 2011; Cho et al., 2013). Furthermore, living in areas with higher versus lower levels of neighbourhood greenness results in reduced ability to resist immediate small rewards on the Delay Gratification Task (Taylor, Kuo, & Sullivan, 2002), indexing that neighbourhood greenness influences impulsivity in the short-term. Although the reason for childhood environments having no long-term effect on impulsivity is unclear, it may be due to participants' current environment countering any effect that their childhood environments might have had.

In summary, I found some evidence that neighbourhood greenness of childhood residency has a long-term effect on behavioural adjustment that lasted into young adulthood. Although overall childhood environment, population size and air pollution levels did not modulate behavioural adjustment in young adulthood, they instead influenced the likelihood of making an error after an erroneous response, demonstrating that these also modulate adult cognition. Overall, these highlight the importance of children being raised in a healthy environment, to ensure the best possible outcomes for them.

Chapter 5. Effect of childhood environment on well-being in young adulthood

Abstract

Exposure to large population size, high air pollution levels and low neighbourhood greenness have been linked with diminished well-being at the time of exposure. Although there is growing evidence that exposure to these during childhood increases the risk of mental disorder diagnosis in young adulthood, it remains unclear whether it also modulates other indicators of well-being, such as psychopathological symptoms or negative mood. To investigate, young adults completed the 21-items Depression, Anxiety, Stress Scale to report their levels of depressive, anxiety, and stress symptoms. I combined population size, neighbourhood greenness and air pollution levels of participants' childhood residence to categorise their overall childhood environments as better versus worse. Additionally, I categorised childhood environments as cities, towns versus rural areas using population size, as more- versus less-polluted using air pollution levels, and as more- versus less-green using neighbourhood greenness for each place of residence. I found no association between childhood environment and well-being. Similarly, overall childhood environment did not affect well-being in young adulthood. Nevertheless, young adults who were raised in areas with high neighbourhood greenness and air pollution levels reported marginally lower levels of depressive, anxiety, and stress symptoms, indexing greater well-being. Likewise, young adults who were raised in cities versus towns or rural areas reported somewhat lower levels of stress symptoms, indicating that population size also influenced some aspect of well-being. Overall, these indicate that childhood environment has long-term effects on well-being that lasts into young adulthood.

Throughout history, humans have lived in close contact with natural green environments (Miyazako, Park, & Lee, 2013; Song, Igarashi, Ikei, & Miyazaki, 2017). However, due to urbanization over the last century, majority of the world's population is currently living in human-made urbanized environments that are often crowded, polluted, and lack natural green spaces (Dye, 2008). In several countries, including the United Kingdom, this relatively sudden transition to an urban environment has been linked to diminished well-being (Fett, Lemmers-Jansen, & Krabbendam, 2019).

Well-being is a broad construct that refers to positive indicators of psychological adjustment, such as positive emotions, in the absence of negative indicators of maladjustment, such as negative emotions, psychological symptoms or diagnoses (Houben, Van Den Noortgate, Kuppens, 2015). Notably, well-being is modulated by a range of factors. For example, people with lower socioeconomic status (SES; Huurre, Aro, & Rahkonen, 2003; Sainz, Martínez, Moya, Rodríguez-Bailón, & Vaes, 2020) or higher body mass index (BMI), a measure of body weight (Groessl, Kaplan, Barrett-Connor, & Ganiats, 2004; Hawker, 2012; Zayed, Ahmed, Van Niekerk, & Ho, 2017), report diminished well-being.

Importantly, growing evidence suggests that several features of urban environments also diminish well-being and therefore could contribute to the link between urban living and poorer well-being. Numerous experiments apply a conventional urbanicity metric that uses population size (Mortensen et al., 2011) to classify environments as cities versus towns or rural areas. These studies have shown that city versus town or rural dwellers have an elevated risk of developing psychosis, anxiety, and mood disorders (Sunquist, Frank, & Sundquist, 2004; Peen, Schroevers, Beekman, & Dekker, 2010; McKenzie, Murray, & Booth, 2013). Furthermore, participants who live in cities versus towns or rural areas show enhanced activity in the amygdala in response to social stress (Lederbogen et al., 2011), indicating enhanced stress reactivity.

Overall, these indicate that living in areas with larger population sizes may result in lower well-being.

Notably, natural environments that are often scarce in urban environments (Nieuwenhuijsen, Khreis, Triguero-Mas, Gascon, & Dadvand, 2017) also modulate well-being. Indeed, numerous experiments have demonstrated that brief exposure to natural versus urban environments increase positive mood and decrease negative mood, indicating greater well-being (see McMahan & Estes, 2015 for review). Likewise, living in an area with higher levels of neighbourhood greenness is associated with lower levels of depression (Liu et al., 2019; Perrino et al., 2019), anxiety (Gascon et al., 2018) and stress (Roe et al., 2013; Liu et al., 2019; Lega, Gidlow, Jones, Ellis, & Hurst, 2021), further supporting the link between natural environments and well-being. Highlighting the causal relationship between living in green neighbourhoods and well-being, Alcock, White, Wheeler, Fleming and Depledge (2014) demonstrated that moving from a green to an urban neighbourhood decreases well-being, whereas moving from an urban to a green neighbourhood increases it. These findings suggest that high levels of neighbourhood greenness promote whereas low levels diminish well-being.

Finally, air pollution levels that are typically higher in urban environments (Hewitt, Ashwroth, & MacKenzie, 2020), have also been linked to poorer well-being (see Li, Guan, Tao, Wang, & He, 2018, for review). Air pollution refers to a complex mixture of chemicals, volatile organic compounds, metals, and particulate matter (Schauer et al., 2006; Block et al., 2012; Genc, Zadeoglulari, Fuss, & Genc, 2012). Highlighting the link between air pollution and reduced well-being, numerous studies have demonstrated that exposure to higher levels of air pollutants (nitrogen dioxide, particulate matter, ozone and sulphur dioxide) is associated with increased depressive symptoms (Lim et al., 2012; Vert et al., 2017; Fan et al., 2020; Wang et al., 2020), anxiety (Power et al, 2015; Lu, Lee, Gino, & Galinsky, 2020) and stress reactivity (Miller, Gillette, Kircanski, LeMoult, & Gotlib, 2020). In line with this, people who live near higher traffic congestion and therefore, are typically exposed to higher air pollution levels also report lower life satisfaction, an index of well-being (Smyth, Mishra, & Qian, 2008). These demonstrate that similar to large population size and low levels of neighbourhood greenness, high air pollution levels may also lead to poorer well-being.

Importantly, there is growing consensus that our environment may have a long-term effect on well-being. Indeed, numerous experiments have found that adults who were raised in cities versus town or rural areas are more likely to develop mental disorders, such as schizophrenia and major depressive disorder (Mortensen et al., 1999; Krabbendam & Van Os, 2005; Lundberg, Cantor-Graae, Rukundo, Ashaba, & Östergren, 2009) as well as to show increased stress reactivity (Lederbogen et al., 2011). Furthermore, adults who were raised in an area with lower levels of neighbourhood greenness have an enhanced risk of developing schizophrenia (Engemann et al., 2018; 2019; 2020). These demonstrate that childhood exposure to various features of urban environments increases the risk of psychopathological diagnoses in adulthood, an indicator of diminished well-being. However, it remains unclear whether childhood exposure to various features of urban environments also influences other indicators of well-being in adulthood, such as psychopathological symptoms or negative emotions.

To investigate, I assessed the long-term effects of childhood environments on self-reported well-being in young adults. I assessed well-being using the well-validated 21-item Depression, Anxiety and Stress Scale (DASS; Lovibond & Lovibond, 1995). Here, participants indicated the frequency at which they experienced depressive, anxiety, and stress symptoms by rating the extent to which statements regarding these applied to them during the week before this study. Importantly, although the DASS-21 measures well-being during the past week only, frequency has been shown to be a good measure of long-term well-being (Diener, Colvin, Pavot,

& Allman, 1991). A combination of population size, neighbourhood greenness and air pollution levels of participants' childhood residence was used to categorise overall childhood environment as better versus worse. Additionally, childhood environments were categorised as cities, towns or rural areas using population size, as more- versus less-green using neighbourhood greenness and as more- versus less-polluted using air pollution levels. I predicted adults who were raised in worse versus better environments, cities versus towns or rural areas, more- versus less-polluted areas or less- versus more-green neighbourhoods to report higher levels of depressive, anxiety, and stress symptoms, indexing poorer well-being.

Methods

Participants

Complete data sets were collected from 278 undergraduate students (246 females, mean age = 18.78, s.d. = .79) in exchange for course credit. All were fluent English speakers and readers, reported normal or corrected-to-normal vision and no history of neuropsychological or psychiatric disorders. Furthermore, all participants spent their entire life in England, United Kingdom, as the database used to categorise their childhood environment as more- versus less-green was only available for this region. Notably, all participants lived in Birmingham, United Kingdom, at the time of the experiment to ensure that the effect of childhood environments is not confounded by participants' current environments. The study was approved by the University of Birmingham Ethics Committee.

Apparatus

The survey was presented, and data was recorded online using Qualtrics (https://www.qualtrics.com). Any device with access to the internet could be used to complete the experiment.

Materials

Well-being was assessed using the 21-item Depression, Anxiety, Stress Scale (DASS-21, Lovibond & Lovibond, 1995). Participants rated the extent to which each of twenty-one statements applied to them during the past week on a 4-point Likert scale (0 = did not apply to me at all; 1 = applied to me to some degree, or some of the time; 2 = applied to me to a considerable degree or a good part of the time; and 3 = applied to me very much or most of the time). Depression items concern worthlessness, lack of positive feelings and motivation; anxiety items concern feelings and physical symptoms of panic; and stress items concern relaxation and feeling oversensitive.

Procedure

The experiment consisted of a single session. First, participants reported their weight and height as well as their current family income using a 11-point Likert scale (1 = '<£15,000', 11 = '>£60,000'). Afterwards, they reported their home postcode for each year of life from birth to present and then completed the DASS-21.

Data analysis

For each participant, weight (kilograms) was divided by the square of height (meters) to calculate BMI. Current family income was used to index SES.

Scores for depression, anxiety, and stress subscales were summed separately to produce three scores. Scores for each subscale were doubled to ease comparison with DASS-42 data that has been used in several studies using the DASS (Bayram & Bilgel, 2008; Asif, Mudassar, Shahzad, Raouf, & Pervaiz, 2020; Cheung, Tam, Tsang, Zhang, & Lit, 2020; Hanawi et al., 2020). Higher score on each subscale reflected poorer well-being.

In line with Chapters 2 and 4 as well as previous studies (Mortensen et al., 1999; Lundberg et al., 2009; Lederbogen et al., 2011), environments were categorised using home postcodes for the childhood period of the first fifteen years of life.

Childhood environments were categorised as cities, towns, or rural areas via a conventional urbanicity metric that uses population size of each place of residence during childhood (Mortensen et al., 1999). Population size of each place of residence was determined based on the 2011 Census data (https://www.ons.gov.uk/census/2011census/2011censusdata). Each place of residence was assigned a score based on population size (1 – <10,000, 2 – 10,000-100,000, 3 – >100,000), then multiplied by years dwelt there. Products were then summed over the childhood period to determine the final urbanicity score (values range from fifteen to forty-five). Typically, a score of fifteen indexes rural areas, a score of thirty indexes towns and a score of forty-five indexes cities as the place of residence. Importantly, however, to avoid the rejection of the thirty-two participants who moved between these types of settlements during childhood, and therefore, did not have an urbanicity score of forty-five, thirty or fifteen, I used a range of scores to categorize childhood environments into the three categories. Scores ranging from fifteen to twenty-four indexed rural areas, scores ranging from twenty-five to thirty-five indexed towns and scores ranging from thirty-six to forty-five indexed cities. 118 participants' childhood environments were categorised as cities, ninety-eight's as towns and sixty-one's as rural areas.

Childhood environments were categorised as more- versus less-green based on neighbourhood greenness that was defined as a combination of land cover by private and public green spaces (White, Alcock, Wheeler, & Depledge, 2013; Martin et al., 2020; Mueller & Flouri, 2020), using the Generalised Land Use Database Statistics for England (Office of the Deputy Prime Minister, 2005) within England, United Kingdom. This database defined land use for 32,482 neighbourhoods (called lower-layer super output areas; LSOAs). On average, neighbourhoods are four km^2 large with 1,500 residents. To calculate neighbourhood greenness for each place of residence, land cover by private gardens and public green space was summed then divided by the total land cover for each neighbourhood. This score was then multiplied by the number of years dwelt there. Products were summed over the childhood period to determine the final neighbourhood greenness score. Using median split on final scores, half (139) of all participants' childhood environments were categorised as more-green and the other half's as less-green (see *Table* 5.1). On average, participants in the less-green group had a neighbourhood score of 811 (s.d. = 191) that is 329 lower than the national average over the childhood period (1140). In contrast, participants in the more-green group had a neighbourhood greenness score of 1209 (s.d. = 136) that is 69 higher than the national average over the childhood period.

Distribution of neighbourhood greenness scores in the more- versus less-green groups is shown in *Figure* 5.1.

Childhood environments were categorised as more- versus less-polluted based on air pollution levels that were determined using the Defra UK-AIR GIS Tool (https://uk-air.defra.gov.uk/data/gis-mapping). This provides the average annual level of numerous pollutants for each place of residence in the United Kingdom. Similar to Chapter 4, I focused on four pollutants; nitrogen dioxide (NOx), particulate matter 10 (PM_{10}), particulate matter 2.5 ($PM_{2.5}$) and ozone (O_3) because these pollutants have been linked to well-being (see Li, Guan, Tao, Wang, & He, 2018, for review; Power et al., 2015; Vert et al., 2107; Fan et al., 2020; Miller et al., 2020; Wang et al., 2020). For each place of residence, the average annual level of each pollutant was determined. Data was available for NOx and PM_{10} since 2001, for $PM_{2.5}$ since 2002, and for O_3 since 2003. For earlier years, level of each pollutant was calculated by averaging the available data for the childhood period. The scores were then summed over the childhood period to determine the final score. Using median split on the final scores, 142 participants' childhood environment was categorised as more-polluted and 136's as less-polluted. Distribution of air pollution scores in the more- versus less-polluted groups is shown in *Figure* 5.1.

Notably, similar to Chapter 4, urbanicity, neighbourhood greenness and air pollution scores were strongly correlated ($r_s > 0.572$, $N = 278$, $p < 0.001$; see *Fig*. 5.2). Higher neighbourhood greenness was associated with lower population size and air pollution levels while higher population size was associated with higher air pollution levels. Scores for these scales were combined to quantify participants' overall childhood environment. Similar to Chapters 2 and 4, first, I turned scores for each scale into Z-scores by subtracting the group's mean from each participant's score then dividing it by the group's standard deviation. Neighbourhood greenness Z-scores were then reversed so that positive values became negative and vice versa, thus higher Z-scores represented less green environments. Z-scores for each scale were then summed to create a single score, called overall childhood environment. High scores for this scale represented childhood environments that had high population size and air pollution levels as well as low levels of neighbourhood greenness, characteristics that have been linked to negative outcomes, such as poorer mental health (Sunquist et al., 2004; Lundberg et al., 2009; Peen et al., 2010; Engemann et al., 2018; 2019; 2020) or poorer well-being (see McMahan & Estes, 2015 for review; Lederbogen et al., 2011; McKenzie et al., 2013; Lim et al., 2012; Power et al, 2015; Vert et al., 2017; Fan et al., 2020; Lu et al., 2020; Miller et al., 2020; Wang et al., 2020). Based on the final scores, 139 participants' childhood environments were categorised as better childhood environment and another 139's as 'worse childhood environment using median split (see *Table* 5.1). Distribution of overall childhood environment scores in the worse versus better childhood environment groups is shown in *Figure* 5.1.

			Worse childhood environment	Better childhood environment
City	More-green	More-polluted	14	1
		Less-polluted	7	10
	Less-green	More-polluted	72	0
		Less-polluted	14	0
Town	More-green	More-polluted	5	15
		Less-polluted	0	30
	Less-green	More-polluted	26	5
		Less-polluted	1	16
Rural area	More-green	More-polluted	0	2
		Less-polluted	0	54
	Less-green	More-polluted	0	2
		Less-polluted	0	3

Table 5.1. Number of participants in the urbanicity (city, town, rural area), neighbourhood greenness (more-green, less-green) and air pollution groups (more-polluted, less-polluted) within the worse and better childhood environment groups.

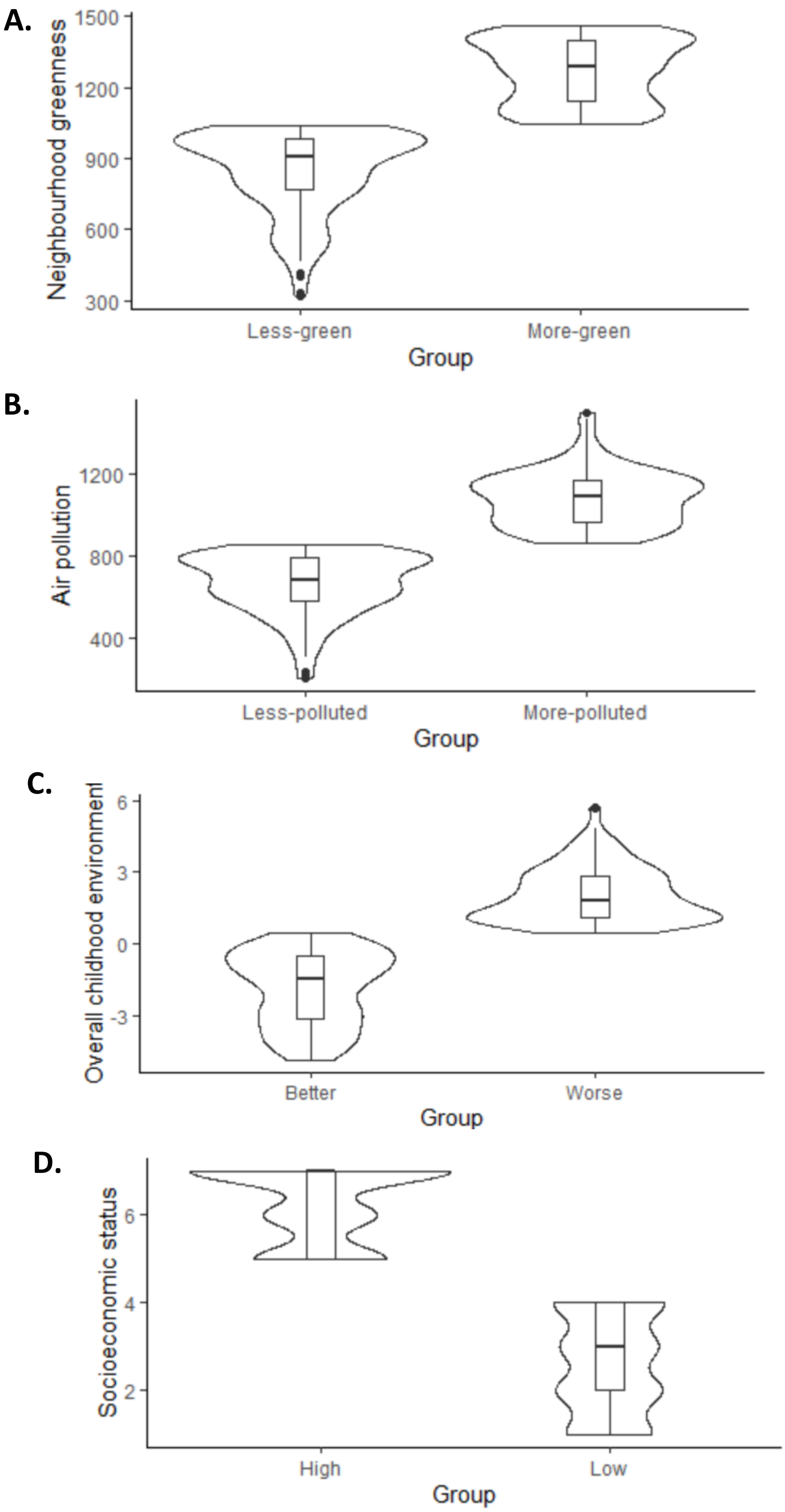

Figure 5.1. **A.** Distribution of neighbourhood greenness scores in the more- (left) versus less-green groups (right). **B.** Distribution of air pollution scores in the more- (left) versus less-polluted groups (right). **C.** Distribution of overall childhood environment scores in the better- (left) versus worse childhood environment groups (right). **D.** Distribution of socioeconomic status scores in the high- (left) versus low-SES groups (right).

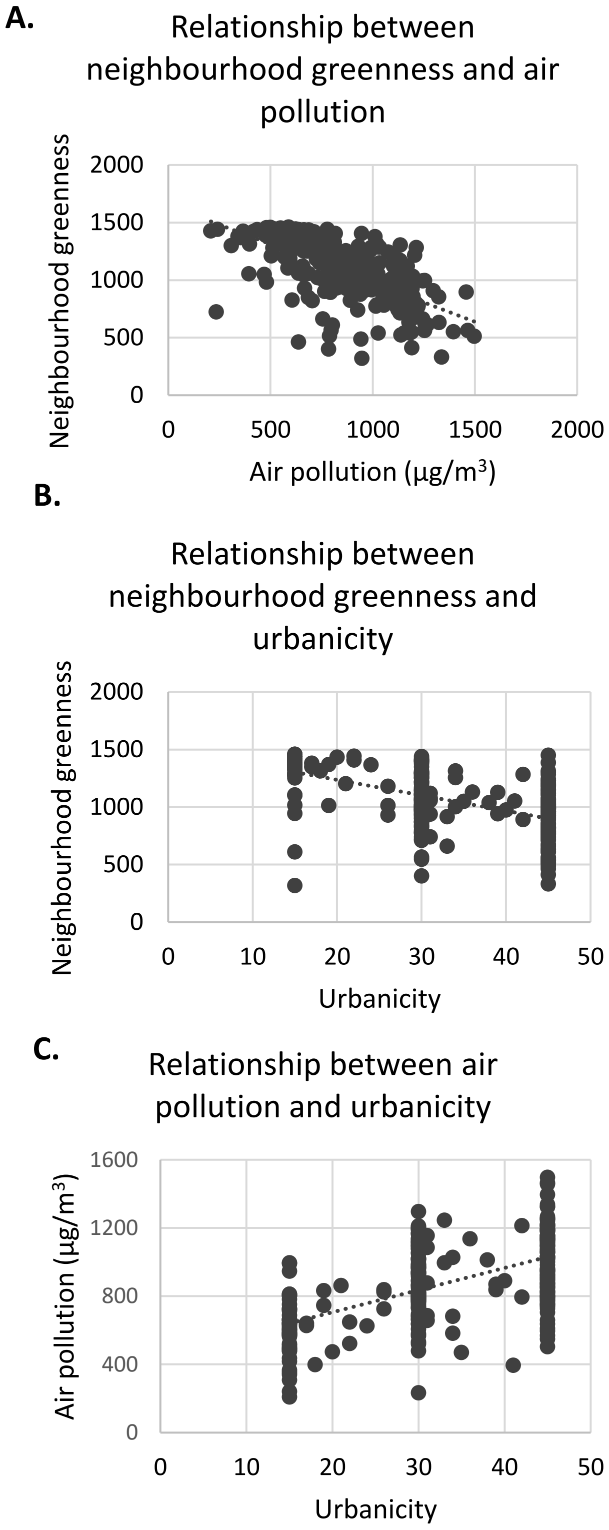

Figure 5.2. **A**. Relationship between neighbourhood greenness and air pollution scores of childhood residence. **B**. Relationship between neighbourhood greenness and urbanicity scores of childhood residence. **C**. Relationship between urbanicity and air pollution scores of childhood residence.

Individual BMI and SES scores were compared between the overall childhood environment (worse childhood environment, better childhood environment), neighbourhood greenness (more-green, less-green) and air pollution groups (more-polluted, less-polluted) separately using Mann-Whitney U tests (2-tailed). Additionally, as there were three urbanicity groups (city, town, rural area), individual SES and BMI scores were analysed using a Kruskal-Wallis test with urbanicity as a between group factor. Furthermore, the relationship between each measure of childhood environment (overall childhood environment, urbanicity, neighbourhood greenness, and air pollution) as well as BMI and SES was examined using linear regression. Here, SES and BMI were the dependent variables, and each measure of childhood environment was the predictor. To ensure that significant SES effects of the above analyses did not modulate the effect of childhood environments on DASS-21 scores, participants were grouped as either low or high on SES using median split. 138 participants were in the high-SES group and 140 participants in the low-SES group. Distribution of SES scores in the high- versus low-SES groups is shown in *Figure* 5.1. Individual score for each subscale of the DASS-21 were compared between these groups using Mann-Whitney U tests (2-tailed). For these analyses, alpha levels were set at 0.05.

To investigate the effect of childhood environment on well-being, individual scores for each subscale of the DASS-21 were compared between the overall childhood environment, neighbourhood greenness and air pollution groups separately using Mann-Whitney U tests (2-tailed). For these analyses, alpha levels were set at 0.05. Additionally, to investigate the effect of childhood urbanicity on well-being, individual score for each subscale of the DASS-21 was analysed using a Kruskal-Wallis test with urbanicity as a between group factor. Follow-up analyses used Mann-Whitney U test (2-tailed). For these analyses, Bonferroni corrections were applied, and alpha levels were set at 0.017. To investigate the relationship between well-being and childhood environment, I conducted linear regressions with individual scores for each subscale of the DASS-21 as dependent variable and overall childhood environment, population size, neighbourhood greenness or air pollution scores as a predictor. Alpha levels were set at 0.0125.

Results[5]

BMI and SES

Linear regression showed no significant relationship between BMI and any measure of childhood environment (all *p*'s > 0.144). Furthermore, BMI did not differ across any measure of childhood environment (all *p*'s > 0.1), suggesting that in this sample, adulthood BMI is unlikely to have contributed to the effect of childhood environment on well-being in young adulthood. Average BMI for each group of each feature of childhood environment are shown in *Table* 5.2.

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[5] Effects described in this section remained the same when 1) childhood length was reduced to 10 years (Engemann et al., 2018; 2019; 2020), 2) only female participants were included in all analyses, or 3) only participants with an urbanicity score of fifteen, thirty, or forty-five were included in the analyses of urbanicity results. However, effect of neighbourhood greenness disappeared when 1) neighbourhood greenness was defined using public green space only (Ord, Mitchell, & Pearce, 2013; Weeland, Lacuelle, Nederhof, Overbeek, & Reijneveld, 2019), or 2) neighbourhood greenness groups were defined using the national average instead of median split.

Feature of childhood environment	Group	BMI
Overall childhood environment	Worse	22.2 (3.9)
	Better	22.2 (4.1)
Urbanicity	City	22.2 (3.7)
	Town	22.2 (4.8)
	Rural area	22.4 (3)
Neighbourhood greenness	More-green	22.1 (3.2)
	Less-green	22.3 (4.6)
Air pollution	More-polluted	22.1 (3.8)
	Less-polluted	22.4 (4.1)

Table 5.2. Average BMI in each group of overall childhood environment (worse, better), urbanicity (city, town, rural area), neighbourhood greenness (more-green, less-green) and air pollution (more-polluted, less-polluted). S.d. are shown in parentheses.

Similarly, there was no significant relationship between SES and any measure of childhood environment (all *p*'s > 0.207). However, SES was significantly higher in the less- (mean = 4.86, s.d. = 2) versus more-polluted group (mean = 3.97, s.d. = 2.08; Z = -3.523, *p* < 0.001). Furthermore, SES significantly differed across urbanicity groups; $\chi^2(2) = 13.321$, *p* = 0.001. Follow-up analysis revealed that SES was significantly higher in the rural (mean = 5.26, s.d. = 1.81) versus city (mean = 4.08, s.d. = 2.1; Z = -3.543, *p* < 0.001) or town groups (mean = 4.27, s.d. = 2.11; Z = -2.944, *p* = 0.003). SES in the city versus town groups did not differ (*p* = 0.564). Similarly, SES did not differ between the more- versus less-green groups (*p* = 0.147). Importantly, however, there was no difference between high- versus low-SES groups on depression (*p* = 0.617), anxiety (*p* = 0.315) and stress scores (*p* = 0.428), indicating that in this sample, SES is unlikely to have contributed to the effect of childhood environment on well-being in young adulthood.

Well-being

Participants in the worse versus better childhood environment groups scored similarly on the depression (worse childhood environment: mean = 11.4, s.d. = 9.8; better childhood environment: mean = 10.9, s.d. = 10; *p* = 0.496), anxiety (worse childhood environment, mean = 9.6, s.d. = 7.9; better childhood environment: mean = 9.4, s.d. = 7.5; *p* = 0.165) and stress subscales (worse childhood environment: mean = 14.3, s.d. = 8.4; better childhood environment: mean = 12.7, s.d. = 9.2; *p* = 0.106). This indicates that overall childhood environment is unlikely to have influenced well-being in young adulthood.

In contrast, participants in the more- versus less-green groups scored marginally higher on the depression (less-green: mean = 10.2, s.d. = 9.7; more-green: mean = 12.1, s.d. = 10; Z = -1.902, *p* = 0.057), anxiety (less-green: mean = 7.9, s.d. = 7; more-green, mean = 10.1, s.d. = 8.3; Z = -2.120, *p* = 0.034), and stress subscales (less-green: mean = 12.5, s.d. = 8.9; more-green: mean = 14.5, s.d. = 8.7; Z = -1.904, *p* = 0.057). These suggest that higher childhood neighbourhood greenness resulted in poorer well-being in young adulthood. Mean scores for the depression, anxiety, and stress subscales in the more- versus less-green groups are shown in *Figure* 5.3.

Similarly, participants in the more- versus less-polluted groups reported marginally lower levels of depressive (more-polluted: mean = 10.21, s.d. = 10, less-polluted: mean = 12.09, s.d. = 9.72; Z = -2.152, *p* = 0.031), anxiety (more-polluted: mean = 8.13, s.d. = 7.66, less-polluted: mean = 9.88, s.d. = 7.74; Z = -2.256, *p* = 0.024) and stress symptoms (more-polluted: mean = 12.55, s.d. = 8.96, less-polluted: mean = 14.49, s.d. = 8.56; Z = -1.986, *p* = 0.047). These suggest that childhood exposure to higher air pollution levels also led to better well-being in young adulthood. Mean scores for the depression, anxiety, and stress subscales in the more- versus less-polluted groups are shown in *Figure* 5.3.

Kruskal-Wallis test revealed marginally significant effect of urbanicity on stress scores; $\chi^2(2) = 5.611$, *p* = 0.06. Subsequent analysis revealed that stress levels were marginally lower in the city (mean = 12.15, s.d. = 9.95) versus town (mean = 14.55, s.d. = 8.87; Z = -2.085, *p* = 0.037) or rural groups (mean = 14.46, s.d. = 8.18; Z = -1.851, *p* = 0.064). Notably, stress levels in the town versus rural groups did not differ (*p* = 0.965). In contrast with stress, urbanicity did not affect depression (*p* = 0.310) or anxiety scores (*p* = 0.164). Group mean scores for the depression, anxiety, and stress subscales in each urbanicity groups are shown in *Figure* 5.3.

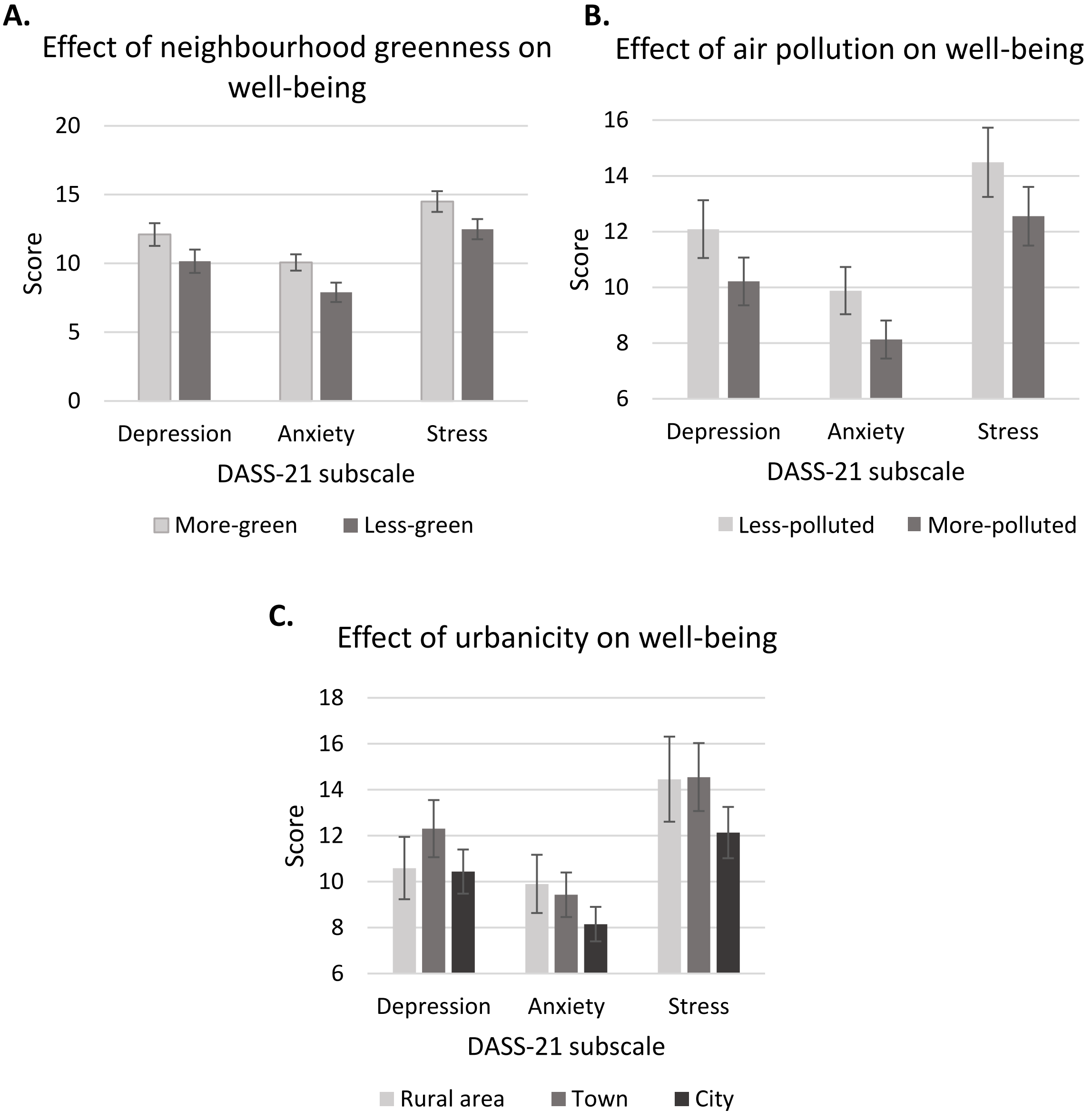

Figure 5.3. **A.** Group mean scores of the less- (light grey) versus more-green groups (dark grey) for each subscale of the DASS-21 (depression, anxiety, and stress). **B.** Group mean scores of the less- (light grey) versus more-polluted groups (dark grey) for each subscale of the DASS-21. **C.** Group mean scores of the rural area (light grey), town (dark grey) and city groups (black) for each subscale of the DASS-21. Error bars show standard error.

Regressions

Regression analyses revealed no significant relationships between any measure of childhood environment (overall childhood environment, urbanicity, air pollution or neighbourhood greenness) and depression (all *p*'s > 0.395), anxiety (all *p*'s > 0.157) or stress scores (all *p*'s > 0.135) in young adulthood.

Discussion

I examined the long-term effect of childhood environment on well-being in young adulthood. Well-being was measured by asking participants to report the frequency at which they experienced depressive, anxiety, and stress symptoms during the week before this study using the DASS-21. A combination of population size, neighbourhood greenness and air pollution levels of participants' childhood residence was used to categorise overall childhood environment as better versus worse. Additionally, childhood environments were categorised as cities, towns or rural areas using population size, as more- versus less-green using neighbourhood greenness and as more- versus less-polluted using air pollution levels of each place of residence. There was no significant association between any measure of childhood environments and well-being in young adulthood, suggesting that there is not a close relationship between these. In line with this, overall childhood environment did not affect well-being in young adulthood. Nevertheless, supporting my hypothesis, adults who were raised in areas with higher levels of neighbourhood greenness reported marginally lower levels of depressive, anxiety, and stress symptoms, indexing greater well-being. In contrast with this and my hypothesis, adults who were raised in areas with higher air pollution levels also reported marginally lower levels of depressive, anxiety, and stress symptoms. Finally, adults who were raised in cities versus towns or rural areas reported marginally lower stress symptoms, indicating that population size also had a long-term effect on some aspect of well-being. Importantly, as all participants lived in Birmingham, United Kingdom, at the time of this study, population size, neighbourhood greenness and air pollution levels of participants' place of residence at the time of the study were very similar. Therefore, these are unlikely to account for these effects.

Notably, the finding that exposure to more greenery resulted in marginally greater well-being matches results of previous experiments that have demonstrated that brief nature exposures promote well-being (see McMahan & Estes., 2015 for review). Furthermore, my finding builds on these results, as to my knowledge, this is the first study to indicate that childhood nature exposure may have some long-term effect on well-being that lasts into young adulthood. Notably, it has been suggested that nature exposure promotes lower BMI (Bell, Wilson, & Liu, 2008; de Bont et al., 2020) that in turn promote well-being (Groessl et al., 2004; Hawker, 2012; Zayed et al., 2017). However, I found no effect of childhood environment on BMI, casting doubt on the notion that BMI underpinned the relationship between childhood neighbourhood greenness and well-being in young adulthood. Similarly, despite the relationship between SES and well-being (Huurre et al., 2003; Sainz et al., 2020) and that between SES and neighbourhood greenness (Chaparro, Benzeval, Richardson, & Mitchell, 2018), I found no effect of childhood neighbourhood greenness on SES, suggesting that SES is also unlikely to account for the effect of childhood exposure to natural environment on well-being in young adulthood.

Interestingly, long-term effect of neighbourhood greenness on well-being may be underpinned by inflammation. Indeed, both brief and extended nature versus urban exposures have been linked to reduced inflammatory cytokines (Mao et al., 2012; Tsunetsugu et al., 2013), that in turn have been linked to lower depressive symptoms (Miller, Maletic, & Raison, 2009; Raison & Miller, 2011), anxiety (Salim, Chugh, & Asghar, 2012; Vogelzangs, Beekman, De Jonge, & Penninz, 2013), and stress (Sorrels, Caso, Munhoz, & Sapolsky, 2009). However, whether chronic exposure to natural environments indeed have long-term effects on inflammation remains untested.

In addition to high levels of neighbourhood greenness, childhood exposure to higher air pollution levels also resulted in greater well-being. As air pollution levels are typically lower in natural environments (Hartig, Mitchell, De Vries, & Frumkin, 2014; Nowak, Hirabayashi, Bodine, & Greenfield, 2014; Hirabayashi & Nowak, 2016), this sharply contrasts with the above finding that neighbourhood greenness promoted well-being. Likewise, this air pollution effect also diverges from previous findings that exposure to higher air pollution levels results in diminished well-being at the time of exposure (Lim et al., 2012; Power et al, 2015; Vert et al., 2017; Fan et al., 2020; Lu et al., 2020; Miller et al., 2020; Wang et al., 2020). One explanation for this discrepancy may be that the short- versus long-term effects of air pollution are different, so that air pollution negatively affect well-being in the short-term but positively affects it in the long-term.

Similar to air pollution, childhood exposure to large population size also resulted in somewhat greater well-being. This also contrasts with my finding that childhood neighbourhood greenness promoted well-being as urban environments that have large population sizes often lack natural spaces (Nieuwenhuijsen et al., 2017). Furthermore, this population size finding contradicts Lederbogen et al.'s (2011) results too, that demonstrated that adults who were raised in cities versus towns or rural areas show enhanced stress reactivity, presumably resulting in elevated stress levels. This may also be explained by that Lederbogen et al. investigated social stress, whereas I focused on non-social stress, suggesting that while urbanicity enhances reactivity to social stress, it may build resilience to non-social stress.

Notably, as only my neighbourhood greenness results match previous findings, alternative explanations for the surprising air pollution and population size effects need to be considered. For example, it is possible that participants who were raised in areas with high air pollution levels and large population size adapted to the adverse effects of these. Consequently, they experienced fewer negative effects whilst living in Birmingham, a city that has high air pollution levels and large population size. In comparison, participants who were raised in less polluted and populated areas were not used to the negative impact of these and therefore, experienced greater negative effects whilst living in Birmingham, thus resulting in poorer well-being. Although the possibility of this kind of adaptation has not yet been tested within the well-being literature, there is some evidence that attention functioning differs after urban versus nature exposures due to adaptation to these environments (White & Shah, 2019; Linnell & Caparos, 2020), suggesting that adaptation may also affect well-being.

An alternative explanation may be that baseline perception of well-being differed between those raised in areas with distinct air pollution levels and population size, thus affecting their DASS-21 ratings. This highlights just one of the disadvantages of measuring well-being via self-report measures. Another disadvantage is that participants tend to place more emphasis on the end versus beginning of the tested period (week before the study; Fredrickson, 2000). However, retrospective well-being assessment has been shown to reflect actual experiences (Scollon, Biener, Oishi, & Biswas-Diener 2004; Tov, 2012), meaning that while this experiment should be replicated using objective measures of well-being, self-report measure of well-being is unlikely to account for the surprising effects of air pollution and population size.

As all three features of childhood environment that were investigated in this study influenced well-being to some extent, it is somewhat surprising that overall childhood environment had no effect on well-being in young adulthood. However, this lack of effect is most likely underpinned by neighbourhood greenness having the opposite effect to air pollution and population size.

I showed that population size, neighbourhood greenness and air pollution levels of childhood environment have some long-term effects on well-being that last in young adulthood. This not only shows that understanding how various features of our environments modulates well-being is important, but it also highlights the significance of ensuring that every child is raised in an environment that promotes the best outcomes for them later in life.

Chapter 6. General discussion

Summary of research questions and studies

This thesis aimed to investigate the effect of urban versus natural environments on 1) proactive and reactive cognitive control; 2) attention allocation towards emotional face stimuli; 3) behavioural adjustment; and 4) well-being.

For these purposes, I utilized two types of experimental procedures. The first type investigated the effect of brief urban versus nature exposures via a two-phase procedure. First, participants were exposed to urban versus natural environments via either videos (artificial exposure; Chapters 2 and 3) or walks (physical exposures; Chapter 2). Afterwards, they completed one of two face attention tasks. The second type of experimental procedure investigated the long-term effects of chronic childhood exposures to various features that differ between urban and natural environments (e.g., neighbourhood greenness) also via a two-phase procedure. First, young adult participants provided their home postcodes for each year of life from birth to present that were used to determine various features of childhood environments. Participants then completed either a face attention task (Chapter 2), the Go/No-go task (Chapter 4) or the DASS-21 (Chapter 5).

Cognitive control

Chapter 2 addressed the first aim of this thesis by investigating the effect of urban versus natural environments on proactive and reactive cognitive control. For this purpose, I used a face attention task, where a target neutral face was simultaneously presented with a distractor image that could be either a neutral, happy, or fearful face or a scrambled meaningless image. I was interested in whether the magnitude of the congruency sequence effect differed 1) immediately after brief artificial (Experiment 1) and physical (Experiment 2) exposures to urban versus natural environments; and 2) in young adulthood after chronic childhood exposure to these environment (approximately 4.5 years, s.d. = 0.97, after childhood period; Experiment 3).

Importantly, brief physical nature exposure resulted in a minimal congruency sequence effect, indicating higher levels of proactive control, whereas brief physical urban exposure resulted in a relatively large effect, indicating higher levels of reactive control. This suggests that physical urban versus nature exposures led to different styles of cognitive control.

In contrast, magnitude of the congruency sequence effect was very small after brief artificial exposures to both urban and natural environments, demonstrating that artificial exposures did not modulate cognitive control. Although this lack of replication might be due to false effects, there are alternative explanations. For example, discrepancy may be due to differences in the urban environments during the physical versus artificial exposures, such as the number of faces participants saw. While features of the videos can be easily quantified, the physical walks cannot be accurately assessed as these were not recorded, meaning that whether differences between the environments could account for the distinct effects of the two types of exposures remains unclear. Nevertheless, in a future experiment, the video could show the same environment as people walk in, thus controlling for possible differences between environments during walks and the video. Alternatively, distinct styles of cognitive control after physical versus artificial urban exposures may be underpinned by these exposure types differentially modulating mechanisms that underpin proactive control, such as the availability of central cognitive resources. For example, while participants needed to do very little during the artificial urban exposure, physical urban exposures required participants to navigate the environment to avoid trip hazards and other pedestrians. This may have taxed the brain to some extent in a way that artificial urban exposure did not, thus diminishing central cognitive resources and potentially explaining why physical and not artificial urban exposure resulted in enhanced use of reactive control. To test this, a future experiment could use a video that involves participants having to navigate an urban environment to avoid trip hazards and other pedestrians, thus increasing the amount of cognitive effort required by the video.

Similar to brief artificial exposures, chronic exposure to urban versus non-urban or relatively green versus non-green environments in childhood did not affect the magnitude of the congruency sequence effect in young adulthood. This suggests that chronic urban versus nature exposures may not have long-term effects on cognitive control. This is surprising as urban versus rural childhoods differentially modulate the prefrontal cortex (Haddad et al., 2015; Besteher, Gaser, Spalthoff, & Nenadić, 2017; Zhang et al., 2018), a brain region that is thought to underpin cognitive control (Braver, 2012). However, as all participants lived in a city at the time of the experiment, it is possible that participants’ current environment counteracted any effect that their childhood environment might have had, implying that any effects of childhood environments could be altered in adulthood. However, numerous studies have found that childhood environments affect the risk of several mental disorders in adulthood (Marcelis et al., 1998; Harrison et al., 2003; Laursen et al., 2007; Lundberg, Cantor-Graae, Rukundo, Ashaba, & Östergren, 2009; Engemann et al., 2018; 2019; 2020), casting some doubt on this notion.

Attention allocation to emotional face stimuli

Chapters 2 and 3 addressed the second aim of this thesis by investigating the effect of urban versus nature exposures on attention allocation towards emotional face stimuli. Therefore, in these chapters, participants completed one of two face attention tasks, where they were asked to report the gender of a target face. In Chapter 2, this task matched that used to measure cognitive control, where the target was always a neutral face and it was simultaneously presented with a distractor image that could be either a neutral, happy, or fearful face or a scrambled meaningless image. In this chapter, I was interested in the extent to which fearful distractors interfered with task performance 1) immediately after brief artificial (Experiment 1) and physical (Experiment 2) exposures to urban versus natural environments; and 2) in young adulthood after chronic childhood exposure to these environment (approximately 4.5 years, s.d. = 0.97, after childhood period; Experiment 3). In the face attention task that was used in Chapter 3, each target face was presented alone with either a neutral, happy, fearful, or angry expression. Notably, in this chapter, I measured participants' brain activity during the task using electroencephalography (EEG). I was interested in how neural markers of exogenous (P1 ERP component) and endogenous (theta oscillations) attention allocation to each facial expression differed immediately after artificial exposure to urban versus natural environments.

In Chapter 2, I found that brief artificial urban but not nature exposure induced attention bias towards fearful face distractors compared to baseline. As emotional stimuli are processed via bottom-up processes (Sussman, Jin, & Mohanty, 2016), this suggests that artificial urban exposure enhanced the influence of bottom-up processes so that greater attention is allocated to negative face stimuli. In line with this, Chapter 3 showed that artificial urban versus nature exposure resulted in larger P1 amplitude over the right hemisphere to all facial expressions, further supporting the above finding that artificial urban exposures increased the influence of bottom-up processes. Additionally, artificial urban versus nature exposure also led to greater theta power increase in response to angry expressions, indicating that artificial urban exposure also enhanced the influence of top-down processes on attention allocation. It is possible that greater top-down processes were applied after the urban exposure to suppress enhanced bottom-up attention capture at earlier stages of attention. However, why this would only happen in response to angry faces is unclear. Regardless, overall, these results show that artificial urban exposures enhanced both top-down and bottom-up processes to increase attention allocation to face stimuli. Notably, as application of top-down processes results in ego-depletion (Van den Linden & Eling, 2006; Faber, Mauritz & Loris, 2012), this might explain how urban versus nature exposures result in greater ego-depletion (Taylor, Kuo, & Sullivan, 2002; van der Wal, Schade, Krabbendam, & Van Vugt, 2013; Jenkin, Frampton, White, & Pahl, 2018).

Interestingly, both ERP and oscillatory effects disappeared when faces in the urban video were blurred beyond recognition (Chapter 3). This suggests that enhanced top-down and bottom-up attention allocation after artificial urban versus nature exposures may be underpinned by exposure to faces. Although the reason for this effect is beyond the data that I collected, it is likely to be underpinned by the amygdala, a brain region that is activated by faces (Thomas et al., 2001; Canli, 2002; Öhman, 2002; Wright & Liu, 2006; Wright, Wedig, Williams, Rauch, & Albert, 2006) and is thought to underpin attention allocation to face stimuli (see Vuilleumier, 2005 for review). Notably, as blurred faces may have not seemed realistic, future experiments should be conducted to conclusively show that exposure to faces indeed underpins differences in attention allocation to faces after urban versus nature exposures. In these experiments, either both or neither videos should include faces, thus resolving the confound of exposure to faces.

Furthermore, the importance of faces for urban exposures to enhance top-down and bottom-up attention allocation might explain why artificial nature exposure that contained no faces did not modulate attention allocation (Chapter 2). Notably, the lack of effect of nature exposure sharply contrasts with numerous studies that have consistently shown that nature exposures increased the influence of top-down processes on attention allocation (Ottosson & Grahn, 2005; Berman, Jonides, & Kaplan, 2008; Gamble, Howard, & Howard, 2014; Sonntag-Öström et al., 2014; Greenwood & Gatersleben, 2016; Sahlin et al., 2016). Although the lack of effect of the nature exposure may be due to participants sufficiently applying top-down processes prior to the exposure and therefore these could not be further improved by nature exposure, it is unclear why this would be the case in my but not previous experiments.

In contrast with artificial exposures, the effect of brief physical urban versus nature exposure on threat bias did not differ (Chapter 2). Importantly, this further supports the notion that artificial versus physical urban exposures may have distinct effects on cognition. These highlight that further testing may be required before the effect of one type of exposure can be generalised to another type.

Similar to physical exposures, chronic childhood exposure to urban versus non-urban or relatively green versus non-green environments did not modulate attention allocation to emotional faces in young adulthood (Chapter 2). However, Chapter 4 showed that adults who were raised in urban versus non-urban environments were more distracted by their errors, a type of emotional stimuli (Hajcak & Foti, 2008). This suggests that urban versus non-urban upbringing may result in greater attention allocation to some emotional stimuli and the lack of effect of childhood environment found in Chapter 2 may be specific to faces. As discussed in Chapter 2, this may be explained by the non-associative fear acquisition account (see Hoehl & Pauen, 2017 for review) that argues that if people are repeatedly exposed to faces, as they are in cities (Abbott, 2012; Hartig & Kahn, 2016), they habituate to these. Consequently, they do not allocate additional attention to these. This is supported by the finding that participants who were raised in urban versus non-urban environments were more distracted by faces than scrambled images.

Behavioural adjustment

Chapter 4 addressed the third aim of this thesis by investigating the effect of childhood environment on behavioural adjustment in young adulthood. For this purpose, participants completed a Go/No-go task where they were asked to respond to all stimuli except for the target. When the target was presented, they were asked to withhold their response. I was interested in the extent to which chronic exposure to various population size, air pollution levels and neighbourhood greenness during childhood affected and predicted post-error slowing (PES) in young adulthood (approximately 4.85 years, s.d. = 0.92, after childhood period).

Importantly, I found that adults who were raised in less- versus more-green neighbourhoods displayed greater magnitude of PES, indexing greater behavioural adjustment. Furthermore, there was a marginally significant negative correlation between childhood neighbourhood greenness and PES, further supporting the link between chronic childhood exposure to natural environments and behavioural adjustment in adulthood. In contrast with findings described in Chapter 2, this demonstrates that childhood neighbourhood greenness has a long-term effect on at least some aspects of cognitive control. Furthermore, it suggests that in addition to causing an adaptation (Linnell, Caparos, de Fockert, & Davidoff, 2013), our environment also affects the ability to adapt behaviour.

Although the ability to adapt behaviour is an important skill for everyday life, the ideal magnitude of behavioural adjustment is unclear as both diminished and large PES magnitudes have been linked to mental disorders (Compton et al., 2008; Núñez-Peña, Tubau, & Suárez-Pellicioni, 2017; Voegler et al., 2018; Storchak, Ehlis, & Fallgatter, 2021), demonstrating that both can be maladaptive. In Chapter 4, despite PES differences, adults who were raised in less- versus more-green neighbourhoods performed the Go/No-go task with similar accuracy, demonstrating that greater behavioural adjustment did not result in better task performance and therefore, it may not have been more beneficial. Overall, while these results demonstrated that chronic exposure to natural environments has a long-term effect on behavioural adjustment, these may not show that chronic exposure to less versus more-green environments is more beneficial.

Interestingly, neither population size nor air pollution levels modulated or predicted behavioural adjustment in young adulthood. Although, I used participants' home addresses to measure their childhood environment, similar to numerous previous experiments (Mortensen et al., 1999; Lederbogen et al., 2011; Lundberg et al., 2009), these may not have represented their childhood exposure to air pollution and population size as children often spend time elsewhere, for example in school. Therefore, in a future study, I would use a more comprehensive measure of participants' childhood environment, that would include not only their home addresses, but also their schools and any other significant locations. Regardless, the lack of long-term effect of population size and air pollution levels of childhood environments highlights that each difference between urban versus natural environments is likely to contribute to their distinct effects on various aspect of cognitive control. For example, while exposure to faces contributes enhanced attention allocation to faces (Chapter 3), neighbourhood greenness affects behavioural adjustment (Chapter 4).

Well-being

Chapter 5 addressed the final aim of this thesis by investigating the effect of various aspects of childhood environments on well-being in young adulthood. To measure well-being, participants rated the extent to which they experienced depressive symptoms, anxiety, and stress during the week before the experiment by completing the 21-item Depression, Anxiety and Stress Scale (DASS-21). I was interested in the extent to which chronic exposure to various population sizes, air pollution levels and neighbourhood greenness during childhood affected and predicted scores for these subscales in young adulthood (approximately 3.78 years, s.d. = 0.79, after childhood period).

Importantly, I found that young adults who were raised in more- versus less-green neighbourhoods reported marginally lower levels of depressive symptoms, anxiety, and stress, indexing greater well-being. This shows that similar to brief exposures (see McMahan et al., 2015 for review; Song et al., 2014; Shanahan et al., 2016; Wang et al., 2016), chronic childhood exposure to natural environments also results in greater well-being. However, I found that participants who were raised in more polluted areas also tended to report somewhat lower levels of depressive symptoms, anxiety, and stress, indexing greater well-being. Similarly, adults who were raised in cities versus towns or rural areas also trended to report lower stress levels, indicating that population size of childhood environment may also influence at least one aspect of well-being.

Notably, these results contradict each other as it is unlikely that both more- versus less-natural as well as more- versus less-urban environments promote well-being. As discussed within Chapter 5, air pollution and urbanicity effects may be underpinned by an interaction between participants' childhood and current environments. For example, participants who were raised in low versus high air pollution areas or cities versus towns and rural areas (defined based on population size) may not have adapted to the adverse effects of air pollution and crowds. Therefore, they experienced more negative effects whilst living in Birmingham, the second largest city in the United Kingdom that has high air pollution levels. To verify, a future experiment could compare the well-being of people who were raised in areas with a certain air pollution levels and population size then either moved to a similar or different area, thus revealing the interaction between past and current environments.

Similar to behavioural adjustment, these demonstrate that childhood environments also have a long-term effect on well-being that lasts into young adulthood. Notably, however, while both behavioural adjustment and well-being were influenced by neighbourhood greenness, only well-being was affected by air pollution and population size. Moreover, all three aspects of well-being (depressive symptoms, anxiety, and stress) were influenced by both neighbourhood greenness and air pollution levels, however, only stress levels were affected by population size. These support the notion that each difference between urban versus natural environments is likely to contribute to their distinct effects on various aspect of cognitive control. Therefore, finding one key difference between urban versus natural environment to explain their distinct effects on all aspects of cognition and well-being is unlikely.

Link to theories

Cognitive effects

Three notions have been developed to explain the effect of nature versus urban exposures on cognition. The most influential one of these is the Attention Restoration Theory (ART; Kaplan & Kaplan, 1989, Kaplan, 1995; 2001). ART argues that urban environments induce ego-depletion and therefore impair top-down processes that can only be applied when central cognitive resources are available. Consequently, urban exposures enhance the influence of bottom-up processes on attention capture, resulting in greater distractibility. In contrast, natural environments allow rest, thus resolving ego-depletion and consequently improving the influence of top-down processes. Although not addressed within ART, as the presence versus absence of ego-depletion also modulates proactive control (van der Linden, Frese, & Maijman, 2003; Lorist et al., 2000) and behavioural adjustment (Lorist, Boksem, & Ridderinkhof, 2005; Boksem, Meijman, & Lorist, 2006), ART suggests that urban exposures diminish whereas nature exposures improve these too.

Notably, the ‘cities train the brain’ notion (Cassarino & Setti, 2015; Cassarino, O’Sullivan, Kenny, & Setti, 2018) , makes the opposite predictions to ART. It argues that cities improve cognitive abilities of the elderly by eliciting the optimal level of cognitive stimulation. Although this notion does not directly address the effect of natural environments, it implies that nature exposures do not improve cognitive abilities of the elderly due to their reduced complexity.

In contrast with these theories, the ‘shifting’ notion (Linnell & Caparos, 2020) argues that our environment does not impair or improve cognitive abilities. Instead, it states that urban exposures shift the mode of attentional processing from a focused (top-down) towards an exploratory (bottom-up) mode that results in greater distractibility. In contrast, nature exposures have the opposite effect. Notably, these predictions may also be applicable to cognitive control. Exploratory mode of attention is comparable to reactive control as they both allow all stimuli to capture attention, whereas focused mode of attention is comparable to proactive control as they both bias processing towards task-relevant stimuli thus reducing distractibility. Therefore, the ‘shifting’ notion suggests that urban exposures promote reactive control and nature exposures promote proactive control.

Several of my findings match the predictions of ART and the ‘shifting’ notion. For example, artificial urban versus nature exposures resulted in greater influence of bottom-up processes on attention capture. Furthermore, physical urban exposure resulted in reactive cognitive control whereas physical nature exposure resulted in proactive cognitive control. Finally, adults who were raised in urban versus rural areas were more distracted by their errors, indicating greater distractibility. Despite my findings coinciding with the predictions of these notions, based on my data, it is unclear whether these results are underpinned by urban exposure impairing top-down processes and proactive control as argued by ART or by urban exposure merely reducing the likelihood of these being applied as argued by the ‘shifting’ notion. Therefore, it is unclear whether my results support ART or the ‘shifting’ notion.

Although the finding that artificial nature exposure did not modulate cognitive control or top-down processes seem to contradict their predictions, both ART and the ‘shifting’ notion propose an explanation for these. For instance, focusing on ART, nature exposure can only resolve ego-depletion and thus improve proactive control and top-down processes if ego-depletion is present prior to the exposure (Joye & Dewitte, 2018). This suggests that the lack of effect of nature exposure may be due to ego-depletion being absent during the baseline in my experiments. This is plausible as participants were able to take regular breaks to rest during baseline. Importantly, however, Hartig et al. (2013) showed that the effects of nature exposure are independent of ego-depletion, a finding that is supported by experiments consistently showing that nature exposures improve top-down processes regardless of whether ego-depletion was induced prior to the exposure (see Ohly et al., 2016; Stevenson et al., 2018; for reviews). This casts doubt on the idea that the lack of effect of nature exposure is underpinned by a lack of ego-depletion as suggested by ART. Moving onto the ‘shifting’ notion, for nature exposure to shift the cognition so that proactive control or top-down processes are applied, participants must not be applying these prior to the exposures. However, participants in my experiment displayed a small congruency sequence effect and were not distracted by fearful distractors prior to artificial nature exposure, indicating that participants were already applying the type of cognition that is promoted by nature exposures. This suggests that baseline performance could account for the lack of effect of nature exposures.

Despite it not being directly addressed within the theory, only ART proposes an explanation for artificial urban exposure promoting proactive control and physical urban exposure promoting reactive control. ART argues that central cognitive resources are only depleted by attending to uninteresting but important stimuli while ignoring interesting ones. Importantly, participants could attend to any interesting but unimportant stimuli in the urban videos as missing important stimuli, such as an oncoming car, carried no danger. However, participants had to attend to uninteresting but important stimuli during the urban walk to avoid accidents. These suggest that ego-depletion may have been induced by physical not artificial urban exposure, thus promoting the use of reactive instead of proactive control after physical urban exposure. Although this correctly predicts my findings, Hartig et al. (2003) showed that the effects of urban exposures are independent of ego-depletion, casting doubt on the idea that differences in ego-depletion could account for artificial versus physical urban exposures resulting in distinct styles of cognitive control. Importantly, differences in ego-depletion cannot account for greater bottom-up attention allocation after artificial versus physical urban exposure, as ego-depletion that promotes bottom-up processes is proposed to be present after physical urban exposure that did not affect these processes.

Importantly, the ‘cities train the brain’ notion is contradicted by several of my findings, such as physical urban exposure promotes reactive control, artificial urban exposure increases the influence of bottom-up processes on attention allocation, resulting in greater distractibility. One explanation for this may be that this notion focuses on the effect of urban versus natural environments on cognitive skills of the elderly, whereas I investigated the effect of these on young adults’ cognition. However, greater attention allocation to negative faces after artificial urban versus nature exposure supports this notion, demonstrating that it also makes some correct predictions. Further support comes from my findings that childhood environments have long-term effect on behavioural adjustment that last into adulthood, as the potential long-term effects of childhood environments have only been addressed within the context of the ‘cities train the brain’ notion. Notably, however, I found no effect of childhood environment on either cognitive control or top-down and bottom-up attention allocation to emotional face stimuli, a finding that the ‘cities train the brain’ notion cannot explain.

Importantly, the ‘cities train the brain’ notion argues that childhood urban versus rural (or nature) exposure to result in superior cognitive abilities (White & Shah, 2019), a prediction that may be incorrect. I found that low versus high childhood neighbourhood greenness, that is typically present in urban environment (Nieuwenhuijsen, Khreis, Triguero-Mas, Gascon, & Dadvand, 2017), led to greater behavioural adjustment that has been linked to both healthy cognition (Compton et al., 2008; Storchak et al., 2021), as well as anxiety disorders (Núñez-Peña et al., 2017; Voegler et al., 2018). This indicates that greater behavioural adjustment can be both beneficial and maladaptive, suggesting that the ‘cities train the brain’ notion may be wrong. Moreover, greater behavioural adjustment did not result in greater accuracy, indicating that greater behavioural adjustment is unlikely to reflect superior cognition. Finally, young adults who were raised in urban versus non-urban areas were more distracted by their errors, indexing poorer cognitive abilities. Overall, these demonstrate that childhood exposure to urban environments may not lead to superior cognition, casting doubt on the ‘cities train the brain’ notion.

Importantly, the interpretation that greater behavioural adjustment after chronic childhood exposure to less- versus more-green neighbourhood reflects poorer cognition supports ART and the ‘shifting’ notion. Moreover, the finding that our environment affects behavioural adjustment (regardless of the interpretation of this result) builds on the ‘shifting’ notion as this shows that in addition to our environment causing adaptation (Linnell et al., 2013; White & Shah, 2019; Linnell & Caparos, 2020), it also affects the ability to adapt our behaviour.

Overall, in line with previous experiments, I found limited evidence for the ‘cities train the brain’ notion. Instead, my results match the predictions of ART and the ‘shifting’ notion. Nevertheless, based on my data, it is unclear whether distinct effects of urban versus nature exposures are due to impairment or adaptation of cognitive processes. This means that it is unclear whether ART or the ‘shifting’ notion proposes the correct mechanisms that underpin the effects described in this thesis.

Well-being effects

In contrast with cognitive effects, only the Psycho-Evolutionary Framework (PEF; Ulrich, 1983) has been developed to predict and explain the effect of urban versus natural environments on mood and thus well-being. It argues that nature exposure enhances positive and reduces negative mood including stress, due to certain characteristics, such as the presence of water and the absence of threat. As urban environments do not have these characteristics, such settings are proposed not to improve mood.

Supporting this framework, I found that adults who were raised in more- versus less-green neighbourhoods reported marginally greater well-being, indicating that similar to brief exposures (see McMahan et al., 2015 for review), chronic childhood exposure to natural environments also result in greater well-being. As PEF does not consider the potential long-term effects of urban versus nature exposures, these findings build on this framework by demonstrating that the effects of natural environments are not limited to short-term.

Importantly, however, I also found that adults who were raised in areas with relatively high versus low levels of air pollution or cities versus towns and rural areas showed a trend towards reporting greater well-being. As high air pollution levels are typical present in urban environments (Hewitt, Ashwroth, & MacKenzie, 2020), both results indicate that chronic childhood exposure to urban environments led to superior well-being. This contradicts PEF, previous research (see McMahan et al., 2015 for review; Song et al., 2014; Shanahan et al., 2016; Wang et al., 2016) as well as my findings that childhood exposure to more- versus less-green environments promote well-being. Although the reason for this is unclear, greater well-being after childhood exposure to urban environments may be underpinned by an interaction between features of participants' childhood and present environments, as discussed in the 'well-being' section above.

Regardless of the exact effect of neighbourhood greenness, air pollution levels, and population size of childhood environments, these findings highlight that these are key differences between natural and urban environments that may underpin the effect of these environments on well-being. Therefore, these findings expand on PEF that only considers the differences in threat and water to explain the distinct effect of urban versus natural environments on well-being.

Future considerations

The studies in this thesis added to the literature by not only examining how nature versus urban exposures affect cognitive control, selective attention, behavioural adjustment, and well-being, but by also highlighting some key differences between these environments that could underpin their effects on these. Nevertheless, the results described in this thesis raised some interesting questions to be examined by follow-up experiments, that could be designed so that they address some of the limitations of the studies in this thesis.

Firstly, I found that artificial versus physical urban exposures had distinct effects on cognitive control and attention allocation to emotional face stimuli, suggesting that the effects of urban exposures obtained by one exposure type (e.g., videos) should not be generalised to other types of exposures (e.g., walking). Notably, however, as no such discrepancy has been found between artificial and physical nature exposures (Gatersleben & Andrews, 2013), it is crucial that the reliability of these effects is investigated. This could be done by conducting a similar experiment to that done by Gatersleben and Andrews (2013) where the effect of artificial versus physical exposures to the same urban environment are compared. If this investigation yields no discrepancy between exposure types, then it could be investigated whether distinct effects of artificial versus physical exposures could be explained by methodological discrepancies that should be addressed in follow-up experiments. For example, in my experiment, one such difference is that participants watched the video alone but walked with three other people. The presence versus absence of other people has been shown to modulate the effect of urban environments on revitalization (Johansson, Hartig, & Staats, 2011), however, whether this also modulates its effect on cognition remains untested. Alternatively, future work could investigate whether differences between the environments used in my experiments could account for distinct effects of artificial versus physical exposures. One such difference may be that the artificial exposure contained more faces, that I found to underpin enhanced attention allocation to faces after urban exposures. Importantly, in addition to understanding the distinct effects of artificial and physical urban exposures, this could also aid the identification of the number of faces that subsequently lead to enhanced top-down and bottom-up attention allocation to face stimuli, thus indexing how crowded urban environments can be without leading to adverse effect. To do this, walks should be recorded so that their features can also be quantified similar to videos.

The finding that exposure to faces in artificial urban environments underpins enhanced top-down and bottom-up attention allocation to face stimuli, particularly those with negative expressions, raises the possibility that exposure to faces within a natural environment may also have similar effects. As previously mentioned, this is plausible as exposure to faces has been shown to activate the amygdala (Thomas et al., 2001; Canli, 2002; Öhman, 2002; Wright & Liu, 2006; Wright et al., 2006), the brain region that is thought to underpin attention allocation to faces, particularly those with negative emotional expressions (see Vuilleumier, 2005 for review). Such findings could aid the identification of key differences between urban versus natural environments that underpins their distinct effects.

Another line of potential future investigation could further examine whether urban versus non-urban childhoods enhance attention allocation to emotional stimuli. Although, attention allocation to emotional face stimuli was unaffected by childhood environment, participants who were raised in urban versus non-urban environments were more distracted by their errors that are a type of emotional stimuli (Hajcak & Foti, 2008). Although it is possible that one of these effects is false, it is also plausible that urban childhoods only result in enhanced attention allocation to non-face emotional stimuli, such as error or snakes, that have also been shown to capture attention automatically (Carlsson et al., 2004; Almeida, Soares, & Castol-Branco, 2015; Hoehl & Pauen, 2017).

The final area for future work could examine whether an interaction between childhood and current environment could indeed account for higher well-being after childhoods in high versus low air pollution areas or cities versus town and rural areas. As mentioned in the 'well-being' section above, it is plausible that adults who were raised in less polluted and populated areas were less adapted to the adverse effects of these, and therefore, experienced poorer well-being whilst living in Birmingham, a city that has high air pollution levels and large population size. If this can indeed account for my effects, then young adults who live in areas with low air pollution levels and small population size should report similar well-being regardless of their childhood environment. Importantly, this line of research could also address the limitation of self-report questionnaire that is not only susceptible to memory and heuristic biases (Schwarz & Clore, 1983; Frederickson, 2000) but could also be affected by participants' baseline perception of their well-being. These limitations could be avoided and thus reliability of these results could be enhanced by using more objective measures of well-being, such as cortisol, skin conductance or heart rate.

Wider implications

The research discussed in this thesis has wide reaching implications. Due to rapid urbanization over the last century, humans have moved from natural landscapes to urbanised human-made environments. Currently, over half of the world's population lives in cities, a number that is predicted to increase to 66% by 2050 (Dye, 2008). While numerous experiments have investigated the effects of our changing environment on mental health (Marcelis et al., 1998; Laursen et al., 2007; Lundberg et al., 2009; Peen et al., 2010, Engemann et al., 2018; 2019;

2020) and parts of selective attention (see Ohly et al., 2016; Stevenson et al., 2018; White & Shah, 2019; for reviews), only studies described in this thesis investigated the effect of urban versus natural environments on several other parts of cognition that has been previously overlooked, such as cognitive control, attention allocation to emotional stimuli or behavioural adjustment. Therefore, this research contributes to our understanding of how cognitive abilities of a large part of society are affected by the fast and drastic change in the type of environment that we live in. This is particularly important in the case of children, who based on my findings, will experience long-term effects of their childhood environment that last into young adulthood if not beyond.

Furthermore, research in this thesis highlighted several differences between urban versus natural environments that result in distinct cognition. This helps to develop our knowledge of the root cause of why exposure to urban versus natural environments have distinct effects on cognition and well-being. This knowledge will aid the identification of people who are exposed to environments that have been linked to adverse effects. Therefore, they will be able to seek additional support, thus potentially avoiding the adverse effects of their environment. Moreover, this will aid city planners to improve existing cities as well as to design new cities in a healthier way so that their adverse effects are minimised. The latter will particularly aid developing countries, who are predicted to account for most of the predicted urbanization over the next two decades (United Nations, 2018).

Moreover, studies in this thesis increased the understanding of the distinct effects of urban versus nature environments on cognitive processes, such as cognitive control, attention allocation to emotional stimuli or behavioural adjustment, that have been linked to schizophrenia, mood and anxiety disorders (Mathews & MacLeod, 2002; Compton et al., 2008; Krug & Carter, 2012; Lesh et al., 2013; Vanderhasselt et al., 2014; Núñez-Peña et al., 2017;

Voegler et al., 2018; Storchak et al., 2021). As the risk of these mental disorders is increased by urban environments (Marcelis et al., 1998; Laursen et al., 2007; Lundberg et al., 2009; Peen et al., 2010) and is reduced by natural settings (Song et al., 2014; Shanahan et al., 2016; Wang et al., 2016; Engemann et al., 2018; 2019; 2020), research described in this thesis may help to explain the link between these environments and mental health. Importantly, once this link is better understood, steps can be taken to address the root causes of mental health problems associated with urban living, thus potentially countering the negative effects of urban environments on mental health.

Finally, in addition to understanding how our environment can be changed to benefit humanity, highlighting the benefits of natural settings may also support the natural world. Due to urbanization, people’s contact and connection with nature has diminished (Schultz, 2000; Zenghelis & Stern, 2016; Nieuwenhuijsen et al., 2017), that has been linked to reduced likelihood of protecting natural spaces (Schultz, 2000) as people are unwilling to protect something that has little value to them. However, if natural environments are shown to have a direct positive impact on people, then they may start spending more time in natural environments to gain its benefits. This will increase their connection with nature and enhance the likelihood of natural settings being protected. This will not only aid biodiversity, but it may also counter global warming to some extent by having more trees that take carbon dioxide out of the air (Nowak, 1993; Nowak & Crane, 2002).

Chapter 7. List of references

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