IMPLIED BETWEEN-OBJECT ACTION AFFECTS AFFORDANCE SELECTION

by

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ABSTRACT

In real life, many actions involve using one object upon the other, for instance, using a spoon to scoop from a bowl. The present thesis investigated the influence from such between-object actions on affordance selection, i.e. choosing between action possibilities (affordances) provided by objects. This research question was examined by adapting a stimulus-response compatibility paradigm in the following way. Images of task-irrelevant object pairs (e.g. a spoon and a bowl) were followed by imperative central targets. Participants made speeded left/right responses to the targets, and the responses were randomly aligned with the objects. The orientation of the objects was manipulated across trials, rendering the co-location between the objects correct or incorrect for potential interactions. With this paradigm the thesis identified two behavioural effects from implied between-object actions. Both effects suggested an automatic prioritization of the affordance of the active objects (e.g. a spoon) in object pairs (e.g. a spoon and a bowl). In particular, the thesis demonstrated a novel inhibitory effect on the passive objects (e.g. the bowl). Both action-related object structures and the configuration of object pairs are critical in producing these effects. Further, online Transcranial Magnetic Stimulation (TMS) on left anterior parietal sulcus (aIPS) and left lateral occipital complex demonstrated contributions from the dorsal visual stream. In addition, altered performance of healthy older adult participants as well as patients with deficits in selective attention and response inhibition pointed towards contributions from executive functions. Distinct dynamics of the acquisition of action association between novel objects and that of affordance-selection pattern congruent with the learned action associations suggested that these effects do not depend on quickly established declarative knowledge about actions, but on slow sensorimotor-based consolidation. Collectively, the results confirmed that the implied between-object actions do affect affordance selection through sensorimotor processes. The findings reinforced the notion that vision and action is closely linked, and highlighted the need to study affordance perception not only on the object level, but also on the level of object relations and visual scenes.

Keywords: implied actions, affordance selection, inhibition, paired objects.

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Chapter 1

Affordance in Context

1.1 Introduction

In real life, many actions involve using one object upon another, e.g. using a spoon to scoop from a bowl. When facing such situations, numerous cognitive processes have to be carried out, such as locating the objects in the space, extracting their shapes and colours, identifying the objects, perceiving the spatial relation between the objects, recognizing possible actions to carry out with individual objects as well as the possible actions between them, and selecting the best response in the current context, etc. The present thesis focuses on one important challenge arising in such situations, i.e. to select the right motor program for between-object actions the paired objects collectively afford. In other words, the present thesis investigates the influence from implied between-object actions on the selection between affordance (i.e. action possibilities provided by objects, Gibson, 1979).

Each object in a given pair affords actions, which are very likely to be different from each other. For example, in the case of a spoon and a bowl, the afforded action of the spoon is a particular precision grasp, while the afforded action of the bowl is a power grasp. The question then comes: How may these different affordances interact with each other and how are they accommodated in the between-object actions? For instance, the affordance of two objects may mutually strengthen to facilitate an action between them, or the affordance linked to one object may dominate over the other to ensure successful execution of a “major” action, i.e. grasping the spoon in order to scoop from the bowl, or the afforded action of one object might be actively inhibited to reduce its interference on the execution of the other object’s affordance. To provide insight into this question is the primary goal of the present thesis.

This topic of affordance selection in paired objects has not been sufficiently addressed in previous literature. This chapter intends to review existing empirical and theoretical work that is relevant to this topic. In Section 2, I will present the empirical and theoretical works most relevant to the present thesis. Starting from the concept of affordance and the notion that vision informs motor processes in a direct manner, I will present the major theoretical considerations relevant to the present thesis. Further, I will provide a brief review of literature in visual affordance of single and paired objects which laid the foundation of the present thesis. Section 3 will move on to the literature about affordance selection, which is an inevitable concept in dealing with affordance embedded in visual contexts. I will endeavour to illustrate the incompleteness of research on the neurocognitive mechanism of paired object affordance and the need for further investigation in certain aspects.

1.2 Affordance: object perception from vision to action

1.2.1 Affordance and the ecological approach

A spoon, besides activating the representation of its colour, shape and texture, is also connected with certain actions available to perceivers. Gibson (1979) argued that such action possibilities are extracted automatically, and can directly contribute to the production of relevant actions (Gibson, 1979), and the term affordance is coined, as part of the ecological approach to visual perception, to highlight that the action possibilities offered to an animal by the environment, which emerge with “the complementarity of the animal and the environment” (p.127). Gibson asserted that these action possibilities are the primary objects of perception. This view is in sharp contrast with cognitive theories of perception. The cognitive theories suggest the importance of internal representation of external stimuli and the computation of these representations (e.g. Fodor, 1981; Marr, 1982). Typically, they view vision as a means to build rich internal models of surrounding reality (e.g. Marr, 1982). For instance, Marr treated vision as an information processing system. He described vision starts from a two-dimensional retina stimulation and finally produces a three-dimensional description of the world as output. In these theories, the cognition consists of internal computation over mental representations, and the results of such computation are further relayed to other modules, including action. In other words, action is the indirect outcome of visual information.

In contrast, Gibson's approach suggested a direct connection between external stimuli and the perceiver. In Gibson's view, relevant information is extracted automatically in a direct manner to support the animal producing online responses to the external environment. Gibson suggested that the animals are active in collecting and generating information about the surroundings at any given moment, aided by actions such as moving eyes, turning bodies, etc. Consequently, the stimuli collected in this process, in the form of "ambient energy arrays", specify the surroundings in a way removing the need of further internal computation. Within these energy arrays, Gibson asserted that animals perceive their environments primarily in terms of *affordances*, the action possibilities provided by the environment compatible with the general way of interaction between the animal and the environment.

There are some important characteristics of affordance. First, being the primary information retrieved from the environment, affordance is picked up involuntarily, and visual information informs motor control and preparation directly and automatically. Second, affordances are system properties (see also Stoffregen, 2003), which means that affordance is under the constraints of the physical properties of the environment as well as the action capabilities of the animal. In other words, affordance is the set of action possibilities which have to fulfil both conditions: a) the environment can be interacted in this way (e.g. the object is graspable), and b) that interaction is physically possible for the animal in question (e.g. it can do grasping). Consequently, affordances are specific to, and may vary across, individual animal-environment systems; the same object affords certain actions to one animal but other actions to animals of different action capability. For instance, a spoon affords grasping to an adult, but not to a cat or a very young infant. A third characteristic of affordance, according to Gibson, is that it is the primary information an animal extracted from external environment. An animal perceived the surrounding world in forms of potential further interactions with the environment, i.e. the affordances (Gibson, 1979, Chapter 8), instead of the veridical qualities of external objects, e.g. shape, texture and colour (p134). Moreover, the utility of the external environment is perceived directly during animal-environment interaction, instead of being deciphered via mental representation of external stimuli by internal computation, as suggested by cognitive theories of perception.

Some current theories have been inspired by Gibson's ideas, e.g. the close integration of perception, action and environment (for a review see Barsalou, 2008). These theories include but are not limited to various views of grounded and embodied cognition. Though there are various delicate differences between them, these theories generally suggested that (a) actions, which is often generalized to body states, is important to both visual perception and high-level cognition (e.g. Barsalou, 2009; Borghi & Cimatti, 2010), (b) one of the primary functions of vision, as well as other sensory modalities, is to support action (Varela, Thompson, and Rosch,1992; Clark, 1999; Goodale, 2011), and (c) the action-perception link receives input from context / environment / situation (for a review see Barsalou, 2008).

1.2.2 Affordance and object representation

Importantly, the concept of affordance has been recently extended beyond the Gibsonian non-representational approach to visual cognition. A representational conceptualization of affordance was proposed. According to this view, affordance largely refers to "the motor patterns whose representation visual objects and their properties give rise to… it nonetheless has its basis in a similar emphasis of the intimate link between perception and action."(Tucker & Ellis, 1998, p. 833). Here, affordance is effectually operationalized as a property of the visual objects, salient for an animal's behaviour (Turvey, Shaw, Reed, &

Mace, 1981; for a review, see Caiani, 2014). In research following this approach, affordance is almost always solely manipulated by the physical characteristics of the objects. For instance, in Tucker and Ellis's (1998) study, images of graspable objects were presented as visual stimuli, and affordance of the object is manipulated by the orientation of the graspable part of the object. An important example of this representational approach is the concept of micro-affordances (Ellis & Tucker, 2000; Vainio et al., 2007). Micro-affordances concerns specific components of the action in question, e.g. the grip type, wrist orientation or effector defined by the orientation, size or location of the objects, and research is conducted to examine how these sub-features of affordance affect responses selection and object perception, regardless the holistic action afforded by the visual stimuli.

This approach no longer views affordance as being carried by a continuous energy array the pattern of which specifies affordance. Instead, they took an analytic approach and project affordance as a multi-dimensional feature of the visual stimuli. Such a conceptualization allows affordance research to communicate directly with research about object perception and object-oriented action. However, this "representational" affordance research did not address some theoretical features of affordance proposed by Gibson, for instance the claims that the characteristics of the animal in a given animal-environment system affect affordance, and that the animal actively pick up affordance as part of the continuous information inflow from the environment (for exception of the first point, see Ambrosini & Costantini , 2013; Costantini, Ambrosini, Tieri, Sinigaglia, & Committeri, 2010; Fajen & Matthis, 2011; Ranganathan, Lee, Brown & Newell, 2011).

1.2.3 Affordance in laboratories

In this section I will review the research paradigm and main empirical evidence of affordance, especially in its effects on response selection.

1.2.3.1 Single-object Scenarios

Most existing research studied affordance-based effect in single-object scenarios (e.g. Bub, Masson & Cree, 2008; Goslin, Dixon, Fischer, Cangelosi, & Ellis, 2012; Handy, Grafton, Shroff, Ketay & Gazzaniga, 2003; Masson, Bub, & Breuer, 2011; Pellicano, Iani, Borghi, Rubichi, & Nicoletti, 2010; Phillips, & Ward, 2002; Tucker & Ellis, 1998). A common finding in these studies is, when the required responses resembled the actual manipulation of the objects, the responses were quicker than when the responses do not resemble any manipulation of the objects (e.g. Bub et al., 2008; Ellis & Tucker, 2000; Tucker & Ellis, 1998). For instance, Tucker and Ellis (1998) presented photographs of common graspable objects which afford actions by either left or right hand, and required the participants to decide whether each object was upright or inverted. The horizontal orientation of the objects were varied so that they afford either left or right hand responses, and the responses can be either congruent or incongruent with this task-irrelevant affordance. The left-right object orientation, being task irrelevant, was found facilitating responses made by the according hand, suggesting the automatic potentiation of the afforded actions. Other resemblance between response and task-irrelevant object affordance has also been tested, including types of action, e.g. of the same grip orientation and type of grips (Bub et al., 2008; Derbyshire, Ellis, Tucker, 2006; Masson, Bub & Breuer, 2011; Tucker & Ellis, 1998). The effect is often termed the affordance-based compatibility effect. In this chapter, I will focus on the left-right compatibility between affordance and responses, due to its higher relevance to the paradigm used in the present thesis.

Studies of this kind typically adopted the response compatibility paradigm described in the last paragraph (Tucker & Ellis, 1998, see also Bub & Masson, 2010; Cho & Proctor, 2010; Phillips & Ward, 2002). The affordance is defined as the orientation and handle location of the object, while the explicit task is often left-right responses about another feature (e.g. an additional central cue, see Phillips & Ward, 2002). The typical finding from this paradigm is that reaction time is often shorter when the graspable handle (which is a task-irrelevant feature) of an object corresponds with the location of the key press response (which is to the task-relevant attribute) than when it does not. This effect has been replicated many times (e.g. Bub & Masson, 2010; Cho & Proctor, 2010; Goslin et al., 2012; Phillips & Ward, 2002; Tucker & Ellis, 1998), and is considered a demonstration of the automatic extraction of affordance. This effect is also related to the Simon effect in some papers (e.g. Cho & Proctor, 2010).

A question which has invited much discussion regarding this series of studies is the exact cognitive mechanism behind affordance-associated response compatibility effect, i.e. what is actually evoked by the presence of affordance, and relative to what the responses are compatible or incompatible? Is it the activation of a specific action program (i.e. the motor preparation of the afforded action, specifying effectors, posture, motor trajectory, etc, which is presumably reflected in the activation of motor-related regions and the visuomotor dorsal stream regions)? A broadly defined action codes or spatial codes? A shift of object-based attention? The following three paragraphs list corresponding evidences for each possibility.

The motor activation of specific afforded actions is well supported by electrophysiological and functional neuroimaging studies. Single cell recording observed the canonical neurons in monkey F5 (Murata, Fadiga, Fogassi, Gallese, Raos & Rizzolatti, 1997). These neurons are active when the monkey simply views an object, as well as when the monkey grasps that object. In humans, functional neuroimaging has shown that cortical areas involved in the visual dorsal stream (the vision for action stream, e.g., Chao & Martin, 2000; Grèzes & Decety, 2002; Johnson-Frey, Newman-Norlund, & Grafton, 2005; Valyear, Culham, Sharif, Westwood & Goodale, 2006; for review, see Lewis, 2006), supplementary motor area (Grèzes & Decety, 2002) and premotor areas (Grèzes, Armony, Rowe, & Passingham, 2003) are differentially activated during viewing of graspable objects, compared to living things or non-graspable objects. Collective with the affordance-based compatibility effect, the activation in motor areas suggest that actions afforded by seen objects are automatically "potentiated", and the compatibility effect comes from the congruency between the required response and the objects' affordance, i.e. to be grasped by either the left or the right hand (Pellicano et al, 2010; Tipper, Paul & Hayes, 2006; Tucker & Ellis, 1998).

However, it has also been suggested that what is activated by visually presented graspable objects is not necessarily the exact motor program specifying all motor parameters of the afforded action, at least in some cases. It was suggested that the left-right feature of visual affordances might have evoked abstract response codes which potentiates a broad category of lateralized actions corresponding with that affordance, instead of a specific action (Phillips & Ward, 2002), thus the facilitation occurred on the responses made by the afforded hand or responses falling into the same left-right category. This idea is based on the fact that affordance–based response compatibility effects can be observed when the left and right responses are made by crossed responses hand or by feet (Phillips & Ward, 2002). Some more radical suggestions were made that the affordance-based effects are just a variation of the Simon effect and is driven by the coding of the relative location of the graspable part of the object (e.g. Cho & Proctor, 2010) and the saliency of the graspable part compared to other parts of the object (e.g. Cho & Proctor, 2011). However, looking back at the theoretical explanations of the Simon effect, it was suggested that the Simon effect was produced by the automatic activation of the corresponding response when the stimulus set has dimensional overlap, or similarity, with the response set (Kornblum, Hasbroucq, & Osman, 1990). In other words, the Simon-effect explanations still acknowledge the automatic activation of the responses corresponding to certain visual features, which, in the case of the compatibility effect of graspable objects, is probably defined by the same stimuli property defining affordance.

A slightly different explanation emphasizes the role of an automatically activated attentional shift corresponding to the visual affordance of objects. For instance, Goslin and colleagues (2012) presented images of objects affording left or right hand responses, and reported an increase of early ERP components including N1 and P1 when the affordance of the presented objects were congruent with the response hand. Since both components are associated with early visual processing, Goslin and colleagues (2012) suggested that the affordance-based effects on early visual responses are the outcome of object-based attention. In other words, instead of responses directly related to object manipulation, it is visual attention that responds to affordance-related object features and binds the visual and action-related responses in order to establish the visual representation of objects. However, according to the "premotor theory of attention" (Craighero, Rizzolatti & Umiltà, 1999), attention derives from the very mechanisms that are intrinsic to the control of perception and action, and attention selection is part of the planning of goal-oriented action such as eye-movement (Rizzolatti, Riggio, Dascola & Umiltá, 1987). In this sense, the attentional account does not necessarily conflict with the motor account of affordance-based effects. However, the exact role of attention is definitely an issue meriting further investigations.

The common point among opinions is apparent, that is, affordance-related information is automatically extracted. The difference between explanations lies in on which level responses are automatically activated by the extracted affordance, instead of whether such automatic activation of affordance-based response exists. In this thesis two experiments were devoted to examining a corresponding question in paired-object scenarios. These are detailed in Chapter 2 and 3.

1.2.3.2 Paired-object scenarios

It may be argued that research should not stop at single-object scenarios. As I mentioned in the beginning of this chapter, in daily life, some objects are repeatedly used together. Very often, one of the objects in a given pair is used to act upon the other, e.g. a spoon and a bowl. Such scenarios are of great methodological importance as they provide a starting point to put affordance perception back into the real world crowded with objects.

Especially, it addresses a feature of the world, i.e. the objects in reality are not randomly clustered together. They are connected, though flexibly and variably, by functional link, theme of scene, etc. By studying affordance of paired objects, one starts addressing these connections, as well as their impact on object perception and affordance extraction.

It has been established that this type of action relations between objects can be extracted, and influences cognitive progresses including attention, object perception, and awareness both in healthy population and certain neurologically atypical populations (e.g. Adamo & Ferber, 2009; Green & Hummel, 2006; Humphreys & Riddoch, 2001; Humphreys, Riddoch, Forti, & Ackroyd, 2004; Humphreys, Wulff, Yoon & Riddoch, 2010; Riddoch, Humphreys, Edwards, Baker, & Willson, 2003; Roberts & Humphreys, 2010a; 2010b; 2011a; 2011b). On the whole these studies demonstrate that positioning pairs of objects in co-location conducive to between-object actions facilitates grouping the objects as a perceptual unit (e.g. Riddoch et al, 2003). Consistent findings have also been reported in healthy participants (Roberts & Humphreys, 2010a).

As in the single object scenarios, the effects associated with affordances of paired objects are subjected to discussion regarding their neurocognitive mechanism. In this case, the discussion mainly focuses on whether the effect of paired-object affordance is driven by potentiation of the afforded action, i.e. the between-object actions, or whether it is merely the results of recognition of familiar visual scenes. Previous evidence from neuroimaging studies suggests that there was enhanced visual coding for paired objects (Roberts & Humphreys 2010b). In contrast, unlike in single-object scenarios, evidence for action potentiation in response to action-related paired objects is indirect. As we have noted, visual extinction is reduced when patients are presented with a pair of interacting objects relative to when the objects do not interact (Riddoch et al., 2003). This effect is particularly strong if participants see the objects held ready for use and if the stimuli are seen from a first-person perspective (Humphreys, Wulff et al, 2010), and when pairs of objects appear in correct co-locations affording actions by their dominant hand compared to when they appear in mirrored locations (Yoon, Humphreys & Riddoch 2010). The handedness effect and perspective effect suggest the involvement of motor-related processes, because both effects rely on manipulation of the features of afforded action instead of physical features of objects.

Worthy of note, the majority of these studies used object detection or identification task, and participants have directly responded to the object pairs, in some cases making identification responses (Riddoch et al., 2003). Hence in this task the semantic knowledge of objects was directly task-relevant and it is conceivable that the outcome of such experiments might not only be influenced by affordances but also reflect influence from top-down task-set, e.g. the semantic knowledge of the objects. The retrieval of the semantic knowledge of objects might have affected the selection of affordance and response. This leads to one of the motivations of the present thesis, that is, to explore the existence and nature of affordance extraction for paired objects in a task irrelevant to the identity of the objects, and thus unlikely to be affected by semantic knowledge of objects. Chapter 2 will present a task derived to serve this purpose.

1.3 Affordance selection: in a complex world

An issue naturally associated with the processing of paired object affordances is affordance selection, given the fact that humans live in a world full of objects, and each and all of them bear multiple affordances. Numerous theories imply that these affordances should be extracted simultaneously in direct nature, largely automatically. However we are only able to interact with a few objects, and execute one of them in real action. Hence it is reasonable to assume that we prioritize among affordances, and, in the case of multi-object scenarios, among objects, in order to maintain a coherent response to the environment, as well as to avoid being distracted or interfered by unwanted affordances.

The problem of affordance selection can occur at multiple levels. For single objects, it has been well established that one visual object often afford multiple actions (Buxbaum & Kalénine, 2010), e.g. a cup affords a precision grip at the handle as well as a power grip at its main body. For most tools, they afford both "manipulational"/"volumic"/structure-based and "functional" actions (Borghi, Flumini, Natraij & Wheaton, 2012; Bub et al, 2008). The first is of the structure-based "grasping" action and the second is of the function-based "using" action (Creem-Regehr & Lee, 2005). For instance, a jug does not only afford a grasping action towards its main body (volumic affordance), but also affords the grasping-by-handle action associated with its functional use (functional affordance). Then, how do we decide to pursue one, but not the other among the alternatives?

In addition, the selection may have to be done between objects as well. For instance, what if there is more than one object in the visual field? Will the action towards one of the objects be interfered by the affordance picked up from the distractor objects? If not, how is the interference prevented? The scenarios of paired objects illustrated an even more difficult problem, with the influence from relation between objects. The existence of a second object might not only add a new set of affordances into the available response choices, but also enriches the context of both objects, and might bias the processing of affordance towards certain action in the affordance portfolio of each object. For instance, a spoon in isolation bears its own affordance of power and precision grasps in various ways, but when it is accompanied by a bowl, the visual scene endorses a theme and implies the grasp conducive to a scooping action to a larger extent than when the spoon is presented alone. Does such a correlative feature in a visual scene affect affordance selection? Generalizing to real world scenarios, when even more objects are presented, some sharing a common action and some not, how is affordance selection carried out?

1.3.1 Experimental results on affordance selection

There is already some empirical evidence demonstrating the selection process and the mechanisms behind it. For single object scenarios, it has been suggested that affordance is sensitive to task requirements, pointing to the influence from intention. For instance, it has been reported that functional and volumetric actions afforded by objects can be selectively activated, determined by the task context (Bub & Masson, 2008; Valyear, Chapman, Gallivan, Mark & Culham, 2011). The pattern of affordance effect varies as a function of the functional state, and the effect was more apparent when the objects were presented in active functional state, i.e. as if currently in use, rather than in passive state (Masson, et al., 2011; Pellicano et al., 2010; Tipper et al., 2006). Further, it has been demonstrated that the affordance-based response-compatibility effects increased with manipulation intention. These effects were more apparent when the experiment required processing of an object feature which is relevant (even only remotely) to the manipulation of the visual objects, e.g. shape or orientation, in contrast to colour (Pellicano et al, 2010; Tipper et al., 2006). These effects were also magnified when the task resembled the actual manipulation of the objects to a relatively large extent (e.g. reaching rather than key-pressing, Bub & Masson, 2010; Pavese & Buxbaum, 2002), and when the task required retrieval of functional rather than schematic knowledge of the objects (Symes, Ellis & Tucker, 2005; Yoon et al., 2010). In addition, when a hand was presented as currently manipulating the objects, the compatibility effect based on object affordance was magnified (Tipper et al, 2006), and the object perception was modulated by the action intention implied in the task context (Borghi et al., 2012). To accommodate these results, it was proposed that contextual factors modulate the processing of affordance by shaping the intention set of the participants, or shaping the participants' representation of the goal states (as well as the manipulation required in achieving such states) in the current context, either explicitly or implicitly (Tipper, et al., 2006); the effects of affordance only became apparent when the corresponding action was primed/emphasized by the context (Bub & Masson, 2010; Thill, Caligiore, Borghi, Ziemke & Baldassarre, 2013).

Evidence about affordance selection in multi-object scenarios is limited and indirect. One line of relevant studies addressed the influence of distractor objects on responses to the target objects. For instance, Pavese and Buxbaum (2002) found that when the participants need to make reaching-grasping actions upon the target objects, the distractor objects with a handle produced larger interference effects than the objects without handles. Ellis, Tucker, Symes, and Vainio (2007) examined affordance-based response compatibility effects in geometric classification of a target object when it was presented along with a distractor object. They found that grasps compatible with the target-object's affordance were facilitated, but the distractor-compatible grasp responses were impaired when the target and the distractor were defined by different colours. Their results suggested inhibitory control in affordance selection, i.e. the slowing of responses compatible with the affordances of the distractor objects, compared to a baseline (e.g. when these objects were presented alone). The term inhibition and inhibiting are used referring to such slowing of responses or response tendency in question in the following review of experimental and modelling work, as well as throughout the whole thesis.

Another line of evidence illustrated the dissociated effect of affordance between objects in paired-object scenarios. As we have noted, in object pairs, one object (the "active object", e.g. a spoon) tends to be used upon the other one (the "passive object", e.g. the bowl). Intuitively, one can assume that the active objects have higher action potentials because the manipulation of the active objects directly produces the desired outcome of the afforded action, while the manipulation of the passive objects is relatively secondary in serving the goal of the action. It won't be surprising if, when having to select between the actions afforded by active and passive objects, the observer selects the one offered by the active object but inhibits or ignores the one offered by the passive object. Such bias towards active objects was proved by previous research, which suggests that action relation affected active and passive objects differently. For instance, Riddoch et al. (2003), in the study mentioned earlier, reported that patients suffering from extinction have a bias in reporting the active objects in action-related object pairs when only one object can be correctly reported, given the objects in the pairs were positioned in accordance with their action relation. In healthy participants, Roberts and Humphreys (2011a) reported that in object identification, active and passive objects were affected by different factors; the identification of active objects was facilitated by the compatibility between the objects' orientation and the participants' dominant hands, while the identification of passive objects was facilitated by the action relation it shared with other objects in the scene. This dissociation was explained as that the active objects were subjected to an effect based largely on their own affordance, which presumably resulted from automatic motor priming and activation in visuomotor dorsal stream regions. In contrast, it was further suggested that the passive objects were affected by the action relation collectively afforded by the object pairs. The dominant status of the active object in a given action-related object pair is also suggested by the results that the active objects act as attentional cues and guide attention towards the passive objects, while the passive objects do not have this capability (Roberts & Humphreys, 2011b). These effects suggest that the active objects possess certain advantage over passive objects, and they are relatively independent from the action relation compared to the passive objects. However, to our knowledge there still lacks direct comparison between responses to active and passive objects, and it is still not clear whether the active and the passive objects will be affected differently by the implied actions between objects, for instance, whether the sensorimotor responses to the active objects will be selectively facilitated compared to those to the passive objects.

1.3.2 Theoretical suggestions: co-activation and inhibition in affordance selection

It is worth noticing, the empirical evidence of affordance selection did not address some prevalent scenarios in life. This aspect is also not fully addressed in existing theories about affordance selection. Most existing works focused on the affordance selection in single-object scenarios, or limited their theoretical interpretation to such scenarios. Generally, the selection of affordances is proposed to be a product of the interaction between two dorsal visual sub-streams in parietal regions (dorso-dorsal and ventro-dorsal; Buxbaum & Kalénine, 2010; Cisek, 2007; Cisek & Kalaska, 2010; Thill et al., 2013), the ventral pathway and the prefrontal cortex (PFC; Cisek & Kalaska, 2010; Thill et al., 2013). The dorso-dorsal sub-stream is assumed to process structure-based/volumetric actions afforded by objects, while the ventro-dorsal sub-stream of human dorsal neural pathway analyses the functional manipulation of objects, related more closely with experience and learned stimuli-action association (Buxbaum & Kalénine, 2010; Thill et al., 2013; for a related differentiation between the stable/variable affordance, see Borghi & Riggio, 2009). Affordances processed in these streams are associated with different action possibilities, and they compete against each other under modulation from top-down control (from ventral and pre-frontal cortex) based on relevant semantic information, internal motivations and external context, until a single winner action emerges (Cisek, 2007; Thill et al., 2011).

Besides competition, there is also evidence suggesting the contribution from inhibitory processes. Aside from Ellis and colleagues' (2007) finding of inhibitory effect on affordance of distractor objects, as described in the previous section, Loach, Frischen, Bruce, and Tsotsos's work (2008) reported a suppressive surround effect in affordance-based compatibility effect. They presented two images of door handles successively, and asked the participants to make responses either compatible or incompatible with the second handle. It turned out that compatible responses were faster than incompatible responses if the second handle shared an identical orientation with the first (the prime handle), but slower than incompatible ones if the two handles were aligned at slightly dissimilar orientations. In other words, the orientations surrounding that of the first handle were suppressed after the presentation of the first handle. Loach and colleagues related this result to the suppressive surround effects prevailing in vision and attention domain, and suggested that it reflects the role played by inhibition in affordance selection. In their case, they suggested that the affordance of the preceding objects inhibited motor activation congruent with competing affordances (of the distractor objects), i.e. those of a slightly different orientation, but facilitated those of the same orientation.

Aside from demonstrated by experimental evidence, the involvement of inhibition is suggested by modelling work. For instance, Caligiore and colleagues (2013)'s computational model TRoPICALS proposed an inhibitory neural pathway connecting prefrontal cortex (PFC) to parietal dorsal-stream areas, which modulated affordance processing according to its congruence with the current action goal held in PFC. The model managed to produce the inhibition on distractor affordance similarly to that reported by Ellis and colleagues (2007).

However, it is still not clear whether an inhibitory process is involved in affordance selection between affordances of different objects but linked by actions. The present thesis will address this issue by directly examining the competition among affordances from different objects involved in the same between-object actions.

1.4 Conclusion and the outline of the present thesis

The importance of investigating affordance-based processes in visual contexts is inherent in the very concept of affordance, and is well supported by existing empirical and theoretical works (see Section 2 and 3). As reviewed in Section 2 and 3, direct and specific investigation is lacking regarding affordance extraction and selection in multi-object scenarios. Addressing these issues would be a preliminary step towards the thorough understanding of affordance-related processes in realistic visual world.

Of course, it is impossible to tackle thoroughly a question as grand as affordance extraction and selection in multi-object scenarios in one thesis. In this thesis, I will take scenarios consisting of action-related object pairs, e.g. a spoon and a bowl, as a starting point. Just for clarity, in this thesis the object which carries out an action towards the other is called the “active object”, for instance a spoon in the spoon-bowl pair, while the object being acted upon is called the “passive object”, e.g., the bowl in the same pair. Following this definition, the active objects typically require substantial action in manipulation, while the passive objects would only require, if at all, stabilization. The term “paired objects” refers to a pair of objects consisting of an active and a passive object collectively affording a between-object action, e.g. a spoon-bowl pair.

I will focus on the influence of implied between-object actions on response selection, and the underlying neural and cognitive mechanism. The main motivations of the present thesis are: (a) examining the effect of action relation between objects on affordance selection in paired-object scenarios, (b) investigating the dependency of such effects on object identification and explicit intention of manipulation, (c) exploring the cognitive and neural mechanism behind such automated affordance extraction or selection effect in paired-object scenarios and (d) examining the possibility that action-related information is extracted at the level of scenes, instead of solely on an object level.

The first study in Chapter 2 describes the basic paradigm used throughout this thesis, which is modified from the paradigm commonly adopted in studies about affordance effects in single object scenarios (e.g. Phillips & Ward, 2002). Experiments in Chapter 2 identified two behavioural manifestations of the influence from implied between-object actions, i.e. an advantage for responses aligned with the active over those with the passive objects when the two objects were presented in co-location conducive to the action they commonly afford, and an inhibitory influence from such co-location on responses aligned with the passive objects. Both effects suggested an automatic prioritization of the affordance of the active objects (e.g. a spoon) in paired objects, and Chapter 3 and 4 further confirmed the visuo-motor nature of these effects. Chapter 3, by reducing the familiarity of object pairing and manipulating the presence of strong action-related structure (e.g. handles), investigated the stimulus features that dictate these effects. Chapter 4 and 6 applied an online Transcranial Magnetic Stimulation technique and neuropsychological approach respectively in the paradigm established in earlier chapters, in order to investigate potential neural correlates of the effects. Chapter 5 explored the relation between declarative knowledge and effects of paired-object affordance on responses selection. The last chapter will present a brief synthesis of the findings, and their implication in affordance selection, and more generally in the perception of multi-object visual scenes is discussed.

Chapter 2

Implied actions between paired objects lead to affordance selection by inhibition

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Abstract

Evidence from experiments with single objects indicates that perceiving objects leads to automatic extraction of affordances. Here we examined the influence of implied between-object actions on affordance processing. Images of task-irrelevant object pairs (e.g. a spoon and a bowl) were followed by imperative central targets. Participants made speeded left/right responses to targets, and the responses randomly aligned with the affordance of one of the objects. The orientation of one object was manipulated across trials, leaving the co-location between objects correct or incorrect for potential interaction. Four experiments demonstrated that positioning the objects correctly for between-object actions led to a prioritization of the object active in the action (e.g., the spoon) over the passive (e.g., the bowl) object. Moreover, there was an inhibitory effect on responses to the passive object: responses congruent with the passive object were slower when pairs of objects were shown as if in interaction, compared with when they were not. The effects did not change in single-hand response task but disappeared when the passive objects were absent - though an affordance should still have been presented by the active object. These results present evidence for affordance selection in action-related object pairs, and suggest inhibition of the action afforded by the passive objects under conditions of affordance competition.

Keywords: paired objects, implied actions, action relation, affordance selection, inhibition

In his seminal book, Gibson (1979) postulated that humans directly detect action possibilities (affordances) from the physical properties of objects in the environment in an automatic fashion. There is now substantial evidence for this claim (e.g. Bub, Masson, & Cree, 2008; Phillips & Ward, 2002; Riddoch, Edwards, Humphreys, West, & Heafield, 1998; Riddoch, Humphreys, Edwards, Baker, & Willson, 2003; Tucker & Ellis, 1998). This paper aims to examine how the selection of affordances plays out when we see two objects. In particular, how is affordance processing influenced when these objects are commonly used together, e.g. a spoon to scoop from a bowl? One possibility is that the perceived affordances are not affected by the pairing, i.e. the spoon is seen “pick-up-able” and the bowl still considered being “lift-able”. On the other hand, the affordance of the bowl may be suppressed, e.g. in order to successfully execute the reach for the spoon. In other words, the affordance of the object relevant for an immediate action might be selected while the other object’s affordance might be suppressed. This paper explores whether a competitive process of affordance selection exists or whether the detection of the affordance is unaffected by the potential interaction between two objects.

Primary evidence for the detection of affordances from single objects (e.g. Bub, Masson, & Cree, 2008; Phillips & Ward, 2002; Tucker & Ellis, 1998) is based on an experimental procedure sometimes termed the response compatibility paradigm. In these experiments participants are asked to indicate a property of an object which is largely unrelated to the object affordance. Despite being irrelevant to the task the object affordance affects the participants' response. For instance, in their Experiment 1 and 2, Tucker and Ellis (1998) presented photographs of common graspable objects as stimuli, and the participants had to indicate the vertical orientation of the objects (upright or inverted) by making left-right key press responses. They found that when the graspable parts of the objects (e.g., the handle of a frying pan) were aligned with the responding hand reaction times were faster compared to when the handle pointed to the opposite of the responding hand. Subsequently, this finding was extended by Phillips and Ward (2002). They showed that the affordance of the object affected the left-right key responses to a stimulus (abstract symbol) placed on the object. Hence the affordances of objects were detected even though objects are irrelevant to the task. Overall, these findings suggest that there is automatic extraction of affordance.

The detection of affordances in a two-object scenario was examined in a series of studies by Humphreys and colleagues (e.g. Riddoch et al., 2003). In these studies participants see object pairings where one object is "active" while the other object is "passive". Active objects (e.g. a spoon in a spoon-bowl pair) are those items used in the action between the objects (e.g., grasping and scooping from the bowl), while the passive objects only need "stabilization" (e.g., the bowl in the spoon-bowl pair). Importantly these studies show that responses are affected if the objects appear to interact with each other in a typical way. For instance, Riddoch et al. (2003) reported data on patients with visual extinction[1] who show impaired detection to stimuli on the contralesional side of a display when another item is present on the ipsilesonal side. The impairment in detecting contralesional items was alleviated if paired objects were presented one on each side and as

[1] Patients with visual extinction can detect a single item presented on the side contralateral to their lesion but fail to detect the same item when it is placed in competition with another item on the ipsilesional side. The deficit can be conceptualised in terms of the lesion introducing a spatial bias in the competition for selection between the stimuli (Duncan, Humphreys, & Ward, 1997).

if interacting with each other. Here positioning objects for action enabled the patients to attend to both members of a pair. In contrast, there was still extinction if the objects were positioned not to interact with each other. Similarly, in normal participants, correctly co-locating stimuli for action improves the identification of briefly presented objects, compared with when the objects are positioned not to interact (e.g. Roberts & Humphreys, 2011a). These studies also find a bias towards the active objects. That is, with both patients (e.g. Riddoch et al., 2003) and neurologically intact participants (e.g. Roberts & Humphreys, 2010a), response benefits tend to go with the active member of an interacting pair. For instance, when the patients with extinction reported only one object in a pair positioned for interaction, it was more likely to be the active object, regardless of whether the active object fell on the contralateral or ipsilateral side. These results can be interpreted as evidence for the affordance from the interacting objects being coded pre-attentively, since patients are unaware of the contralesional stimulus unless it is paired correctly for action. This affordance further determines which of the two objects is preferentially selected (with a bias towards the active member of the pair).

In addition, there is also evidence suggesting competition among different objects. A study by Ellis, Tucker, Symes, and Vainio (2007) examined the extraction of affordances in a two-object scenario using the response compatibility paradigm. Unlike Riddoch et al. (2003; also Roberts & Humphreys, 2010b), the objects were unrelated to each other and they were not positioned to interact. Participants were asked to indicate a simple geometric property (straight or curved) of a target object by making a power grasp or a precision grip, and the other item was a distractor. When the target object was defined by its colour, Ellis et al. found that required grasps were delayed if the distractor requires a compatible grasp, relative to when the distractor affords an incompatible grasp. The data suggest that there can be competition for action selection between a target and distractor objects, which must be resolved in order to select the action to the target (see also Pavese & Buxbaum, 2002). The time for resolution is increased when the distractor's response is compatible with that required for the target. Other authors have also argued that there can be competition for action selection between affordances offered by single objects (Boehme & Heinke, 2009; Cisek & Kalaska, 2010; Riddoch, Humphreys, & Price, 1989; Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013).

Although previous studies have argued for the role of affordance competition in visual processing, there has been little direct evidence for such competition for paired objects. The present study provides novel evidence on this. We evaluated whether there was competition for action selection between the affordances offered by individual objects that are presented simultaneously, and in particular whether this competition leads to inhibitory processing in order to perform between-object actions. Consider our example of a spoon and a bowl. For the two objects to interact as a pair it requires that the spoon is actively used and the bowl stabilised. However, the bowl itself could afford a lifting action which would be incompatible with the action to the objects as a pair. This may create competition for action selection which may need to be resolved – for example by inhibiting the response to the bowl.

To assess this, we combined the paired-object design (Riddoch et al., 2003) with the procedure reported by Phillips and Ward (2002). Participants were asked to respond to an imperative stimulus in the centre of the screen (square or triangle) with a left/right response while a task-irrelevant object pair was simultaneously presented (see Figure 2-1). The left object in the pair would afford a left response and the object on the right a right response. Hence, analogous to Phillips and Ward's (2002) findings, responses to the imperative target should be affected by the affordance of the object aligned with the response. In our procedure, for instance, an active object may lead to a speed-up of the response as it is linked to an immediate action (e.g., to reach for this item), shortening RTs to the central target. In contrast the passive object may show no effect or even slow down responses to the imperative stimulus, if the action to the passive object is suppressed as a competitor to the action to the object pair. The effect of an affordance between the objects (as in Riddoch et al., 2003; Roberts & Humphreys, 2010b) was assessed by contrasting responses to the imperative target when the objects were in “correct” and “incorrect” co-locations for a common action (see Figure 2-1). For example, take the correct co-location condition when the active objects were presented on the left side (left panel in Figure 2-1a). Here a right hand response to the target shape is aligned with the action afforded by the passive object (the bowl). Whether the orientation of the active object (the spoon) modulated this response was tested by comparing responses against a baseline (the incorrect co-location condition) when a right response was required and the orientation of the active object was incorrect for any interaction between the objects (left panel, Figure 2-1b; Experiment 1 and 4). Effects from the implied actions on the active object were assessed on left hand responses in this layout condition by comparing the correct co-location condition with another baseline condition. In this baseline (the incorrect co-location condition) the same response was required but the orientation of the passive object was manipulated (Figure 2-1c; Experiment 2). It is worth noting that unlike in some previous studies (e.g. Bach, Knoblich, Gunter, Friederici & Prinz, 2005; Bach, Gunter, Knoblich, Prinz & Friederici, 2009), here the incorrect co-location condition was used as baseline for the correct co-location condition, instead of using the correct co-location condition as baseline for the incorrect co-location condition. This better addresses the original research question. By using the correct co-location as a baseline, one investigates the interference effect when the conventional action relations between objects was violated or absent (e.g. Bach et al., 2005; Bach et al., 2009). However, being inspired by the previous finding that an action relation between objects groups the objects into a unit in selective attention (e.g. Riddoch et al., 2003), the present study asked how action relations affect the visuomotor responses and affordance selection. In this case, in the incorrect co-location conditions, when the action relation is absent, it is assumed that only single-object affordances present and compete. Consequently, by using this incorrect co-location condition as a baseline and contrasting correct co-location condition with it, it is possible to explore how the additional affordances of the object pair (conditional to the correct co-location between objects) affect affordance selection.

In Experiment 1, we tested effects of co-locating objects for action on the responses aligned with passive objects, and in Experiment 2 we assessed effects of implied actions in relation to the active object in each pair. If correctly positioning objects for action favourably modulates performance compatible with the passive objects, then any response congruent with the passive objects in the correct co-location condition in Experiment 1 should be faster than in the incorrect co-location condition, while this should be true for active objects in Experiment 2 if the implied action facilitates responses compatible with the active objects. On the other hand, if there is suppression of the response to either item when they are positioned for action, then corresponding responses to the imperative stimulus may be slower when the objects are in the correct relative to the incorrect co-locations for action.

In adopting this paradigm, the present study also went beyond others examining affordances with pairs of objects by having participants respond to an imperative stimulus that was independent of the objects being presented. In other studies participants have directly responded to the object pairs, in some cases using identification responses (Riddoch et al., 2003). It is possible that the affordance effect could have been facilitated by a top-down set to respond to related objects under these conditions. This seems less likely here, as the task set would involve only making a motor response to the imperative stimulus.

Experiment 3 contrasted the qualitative difference between the affordance effect of a single object and that of paired objects. In Experiment 3 we presented only active objects in otherwise the same experiment setting and examined whether the effects of paired-object affordance also occurs when the active objects were presented in isolation and followed by the imperative target. When the passive objects were replaced by empty space, will responses to the imperative target aligned with the empty space be inhibited when the active object was in the correct relative to the incorrect orientation as those aligned with the passive objects being inhibited in Experiment 1? This would be the case if the active object simply inhibited any other response. On the other hand, if inhibition depends on there being competition from the passive object, then there would not be inhibition of the action aligned with the empty space.

In Experiment 4 we aimed to replicate our findings while at the same time asking the question of how affordances are encoded, i.e. what kind of "action code" is activated (e.g. Bub, Masson, & Bukach, 2003; Ellis et al., 2007; Kiefer, Sim, Helbig, & Graf, 2011; Phillips & Ward, 2002; Tucker & Ellis, 2001)? Broadly speaking there are two options. On the one hand, the "action code" can be of a specific nature, specifying the effector, the direction of any action and the kinematic details (see Bub, Masson, & Bukach, 2003; Kiefer et al., 2011; Tucker & Ellis, 2001). On the other hand, it is also possible that any affordance activates categories of actions sharing certain, but not all features. This may have been implied when Gibson referred to objects being "lift-able" or "roll-able". Some evidence for this comes from the study by Phillips and Ward (2002). They showed that the affordance-based response compatibility effect (Tucker & Ellis, 1998) can be observed when the left and right responses are made by crossed hands or by feet (Phillips & Ward, 2002). They argued that graspable objects activate "relatively broadly defined categories of lateralized actions", e.g. actions on the left but not specific to the effector hand or types of grasp. Here we will extend this question to the paired-object scenario (Experiment 4). We borrowed a method from studies about the response compatibility effect of single objects by Cho and Proctor (2010). They had participants respond using button press responses with a single hand rather than assigning the responses bimanually. They still observed an effect of response compatibility between the orientation of the handle of the objects and the finger used for the response, consistent with an effect of response compatibility at an abstract level of response selection rather than specific to the parameters of the actual action to the stimulus. In the present study, we extended this design to displays with paired objects. We varied how participants responded – either using a bimanual response (Experiments 1 and 2), or a unimanual response (selecting the appropriate finger, Experiment 4).

2.1 Experiment 1: The effects of implied actions with active objects rotated as the baseline

The first experiment examined the effect of an action context (objects positioned correctly for action) on left and right hand responses to a central shape stimulus. On each trial two objects were presented, one active and one passive in the action, and the objects were positioned correctly or incorrectly for the interaction. The paired objects were followed by a central target, with the stimulus-onset asynchrony (SOA) being either 240 ms or 400 ms. Two levels of SOA were included to vary the pace of the experiment and prevent the participants from forming a strategy, such as only paying attention at regular time points. Also, previous research suggested that affordance-based effects show a trend of increasing with time (e.g. Phillips & Ward, 2002), therefore the manipulation of SOA was included in case any temporal effect would emerge. However, since the two-object scenario is subjected to the interaction between affordance-based responses to two objects, and may even rely on a distinct mechanism, it is not clear whether a temporal pattern similar to that of the single-object affordance effects will emerge in the present study.

There were two possible target shapes and participants were required to make a speeded choice response by pressing one of two keys with their left or right hands according to which shape was presented. The objects preceding the target shape were task-irrelevant. On half of the trials, the active object was presented on the left side of the pair (in the left visual field) and the passive object on the right. These positions were reversed for the other trials. When the objects were positioned incorrectly for action, the orientation of the active object was changed (see Figure 2-1a for an example of the correct co-location condition and Figure 2-1b for the incorrect co-location condition used in Experiment 1. The left panel shows when the active objects were presented on the left side of the object pair, and the right panel shows when they were presented on the right side). In the incorrect co-location condition, the active objects were always presented in orientations not affording any interaction with the passive objects. For responses aligned with the passive objects, the incorrect co-location condition served as a baseline for the correct co-location condition. The difference between these two conditions enables us to examine the effects of implied actions on responses aligned with passive objects, whose orientations and affordances were maintained across the conditions. In the correct co-location condition, the comparison between responses compatible with the active and passive objects illustrates the relative biases from the different objects when positioned correctly for action.

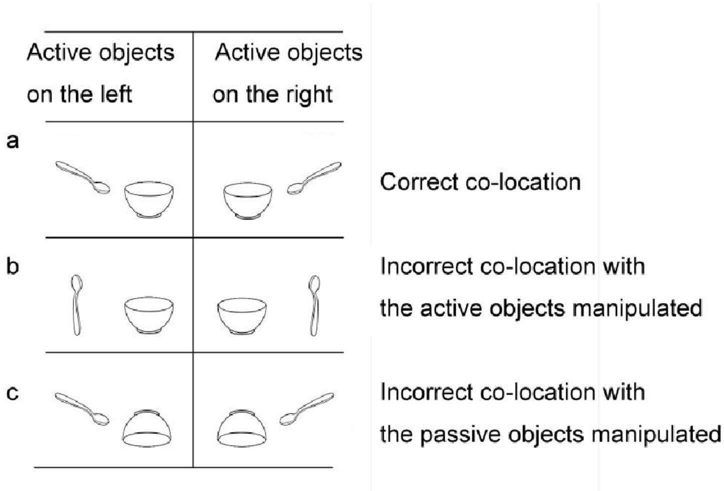

Figure 2-1. Example of the stimuli used in the experiments.

2.1.1 Materials and Methods

Participants

Thirty healthy volunteers (three males, mean age 19 years) from the University of Birmingham research participation scheme were recruited in Experiment 1. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credits for their time.

Another two groups of volunteers (twelve, four males, in each group, mean age 22 and 20 years respectively) from the University of Birmingham research participation scheme were asked to evaluate the stimuli used in Experiment 1 (See Appendix 2-D for more details). All evaluation participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit as compensation for their time.

Materials

The stimuli and the trial sequence were generated using Matlab7 (The MathWorks Inc., Natick, MA, USA) with Psychtoolbox 3. All stimuli were presented on a 17-in Samsung SyncMaster 793s (1280 × 1024 at 75 Hz) connected to a Windows XP computer. The stimuli consisted of 23 pairs of greyscale clip-art style images of objects on a rectangular white background. Each pair included an active object and a passive object routinely used together in an action (see Figure 2-1 for an example and Appendix 2-A for a complete list of the object pairs used). Some stimuli appeared in more than one object pair, for instance a jug appeared in a jug-cup pair and a jug-glass pair. In total, 16 active objects and 15 passive objects were used as stimuli. The stimuli were rated by a separate group of evaluation participants regarding (a) whether the action relations between the objects were familiar and apparent, (b) whether, by changing orientation of the active objects in the incorrect co-location condition we effectively manipulated the implied actions between objects, and (c) whether the objects on the left and right side of the screen afford left- and right- hand responses respectively. A second group of participants evaluated the appropriateness of our assignment of active and passive objects, i.e. whether the participants considered our active objects as operating upon the passive objects. The results revealed that the stimuli fulfilled these criteria. The detailed description of the procedure and the results of the stimulus evaluation process can be found in Appendix 2-D.

On each trial, line-drawings of a pair of objects were presented on the screen. On half of the trials (in the correct co-location condition), the objects were co-located appropriately for interaction. On the other half of the trials (the incorrect co-location condition), the active object was positioned in an orientation inappropriate to interact with the corresponding passive object. In the active-left condition, the active objects were presented on the left side of the screen, while the passive objects appeared on the right side. In the active-right condition, the whole presentation was horizontally flipped from the corresponding active-left presentation. All object images were presented on a white background (255, 255, 255 RGB). Each object image subtended 3.2°×3.2° of visual angle. The relative sizes of the objects within each pair matched their relative sizes in real life. Line-drawings instead of photos or real objects were used as stimuli here because similar line drawings produced affordance-related effects in an object detection task (e.g. Riddoch et al., 2003), and the present study used comparable sets of stimuli in order to allow for a direct comparison between paired-object affordance effects in the present task and in Riddoch and colleagues' (2003) tasks. Also, the stimuli evaluation (See Appendix 2-D) revealed that the line-drawings used in the present study communicate affordance-related information effectively.

The other stimuli included a fixation cross subtending 0.8°×0.8° of visual angle and two response targets (a blue [0, 121, 212 RGB] triangle or a circular disk), both subtended 0.6°×0.6° of visual angle.

Procedure

Participants took part individually in Experiment 1, with their upper arms resting on the table and index fingers of both hands resting on the f and j keys respectively. The experiment consisted of one practice block and five experimental blocks. The practice block consisted of 40 trials, randomly assigned to different conditions. Each experimental block consisted of 128 trials following five warm-up trials. The experimental trials were evenly assigned to the different conditions and were presented in a pseudo-randomized order, with no more than three consecutive trials from the same condition. Each warm-up trial was randomly assigned to a condition. Several participants were required to repeat the practice block because they failed to meet the accuracy criteria (see below) in the first practice block. The accuracy criteria were the same for practice and formal blocks.

At the beginning of each trial, a fixation point was presented at the centre of the screen for 0.4 second. After this the fixation cross disappeared and an object pair appeared. After either 240ms or 400ms (SOA) a response target was presented at the centre of the screen (see Figure 2-2). The target and the object pair remained on the screen either until the participants made a response or a period of 1600 ms passed without response. Participants indicated whether the target was a triangle or a circle by using their left or right index finger to press the f or j key on a QWERTY keyboard. The stimulus–response mapping was counter-balanced across subjects.

The participants were required to respond as quickly and accurately as possible, and they were warned that a block would be repeated either if they missed the target, i.e. if no response were made within the allowed 1600 ms after the target onset, more than three times or if they pressed the wrong key more than three times within that block. Feedback was given immediately after an error.

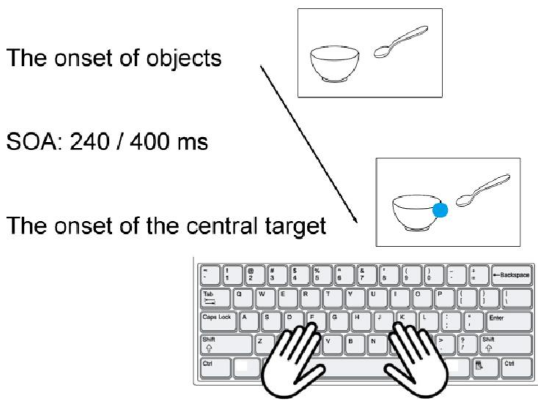

Figure 2-2. The procedure in Experiment 1. The participants were required to make speeded key-press responses with the left or right index finger, according to the shape of the central target (in display 2). The responses made by the hand on the same side with the active objects (right hand response in this figure) were considered congruent with the affordance of active objects and responses on the other side (left hand response in this figure) were congruent with the affordance of the passive objects.

2.1.2 Results and Discussion

Participants were highly accurate, with the average accuracy of each condition being between 97.8% and 99.6% (mean 98.8%, see Table 2-1), and the overall mean RT was 411 ms. For data cleaning, RTs were initially trimmed to remove responses quicker than 100 ms. RTs more than 2.5 standard deviations from the mean of each participant were then discarded in a non-recursive manner. Discarded trials were fewer than 2% of the total trials. The same was done for Experiment 2 - 4.

The mean RTs for the participants were initially entered into an analysis of variance (ANOVA) with SOA (240 ms and 400 ms), co-location of objects (correct vs. incorrect for action), the layout of paired objects (active-left vs. active-right) and response compatibility (compatible with the active vs. passive object) as within-subjects factors.

There was a main effect of SOA, F (1, 29) = 97.57, p < .001, η^2 = .77, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition, mean difference (MD) = 15 ms. The main effect of co-location was significant, F (1, 29) = 7.10, p = .012, η^2 = .20, with responses in the correct co-location condition quicker than in the incorrect co-location condition (MD = 3 ms). The main effect of response compatibility was significant too, F (1, 29) = 16.62, p < .001, η^2 = .36, with responses compatible with the active objects quicker than those compatible with the passive objects (MD = 5 ms). The main effect of the layout of objects (correctly or incorrectly co-located for action) was not significant (F < 1). However, there was a significant interaction between the co-location factor and response compatibility, F (1, 29) = 8.10, p = .008, η^2 = .22. An analysis of the simple effects revealed that the interaction between co-location and response compatibility was mainly driven by the slowing of responses congruent with the passive objects when the objects were correctly positioned for action, compared with when the objects were not correctly located for action (when the orientation of active object changed, F (1, 29) = 19.48, p < .001, η^2 = .40, MD = 6 ms). In contrast to this, there was no difference between responses aligned with active objects in the correct and the incorrect co-location conditions, $F < 1$ (see Figure 2-3). In addition, responses compatible with the active objects were quicker than those compatible with the passive objects when the objects were correctly co-located for action, F (1, 29) = 17.52, $p < .001$, $\eta^2 = .38$, MD = 8 ms, but not when the objects were incorrectly co-located for action, F (1, 29) = 2.29, $p = .141$, $\eta^2 = .07$, MD = 2 ms.

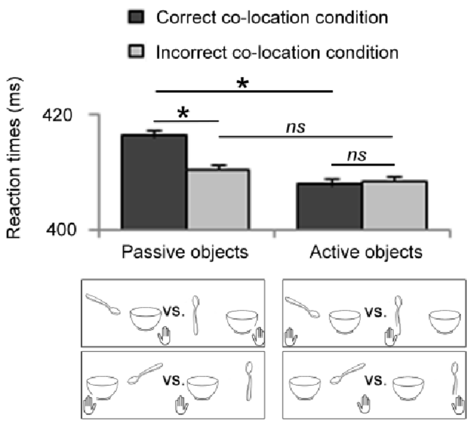

Figure 2-3. In Experiment 1, RTs of responses compatible with the passive objects were shorter in the incorrect co-location condition compared with the correct co-location condition (the black and grey bars on the left side). In the correct co-location condition, the mean RTs of responses compatible with the active objects were shorter than those compatible with the passive objects (the black bars). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

The results of Experiment 1 suggest that (a) the presence of interacting active objects slows down responses compatible with the passive objects, and (b) when both objects were presented in an interacting co-location, the responses aligned with the active objects were quicker than those aligned with the passive objects. The second effect is in line with previous studies reporting differences in the processing of active and passive objects (Riddoch et al., 2003; Roberts & Humphreys, 2010a). The first effect suggests that responses aligned with the passive object (i.e. the affordance of the passive object) are inhibited, relative to when the passive object is in the same orientation but the pair of objects are not positioned correctly for action (due to the inappropriate orientation of the active object). That is, there was an inhibitory effect of implied actions on the responses aligned with the passive objects. We do not consider our results can be solely explained by an advantage for the active objects in the correct co-location condition without there also being an inhibitory influence on the passive objects, because otherwise there should not have been any difference between responses aligned with the passive objects in the correct and the incorrect co-location conditions. To the best of our knowledge, this is the first time an inhibitory effect from implied between-object actions has been directly demonstrated in conditions of paired object affordance. The advantage for active objects over the passive objects and the co-existence of this effect with a suppression of the response to the passive objects is in line with the results of Ellis et al. (2007, see Introduction), but here we show a specific effect for action-implying object pairs.

The question remains open regarding whether the responses aligned with the active objects were also affected by implied between-object actions. One possibility is that, because the object context was irrelevant to the task, participants might have suppressed responses to both objects in the object pairs. However, because the orientation of the active objects changed across co-location conditions, Experiment 1 cannot provide strong evidence regarding whether an inhibitory effect from implied between-object actions also influences the active objects, or whether implied between-object actions selectively affect the passive objects. To solve this problem, in Experiment 2 we compared the responses aligned with the active objects between the correct and the incorrect co-location conditions while the orientation of the passive object was changed and the orientation of the active object was maintained. In this case, the effect of implied actions on responses aligned with the active objects can be examined without influence from their orientation being changed. We do not have a specific hypothesis regarding what will be the effects of action context on active objects. One proposal is that the implied actions between the objects selectively lead to inhibition of the affordance from passive objects. In this case, the responses aligned with the active objects in the correct co-location condition should not be inhibited in Experiment 2. Thus, compared with the incorrect co-location condition, responses aligned with the active objects should not be slower than those in the correct co-location condition. On the other hand, it is possible that the inhibitory effect of presenting the objects in the correct co-location is not selective and affects the active and passive objects equally, regardless of the functional significance of the active objects. Then, we should expect to find a similar inhibitory effect of the correct co-location on responses aligned with the active objects in Experiment 2.

Table 2-1: Average accuracy and reaction times (RTs) of each condition in Experiment 1

Layout (active objects on the left or right)	**Response compatibility (passive vs. active objects)**	**Accuracy**	**RTs (ms)**
240 ms SOA			
Correct co-location			
Left	Passive	0.99	425
	Active	1.00	416
Right	Passive	0.99	424
	Active	0.99	415
Incorrect co-location			
Left	Passive	0.99	418
	Active	0.99	416
Right	Passive	0.99	418
	Active	0.99	415
400 ms SOA			
Correct co-location			
Left	Passive	0.98	403
	Active	0.99	399
Right	Passive	0.98	414
	Active	0.99	401
Incorrect co-location			
Left	Passive	0.98	403
	Active	0.99	401
Right	Passive	0.99	402
	Active	0.99	402

2.2 Experiment 2: The Effects of Implied actions with Passive Objects Rotated as the Baseline.

Experiment 2 replicated Experiment 1 but with a baseline condition in which the passive rather than the active object was rotated.

2.2.1 Method

A new sample of thirty healthy volunteers (four males, mean age 19 years, range: 18-30 yrs) from the University of Birmingham research participation scheme was recruited in Experiment 2. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The basic design of Experiment 2 was the same as Experiment 1, except that in the incorrect co-location condition the orientation of passive objects, rather than that of active objects, was manipulated (see Figure 2-1c).

The materials were based on the same stimulus pool as Experiment 1, but some object pairs were replaced or removed to exclude those passive objects without an obvious upright orientation (e.g. tennis ball, pepper). The final set included 16 object pairs (see Appendix 2-B for a complete list of object pairs). The appropriateness of the materials was verified by independent evaluation (see supplementary materials for detailed report). In addition, the background color of the visual field was changed into light grey (200, 200, 200 RGB).

2.2.2 Results and Discussion

Participants were highly accurate, with the average accuracy of the different conditions being between 97.0% and 99.7% (mean 98.5%, mean RT = 426 ms, see Table 2-2).

The RT data were initially entered into an analysis of variance (ANOVA) with SOA (240 ms vs.400 ms), co-location (correct vs. incorrect), object layout (active-left vs. passive-left) and response compatibility (with active objects vs. passive objects) as within-subject factors.

There was a main effect of SOA, F (1, 29) = 98.73, p < .001, η^2 = .77, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 17 ms). The main effect of response compatibility was significant, F (1, 29) = 64.30, p < .001, η^2 = .69, with responses congruent with active objects quicker than those congruent with passive objects (MD = 11 ms). None of the other main effects or interactions were significant (ps > 0.1, see Figure 2-4). In particular, the interaction of interest (between co-location and response compatibility) was not significant (p = .33). Further, comparing directly the results of Experiment 1 and Experiment 2 with experiment as a between-subject factor reinforced the dissociation: the interaction between co-location, response compatibility and experiment was significant, F (1, 58) = 7.99, p = .006, η^2 = .12.

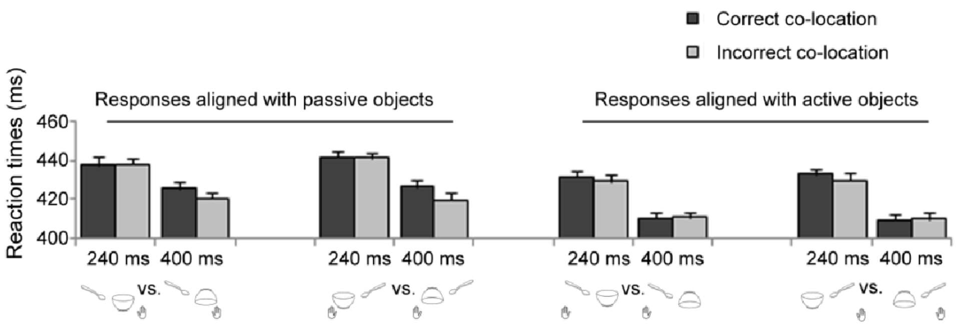

Figure 2-4. RTs in different conditions in Experiment 2.

In this experiment responses aligned with the active objects were in all cases faster than those aligned with the passive object, as shown by the significant main effect of response compatibility. This replicates the findings from Experiment 1 when the objects were correctly co-located for action. The replication is not surprising and demonstrated the robustness of the advantage for the active objects, since the correct co-location conditions were the same in Experiment 1 and 2. However, in Experiment 2, the main effect of co-location did not reach significance, nor was this factor involved in any interaction. Therefore, Experiment 2 did not provide evidence for responses aligned with active objects being affected when the objects were correctly located for between-object action compared with the baseline when the passive object was rotated. These results suggested a difference between active and passive objects in terms of how the affordances evoked by each object are differently affected by a contextual object positioned in the correct location for interaction. The results of Experiment 2 suggest that responses aligned with the active object are not affected by an implied action with a passive object, with it making little difference when the contextual object (the passive object in this case) is in the correct orientation for action or not, in sharp contrast with the results of Experiment 1. The lack of inhibitory effect on the active objects ruled out the possibility that both objects were suppressed unselectively because they are task irrelevant.

Table 2-2: Average accuracy and reaction times (RTs) of each condition in Experiment 2

Layout (active objects on the left or right)	Response compatibility (passive vs. active objects)	Accuracy	RTs (ms)
240 ms SOA			
Correct co-location			
Left	Passive	0.98	438
	Active	0.99	431
Right	Passive	0.99	442
	Active	0.99	433
Incorrect co-location			
Left	Passive	0.98	438
	Active	0.99	429
Right	Passive	0.99	441
	Active	0.99	430
400 ms SOA			
Correct co-location			
Left	Passive	0.98	426
	Active	0.99	410
Right	Passive	0.99	426
	Active	0.98	409
Incorrect co-location			
Left	Passive	0.97	420
	Active	0.99	411
Right	Passive	0.98	420
	Active	0.99	410

2.3 Experiment 3: Compatibility effect of implied actions requires the presence of a passive object

Experiment 1 and 2 suggested that active objects dominate paired-object affordance, inhibiting actions linked to the passive objects. However, it is possible that the active objects might have produced the observed effects in Experiment 1 as single objects. For example, the response evoked by the active object may simply inhibit any other response irrespective of the presence of another stimulus. In this case the implied between-object actions and the presentation of the objects as a pair may have no influence on performance; responses to the imperative target might be slowed if it is simply incompatible with that evoked by the active target (note that in that case the response to the imperative target would have been compatible with the passive object in Experiment 1 and 2). To test this possibility, in Experiment 3, only an active object was presented on each trial, without another (passive) object. It should be noted that there are examples in the literature where similar configurations have revealed response modulations. For instance, Symes, Ellis, and Tucker (2005) showed that the orientation of an action-relevant part of an object (either pointing to left or to the right) presented on one side of the screen modulated responses aligned with the opposite (empty) side of the presentation. Hence in principle it is conceivable that the inhibition effect found in responses to the imperative stimulus in Experiments 1 and 2 also occurs even if the passive object is not present (in Experiment 3).

2.3.1 Methods

A new sample of thirty healthy volunteers (six males, mean age 19 years, range: 18-27 yrs) from the University of Birmingham research participation scheme was recruited in Experiment 3. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The procedure for Experiment 3 was the same as for Experiment 1 except that only the active object in each pair was presented, while the space that was previously occupied by passive objects was left blank (see Appendix 2-C for a complete list of objects used in Experiment 3). For the sake of consistency, in Experiment 3, we still name the condition correct co-location when the active objects were positioned as if interacting with an invisible passive object, in the same orientation as in the correct co-location condition in Experiment 1 (see Figure 2-5 for exemplars of the stimuli). Similarly, the incorrect co-location condition referred to when the active objects were presented in an orientation impossible to perform any action in the direction of the blank space, as in the incorrect co-location condition in Experiment 1.

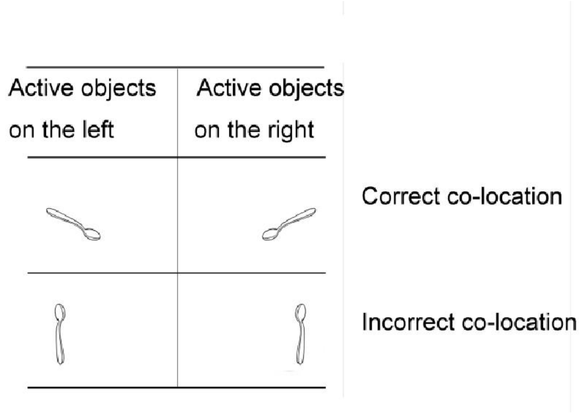

Figure 2-5. Exemplary stimuli in different conditions in Experiment 3.

2.3.2 Results and Discussion

Participants were highly accurate (range = 97.7% - 99.3%, Mean = 98.5%, mean RT = 436 ms, see Table 2-3).

Mean RTs were calculated for each participant in each condition, and were entered into an analysis of variance (ANOVA) with SOA (240 ms and 400 ms), orientation (correct vs. incorrect co-location), the layout of objects (active-left vs. active-right) and response compatibility (aligned with the active objects vs. with the empty space) as within-subjects factors.

There was a main effect of SOA, F (1, 29) = 209.64, p < .001, η^2 = 0.88, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 24 ms). The main effect of co-location was significant, F (1, 29) = 9.33, p = .005, η^2 = 0.24, with responses in the correct co-location condition quicker than in the incorrect co-location condition (MD = 3 ms). There was a significant interaction between the layout of the objects and response compatibility, F (1, 29) = 5.09, p = .032, η^2 = 0.15. The analysis of simple effects revealed that the interaction reflected that right-hand responses were generally quicker than left-hand responses. Responses aligned with the active objects were quicker when they were made by the right hand than when they were made by the left hand (p =.033, MD = 9 ms), and the same trend was significant for the responses aligned with the empty side (p =.047, MD = 9 ms).

Table 2-3: Average accuracy and reaction times (RTs) of each condition in Experiment 3

SOA	**Layout** (active objects on the left or right)	**Response compatibility** (passive vs. active objects)	**Accuracy**	**RTs (ms)**
240 ms	Correct co-location			
	Left	Empty	.97	446
		Active	.99	448
	Right	Empty	.98	452
		Active	.99	440
	Incorrect co-location		.98	
	Left	Empty	.99	450
		Active	.99	452
	Right	Empty	.98	456
		Active	.99	446
400 ms	Correct co-location		.99	
	Left	Empty	.99	419
		Active	.98	425
	Right	Empty	.98	430
		Active	.99	415
	Incorrect co-location		.99	
	Left	Empty	.98	415
		Active	.97	432
	Right	Empty	.99	430
		Active	.98	421

More importantly, the interaction between co-location and response compatibility was not significant, F (1, 29) = 3.07, p =.090, η^2 = 0.10 (see Figure 2-6). Pairwise comparisons suggested that responses to imperative targets congruent with the empty space (replacing passive object) were not slowed down by the presence of an interacting active object (p = .44, MD = 1 ms). In addition, responses congruent with correctly orientated active objects were quicker than those congruent with the empty space (p =.021, MD = 5 ms). Though the interaction approached significant here, the patterns of interaction in Experiment 3 and Experiment 1 were different, with the latter showing a simple effect of co-location on the passive objects (an inhibitory effect), while the former showed an effect on the active objects (a facilitating effect). The marginally significant interaction in Experiment 3 might mainly be driven by the orientation effect being present for the active object but not the empty space.

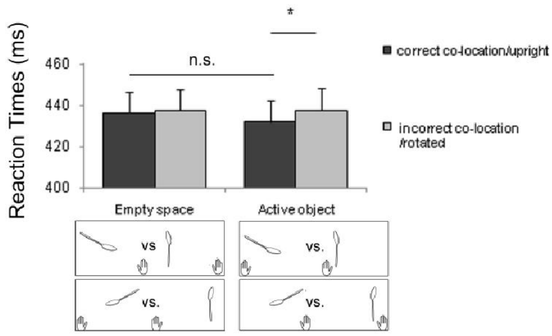

Figure 2-6. In Experiment 3, responses aligned with the active objects were quicker in the correct co-location condition than in the incorrect co-location condition, while the orientation of the active objects did not affect responses on the empty side. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

The results of Experiment 3 did not show the inhibitory effect of implied between-object actions. Notably, RTs to an imperative target that would have been compatible with the passive object (which is replaced by empty space in the experiment) were not slowed when the passive object was absent. This suggests that competition for action selection between the active and passive objects might be critical to observe the inhibition of any response. This effect is not produced by the affordance evoked by the active object alone (e.g., inhibiting all incompatible responses) but needs to have the passive object present. In addition to this we did find that responses compatible with the active objects were quicker than those aligned with the empty space replacing the passive objects. However this might have occurred because the onset of the active objects was beneficial as a spatial cue preceding the imperative target. One should be cautious to conclude that this effect derives from the same source as the quicker responses aligned with active objects relative to those aligned with passive objects/empty space in Experiments 1 and 3.

2.4 Experiment 4: A Test of Abstract Response Coding

Experiment 1 and 2 established the main features of the effects of implied actions on responses aligned with objects in action-related pairs, revealing evidence for the suppression of responses to passive objects and an advantage for active objects over passive objects when the objects are correctly co-located for action. A remaining question, though, is whether these effects reflect activation of specific motor responses to the stimuli or activation at a more abstract level. As noted earlier, this has previously been addressed in studies using single-objects by manipulating whether participants respond using two-choice unimanual or bimanual button-press actions (Cho & Proctor, 2010; Tucker & Ellis 1998). In Experiment 4, we evaluated this possibility by having participants respond to target shapes with one of two fingers on a single hand. Do the effects of implied between-object action remain?

2.4.1 Methods

A new sample of eighteen volunteers (five males, mean age 21 years, range: 18-35 yrs) from the University of Birmingham research participation scheme was recruited. All the participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The basic design of Experiment 4 was the same of Experiment 1 except that the participants were required to use the index and middle finger of their right hands and the j and k keys. One finger response was assigned to one shape and the other to the other shape, with the finger-shape assignment counter-balanced across participants.

The materials used in Experiment 4 were the same of Experiment 1 except that the background color of the presentation was changed into light grey (200, 200, 200 RGB).

2.4.2 Results and Discussion

Participants were highly accurate, with the average accuracy of each condition falling between 97.2% and 99.6% (mean 98.7%, mean RT = 434 ms, see Table 4).

The RT data were initially entered into an analysis of variance (ANOVA) with SOA (240 ms and 400 ms), object co-location (correct vs. incorrect), object layout (active-left vs. passive-left) and response compatibility (compatible with active object vs. with passive object) as within-subject factors. There was a main effect of SOA, F (1, 17) = 55.31, p < .001, η^2 = .77, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 20 ms). The main effect of response compatibility was significant, F (1, 17) = 7.60, p = .013, η^2 = .31, with responses congruent with the active objects quicker than those congruent with the passive objects (MD = 5 ms). There was a significant interaction between co-location and response compatibility, F (1, 17) = 21.59, p <.001, η^2 = .56. The analysis of the simple main effects revealed that the interaction between co-location and response compatibility was mainly driven by the different influence of co-location on responses congruent with the active and passive objects: responses congruent with the passive objects were slower in the correct co-location condition, compared with the incorrect co-location condition, F(1,17) = 9.00, p = .008, η^2 = .35, MD = 6 ms, but those congruent with the active objects were quicker, F(1,17) = 7.23, p = .017, η^2 = .30, MD = 8 ms. In addition, responses congruent with the active objects were quicker than those congruent with the passive objects only when the co-location of the objects was correct, F(1,17) = 30.96, p < .001, η^2 = .65, MD = 13 ms (see Figure 2-7), not when it was incorrect (F < 1).

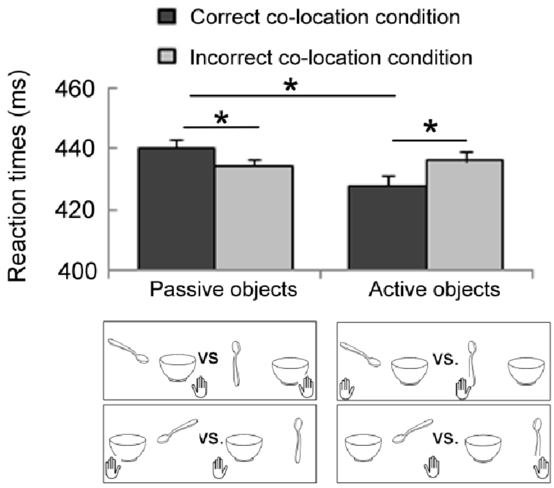

Figure 2-7. In Experiment 4, the mean RTs of responses compatible with the passive objects were longer in the correct relative to the incorrect co-location condition (the black and grey bars on the left side). In the correct co-location condition, RTs for responses compatible with the active objects were shorter than those compatible with the passive objects (the black bars). RTs compatible with the active objects were shorter in the correct than the incorrect co-location condition. The error bars indicate the standard error of each condition following method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

The results of Experiment 4 replicated the results of Experiment 1: responses aligned with a passive object were slower when an active object was positioned to interact with it, compared with when the co-location of the objects was incorrect for action (active objects rotated). In addition, when both objects were positioned in the correct co-locations for action, the responses aligned with the active objects were quicker than those aligned with the passive objects. It is worth noticing that there was also an orientation effect for active objects, i.e. when the active objects were positioned correctly for action, responses were quicker than when the active objects were rotated and positioned incorrectly for action.

In conclusion, the similar effects of implied actions in Experiments 4 and 1 suggest that changing the task from a bi- into a uni-manual one does not alter the influence of the affordances evoked by paired objects, replicating the results in Experiment 1.

Table 2-4: Average accuracy and reaction times (RTs) of each condition in Experiment 4

Layout (active objects on the left or right)	Response compatibility (passive vs. active objects)	Accuracy	RTs (ms)
240 ms SOA			
Correct co-location			
Left	Passive	0.99	457
	Active	0.99	443
Right	Passive	0.99	448
	Active	0.99	429
Incorrect co-location			
Left	Passive	0.99	445
	Active	0.99	447
Right	Passive	0.99	444
	Active	0.98	441
400 ms SOA			
Correct co-location			
Left	Passive	0.98	435
	Active	0.98	420
Right	Passive	0.99	428
	Active	0.97	408
Incorrect co-location			
Left	Passive	0.98	432
	Active	0.99	427
Right	Passive	0.98	422
	Active	1.00	417

2.5 General Discussion

In this study we presented task-irrelevant paired objects which are typically used together in familiar actions. We manipulated the co-location of the objects in order to vary the implied actions within each object pair. We compared the responses aligned with each object and examined how the RTs were affected by the presence of an interacting object, i.e. when the objects were presented as a part of a visual scene implying a common action between the stimuli.

Two major features of the effects of implied between-object actions were established in Experiment 1 and replicated across experiments (Experiment 4). One was that the presence of an interacting active object slowed down responses compatible with passive objects. Second, when both objects were presented in the correct co-locations for interaction, responses congruent with active objects were quicker than those congruent with passive objects. In addition, the inhibitory effect from an interacting object was only observed on responses aligned with passive objects (Experiment 1), not on those aligned with active objects (Experiment 2). This indicates the robustness of the responses associated with active objects and the dominant role of the active objects in a given action relation. Further, the results of Experiment 3 suggested that despite the dominance of active objects, the effects of implied actions between objects cannot be solely attributed to them, as single objects. The presence of a passive object is also crucial to our findings. Moreover, the present study examined the nature of the effects of implied between-object actions and indicated that the effects in our task were not reduced by a mono-manual task (in Experiment 4). This last result suggests that the findings were mainly driven by compatibility between the abstract codes of the object affordance and the response.

Overall, our findings show that the implied action between paired objects affects participants' responses despite the fact that any such action is irrelevant to the task. Hence our findings suggest that an affordance for action between objects can be coded in an automatic manner. In addition to this, we provide critical new evidence for competition for action selection when objects interact. We discuss this evidence below.

2.5 1 Inhibitory effect of implied actions on responses congruent with the passive objects

The present study demonstrated for the first time an inhibitory effect of implied actions between object on responses aligned with passive objects. In addition, this inhibitory effect selectively affects passive objects (Experiment 1 and 2). We suggest that it is functionally important that responses are suppressed to objects that would be passive when two objects are used together in an action, so that the action to the passive object does not then compete with actions to the active objects in the pair. The consequence of this is that there is a slowing of responses to the passive objects in the correct co-location condition. In at least some previous studies (e.g. in the work with visual extinction patients, Riddoch et al., 2003), the detection of both active and passive objects has been shown to increase when an action context is present (Riddoch et. al., 2003). This contrasts with our results and might reflect the different stages of processing where effects emerge in different studies. In particular, studies with extinction have typically required identification of objects. Pairs of interacting objects may be selected as a single "perceptual unit" (Riddoch et al., 2003), which enables patients to report both objects despite their attentional limitations (which generate extinction). In the present study, however, the effects measure response activation – albeit at a relatively abstract level (Experiment 4) – and competition for action (and suppression of the passive item) may specifically be at the level of abstract response codes.

The inhibitory effect of action context on responses aligned with the passive objects here echoes previous reports of inhibitory processes in affordance-based effects with single objects. For instance, suppressive surround effects have been noted in compatibility tasks in which responses compatible with the handle orientation of a target object were even slower than incongruent responses when the orientation of the handle slightly differed from that of the preceding object (Loach, Frischen, Bruce, & Tsotsos, 2008). An inhibitory component has also been included in computational models of affordance selection, i.e. to select among multiple feasible actions afforded by the same object (this includes: the TRoPICALS model, Caligiore et al., 2013, the FARS model, Fagg & Arbib, 1998, and the Selective Attention for Action model, SAAM, Boehme & Heinke, 2009). An inhibitory neural pathway from the PFC, probably involving the basal ganglia (BG) and the supplementary motor cortex (SMC), to the premotor cortex (PMC), has been suggested as the neural basis of inhibitory control over affordance selection (for a review, see Thill et al., 2013). In addition, there is evidence of inhibitory processing in response selection. For instance, Eimer and Schlaghecken (1998) demonstrated active inhibition upon automatically activated responses sharing attributes with distractors. Other studies have shown that responses congruent with the affordance of a nearby distractor are slowed compared with responses incompatible with the distractor affordance, leading to a reversed compatibility effect (Ellis et al., 2007). The suppression of responses congruent with the non-target objects in Ellis et al.'s study (2007) and the passive objects in our study, might serve as a mechanism to ensure the efficient execution of the action most consistent with current action goal. The novel advance we present here is to show that inhibitory effects can be cued by not only the top-down intentional control and target selection, but also the action-related contextual factors in a visual scene, such as the presence of an implied action between objects.

2.5.2 Dominance of the active objects in implied actions

The other main result here was that responses aligned with active objects were quicker than responses aligned with passive objects in the correct co-location condition. This result is in line with the previous conclusion drawn from studies where a bias towards the active objects has been observed when objects are placed in an action context (e.g. Roberts & Humphreys, 2010a, 2011a). For instance, in their study of extinction, Riddoch et al. (2003) found that patients tended to report the active objects when objects were co-located for action, even when the active object was presented on the contralesional (usually extinguished) side. This advantage for active objects is also evident in studies with neurologically intact participants. For instance, in temporal order judgement tasks neurologically intact participants have an attentional bias towards the active object when it is positioned to interact with a passive object (Roberts & Humphreys, 2010a). The present study extents these findings and suggests a bottom-up source for this bias, not contingent on the task-set to respond to the objects present. Our study suggests that the active objects might generate stronger affordance-related codes and exerted a larger facilitative effect on responses sharing the same codes, compared with those responses sharing codes with the passive objects, in the correct co-location condition.

Even though both the inhibitory effects with passive objects and the facilitatory effect with active objects suggest differentiable impacts on active and passive objects from implied between-object actions, we would like to underline that the current study does not specifically suggest that the semantic knowledge of active and passive objects produced the effects. In contrast, we showed that the mere change of object orientation affected responses (the contrast between the correct and the incorrect co-location conditions). Since such change should not have affected semantic knowledge of objects, the observed effects are compatible with an affordance rather than a semantic account.

2.5.3 Evidence for abstract codes of paired-object affordance

The present study found that the effects of implied actions were not greatly reduced in uni-manual task (Experiment 4), compared with the bimanual key-pressing task (Experiment 1). The lack of a response modality effect suggests that the implied actions do not activate action codes for a specific motor program. Instead, the implied actions result in the activation of action codes at a more abstract level for paired-object affordances.

As reviewed in the Introduction, it has been suggested that what is activated by visually presented graspable objects is a relatively broadly defined category of lateralized actions sharing the left-right feature of visual affordances (Phillips & Ward, 2002). According to this account, relative left-right codes are generated according to the action-related feature or affordance. When these codes overlap with the required responses, responses are faster and more accurate than when they do not. In our case, the observed effects might have been produced by compatibility between the automatic activation of the left-right codes of the responses and the automatically generated left-right codes of the implied action, which is biased towards the side of the active objects rather than passive objects in the correct co-location condition. In contrast to the abstract codes account, the affordance account would suggest that the specific actions afforded by objects are automatically “potentiated” (e.g. Goslin, Dixon, Fischer, Cangelosi, & Ellis, 2012; Handy, Grafton, Shroff, Ketay, & Gazzaniga, 2003; Tucker & Ellis, 1998).

The critical difference between these two accounts is that the affordance account predicts the activation of the motor program of the afforded action, while the spatial codes account does not. In Experiment 4, by changing the explicit task from a bimanual into a mono-manual one, we eliminated any compatibility effects between effector hands and the actions afforded by the objects. However, both the inhibitory effect of implied actions on passive objects (6 ms in Experiment 4 vs. 6 ms in Experiment 1), and the advantage for active objects, were still evident (13 ms in Experiment 4 vs. 8 ms in Experiment 1), suggesting the involvement of overlap between abstract codes in producing our results.

Together with the evidence of the involvement of relative spatial coding in compatibility effects with single objects (e.g. Cho & Proctor, 2010, 2011; Iani, Baroni, Pellicano, & Nicoletti, 2011) and on task-irrelevant motion information (Bosbach, Prinz, & Kerzel, 2005), our study adds new support to the notion that relative abstract left-right codes generated by the graspable objects, even when irrelevant to current task, affect responses to such objects (Cho & Proctor, 2010; Phillips & Ward, 2002). However, our results should not be taken as indicating that the effects of implied actions are immune from the influence of action intention. It has been reported that affordance-based action compatibility effects - elusive in left-right key-press tasks - can be observed in reaching and grasping tasks, which incorporate stronger action intention towards the objects compared to a key-pressing task (Bub & Masson, 2010). In the present paradigm, it is possible that action intention might also be able to increase the size of the effects observed here. It is worth noting, however, that the current sizes of effects are not outside the range of compatibility effects typically observed in “affordance” type experiments (Pellicano et al., 2010; Phillips & Ward, 2002; Symes, Ellis & Tucker, 2005, 2007; Tucker & Ellis, 1998). However, it would be interesting to examine performance when the action implied between the objects is explicit or task relevant, and when a response is directly required to the objects, rather than presenting the objects as an irrelevant context. Also, it will be beneficial to examine whether the relatively small effect of implied action will be increased by more realistic stimuli instead of the schematic object images used here.

However, because we used line-drawings instead of images with depth images, it is possible that the influence from spatial codes was enhanced compared to specific motor activation of object manipulation (Pappas, 2014). Nevertheless, the present stimuli should not be considered as completely without depth information, different from silhouettes used as no-depth stimuli in Pappas’s (2014) study. The line drawings do represent critical internal structures of the objects, and still convey depth information, though limited, by perspective. Admittedly, future work is needed to reveal to what extent the 3-D structure can be implicitly re-constructed from line-drawings and whether additional depth information alters visuomotor effects of paired objects. The present study suggested that at least from line-drawings such information can be extracted to some extent, enabling affordance-based processing, though the processing here might be of a nature different from when the stimuli were photos or 3-D objects.

2.5.4 Action relation, affordance selection, and scene perception

Our results also have implications for studies of affordance selection and scene perception.

As mentioned in the introduction part, previous theories of affordance selection have largely focused on the modulation from the decision making process or on an influence from irrelevant distractors on a central object (Cisek, 2007; Thill et al., 2013). However, a more typical, and probably of higher ecological value, challenge is to select the most appropriate action in a loosely structured scene in which the affordance of each object is constrained by their functional and spatial relation with other objects. For instance, when a cup is presented alone, it affords being grasped and moved actively for drinking, but it also affords being held passively to have tea poured into it in the context of an appropriately positioned teapot, in which situation the primary action afforded by the scene is the grasping and moving of the teapot. Our results suggested that such visual and spatial features about action between objects are capable of informing affordance selection. This notion echoes with an existing report that the disturbance of configural features of an interacting object pair interfered with the effect of action relation in reducing visual extinction (Riddoch et al., 2011). Moreover, our results suggested that such contextual information helps narrow affordance selection to the affordance of the active objects, and presumably to the affordance associated with the interaction between objects.

Regarding scene perception, our findings are compatible with the argument that meaningful (functional) relations between objects are coded in the representation of a visual scene (Green & Hummel, 2006). Such representations serve to reduce competition for selection among visual objects (Riddoch et al., 2003) and modulate the distribution of attention and the speed of object identification (Roberts & Humphreys, 2011a, 2011b). In addition to these results, our study suggests that implied actions are extracted automatically from a given scene, and there is greater affordance-related activation for “active” objects in a scene along with affordance-related inhibition for objects not affording the primary action in the scene. The advantage for objects with higher action possibilities is consistent with eye tracking results showing that, when presented in a scene containing objects affording a sequence of actions, the eyes of the user usually orient towards the next object in the action sequence immediately before the actual manipulation of the objects (Land & Mayhoe, 2001). Here potential actions between objects can serve as cues for action and may affect manual responses as well as attention distribution, facilitating further processing of the visual scene. This suggestion echoes with the view that there is a close interaction between object perception, attention and action planning (Gibson, 1979; Goodale & Humphrey, 1998; Humphreys, Yoon, et al., 2010), and that attention to the array of objects (and hence, object selection) can be strongly action-centred (Tipper, Lortie, & Baylis, 1992). Admittedly, the present study tested influence of implied actions in a rather simplified unnatural experimental setting. Further work is needed to examine whether the action-related influences we have observed operate in the more complex visual scenes more characteristic of real-world environment.

2.6 Conclusion

The current study extended previous works demonstrating the effect of action relations between objects on object identification in neuropsychological populations (Humphreys & Riddoch, 2001; Humphreys, Riddoch, Forti, & Ackroyd, 2004; Humphreys, Wulff, Yoon, & Riddoch, 2010; Riddoch et al., 2003) and healthy participants (Roberts & Humphreys, 2010a, 2010b, 2011a, 2011b). Our results illustrated that responses to different objects were modulated by the scene context in opposite ways – responses to objects active in the action being facilitated and responses to passive objects being suppressed. The work points to the competition between affordances of action related objects, and the importance of contextual information in affordance selection in multi-object visual scenes.

Chapter 3

What gives the active objects the dominance in implied between-object actions?

Abstract

Chapter 2 established the automatic processing of implied between-object actions when the object pairs are task irrelevant, and identified two effects of the implied actions between objects on response selection. Both effects suggested dominance of the active objects in implied between-object actions. This chapter aimed to identify properties of the object pairs that give the active objects this dominance. We used unfamiliar and untypical active-passive object pairs in the same paradigm described in Chapter 2 to examine the contribution from familiarity/typicality of object pairing (e.g. a saw and a bowl; Experiment 1), and used passive-passive object pairs (formed by replacing the active with a passive object in a given pair, e.g. a cup-nail vs. bowl-nail) to examine the impact of the presence of active objects and of action-related object structures (Experiment 2). Further, this chapter clarified the immediate response to such features. The involvement of motor activation was examined in Experiment 3 by requiring reaching and grasping responses. Unfamiliar active-passive object pairs (Experiment 1) and passive-passive object pairs (Experiment 2) with handles replicated the effects observed with familiar object pairs, but these effects were absent when the passive-passive object pairs did not have a handle. The reaching-and-grasping task did not alter the effects of implied between-object actions either. These results suggested that the effect of implied between-object actions can be driven by the processing of action-related structures of objects, which activated the abstract instead of specific action codes.

Keywords: stimulus-response compatibility effect, configural processing, implied actions, action possibility, affordance

3.1 Introduction

Experiments reported in Chapter 2 identified two behavioural signatures of the implied actions between objects: the inhibitory effects on responses aligned with the passive objects and the advantage for active objects. Both suggest dominance of the active objects in implied between-object actions. One striking characteristic of the findings is the automatic extraction of distinct functional roles (active vs. passive) in the object-pair. Given that the implied actions are highly synthetic and learned, such automaticity is surprising. A question naturally follows is what the underlying mechanisms of this seemingly sophisticated process are. For instance, it is possible that the advantage for the active objects were generated by recognizing familiar pairs of objects which afford well-learnt actions. It is also possible that selection between objects was made by identifying certain objects which are of "higher" functional value, rather than by identifying the objects as a pair. For example the presence of an active object might be crucial because they can be seen as more usable than the passive object. Yet another alternative could be that the implied between-object actions are determined without identifying the objects, but by locating the action-related object structures, e. g. handles. For instance, the spoon stipulates the stirring due to its handle making it an active object, while the lack of any obvious action-related structures on the bowl makes it a passive object. In sum, the present chapter asks the question what mechanisms lead to the dominance of the active objects in our findings.

Experiment 1 tests the influence of the identification of object pairs by re-pairing the active with passive objects, e.g. a saw is paired with a bowl thus reducing the familiarity of object pairs. Hence if the effects reported in Chapter 2 were generated by the recognition of familiar pairs of objects or the familiar actions between them, the unfamiliar object pairing would eliminate or reduce the influence of interacting co-locations between objects. Alternatively, if the effects may be due to "high" functional values of the individual objects (e.g. the active objects), then we should be able to replicate the effect. Experiment 2 examines further the possible influence from the presence of particular objects of "high" functional values by pairing larger and smaller objects previously used as passive objects (e.g. a bowl and a screw) and treated the larger one as "active". As these pairs don't include real active objects, the effects found in Chapter 2 should be eliminated if the functional-value exclusive to the active objects matters. In addition, some of the assigned "active" objects possess handles while others do not. We expect to replicate the findings of Chapter 2 with "active" objects having handles, but not with the handle-less ones, if the advantage for active objects was due to action-related features. In addition, by treating the larger objects as active objects in each pair, Experiment 2 also tests a possible confounding factor in the experiments of Chapter 2. In these experiments the active objects were generally larger than the passive objects (with exceptions, e.g. a bottle opener and a bottle). Consequently, if the passive-passive object pairs in Experiment 2 cannot produce the same response pattern observed in Chapter 2, it is likely that the two effects observed in Chapter 2 were generated by factors other than relative size difference between the active and the passive objects.

To foreshadow the results of Experiment 1 and 2, we found effects of implied between-object actions in Experiment 1 and for some pairs of objects in Experiment 2 (to be detailed below), which argues against the importance of the familiarity of object pairings and the presence of the active objects as such. Further, Experiment 2 found that the effects of implied between-object actions can only be replicated when the assigned "active" object has a handle, and that the size difference between objects is unlikely to be the cause of these effects. This suggests that the action-related object parts can be a critical source of the object dominance in implied between-object actions.

Experiment 4, Chapter 2 suggested that the effects of implied between-object actions are the result of activated abstract action codes as the effects were independent of the motor program for the task responses (left-right key presses vs. index-middle finger). However, given the importance of action-related structures of objects found in the present chapter, it is possible that the reach and grasp action afforded by the objects is also facilitated by these structures. In other words, the effects of between-objects actions may benefit from the activation of the exact afforded actions, as well as by abstract response codes. Then the effects should be enhanced by a reaching-and-grasping task. In Experiment 3 the participants were required to reach and grasp a joystick with the left or right hand, depending on the shape of the central target. Even though this task does not exactly replicate the real action towards the presented objects it still resembles more the afforded actions than a key-press task.

The basic paradigm and the task setting of experiments in Chapter 3 are the same to that in Chapter 2, with the main interest being the interaction between co-location (correct vs. incorrect) and response compatibility (active vs. passive objects). Based on the findings of Chapter 2 that co-location does not reliably affect responses aligned with the active objects, experiments in Chapter 3 only included the incorrect co-location condition in which the orientation of the active objects was manipulated.

3.2 Experiment 1: Do the effects of implied actions depend on the familiarity of pairing?

Experiment 1 questions the importance of the familiarity of object pairing in our semantic-free task by examining responses to highly uncommon active and passive pairs, e. g. a saw and a bowl. The rationale here is, if object pairing is critical in producing the observed effects, the unfamiliar and functionally irrelevant object should not replicate the effects observed in Experiment 1 of Chapter 2. However, if these effects may be due to other factors such as action-related structures or "high" functionality of individual objects, we should be able to replicate these effects.

3.2.1 Methods

A new sample of twenty-two healthy volunteers (one male, mean age 19 years, range: 18-20 yrs) from the University of Birmingham research participation scheme was recruited in Experiment 1. All participants were right-handed and have normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The stimuli in Experiment 1 consisted of 23 pairs of greyscale clip-art style images of objects on rectangle white background. Each pair consisted of one active object and one passive object. The two objects were functional irrelevant (See Figure 3-1 for exemplary stimuli and Appendix 3-A for a complete list of object pairs used in Experiment 1). Some objects appeared in more than one object pairs, for instance a glass in the knife-glass pair and the ping-pong bat-glass pair. In total, 16 active objects and 15 passive objects were used as stimuli. According to material evaluation by separate groups of volunteers (See Appendix 3-C for details), the objects in each pair are not typically used together, and they look as interacting with each other in the correct co-location condition but not in the incorrect co-location condition.

The procedure of Experiment 1 was the same as Experiment 1 in Chapter 2. The line drawings of objects were presented on background of the object images was light grey (200, 200, 200, RGB).

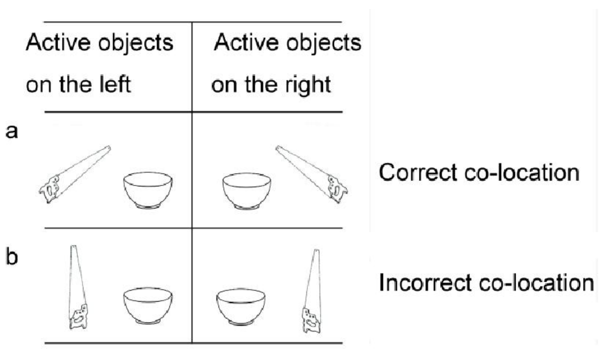

Figure 3-1. Example of the stimuli used in the Experiment 1.

3.2.2 Results and Discussion

Participants were highly accurate, with accuracy between 97.1% - 99.3% (mean 98.5%, mean RT = 417 ms, see Table 3-1) in different conditions. Reaction times (RTs) were initially trimmed to remove responses shorter than 100 ms. RTs out of 2.5 standard deviations were then discarded in a non-recursive manner for each participant. Discarded trials were less than 2% of total trials. The same procedure of data cleaning has been done for all experiments in this chapter.

Table 3-1: Average accuracy and reaction times (RTs) of each condition in Experiment 1

SOA	Layout (active objects on the left or right)	Response compatibility (passive vs. active objects)	Accuracy	RTs (ms)
240 ms	**Correct co-location**			
	Left	Passive	.98	430
		Active	.99	428
	Right	Passive	.99	439
		Active	.99	422
	Incorrect co-location			
	Left	Passive	.99	425
		Active	.99	430
	Right	Passive	.98	432
		Active	.98	424
400 ms	**Correct co-location**			
	Left	Passive	.97	404
		Active	.99	400
	Right	Passive	.98	415
		Active	.98	395
	Incorrect co-location			
	Left	Passive	.98	397
		Active	.99	414
	Right	Passive	.99	410
		Active	.98	403

Mean RTs were calculated for each participant in each condition, and were entered into an ANOVA with SOA (240 ms and 400 ms), co-location (correct vs. incorrect), layout of objects (active objects on the left side vs. on the right side) and response compatibility (compatible with active objects vs. with passive objects) as within-subjects factors.

There was a main effect of SOA, F (1, 21) = 123.70, p < .001, η^2 = 0.86, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 24 ms). The main effect of response compatibility was significant, F (1, 21) = 6.53, p = .018, η^2 = 0.24, with responses congruent with the active objects quicker than those congruent with the passive objects (MD = 4 ms). There was a significant interaction between co-location and response compatibility, F (1, 21) = 20.76, p <.001, η^2 = 0.50, see Figure 3-2. No other interaction was significant. The analysis of simple effects revealed that in the correct co-location condition, compared to the incorrect co-location condition, the responses congruent with the passive objects were slower (p = .033, MD = 6 ms), but those congruent with the active objects were quicker (p = .003, MD = 7 ms). In addition, the analysis showed that the responses congruent with the active objects were quicker than passive objects only in the correct co-location condition (p < .001, MD = 11 ms, see Figure 3-2), not when the co-location was incorrect (F < 1).

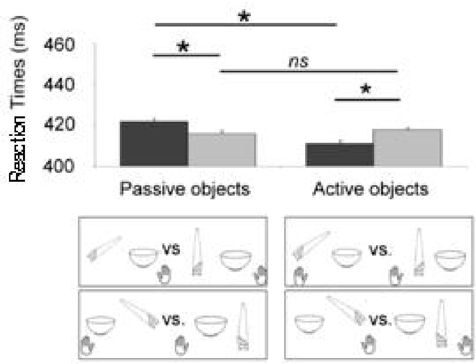

Figure 3-2. Correct co-location slowed down responses congruent with the passive object. Responses congruent with the active objects were quicker than those congruent with the passive objects when the co-location was correct. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

The results of Experiment 1 replicated the main features of the effects of implied between-object actions, as reported in Chapter 2. To examine whether there is any difference between the results of the two experiments, the data of both experiments were entered in an ANOVA, with pairing (familiar vs. unfamiliar) as a between-subject factor. This factor does not interact with any other factor. Especially, there is no interaction between pairing, co-location and response compatibility, $F(1, 50) = 3.17$, p = .081, η^2 = 0.06. Also, pairing does not alter any other interaction involving co-location and response compatibility (ps > .07, η^2 < 0.1), while the interaction between co-location and response compatibility is still significant, $F(1, 50) = 29.00$, p < .001, η^2 = 0.37, with both the inhibitory effect of the passive objects (MD = 6 ms, p = .001) and the advantage for the active objects in the correct co-location condition significant (MD = 9 ms, p < .001).

The three-way interaction between pairing, co-location and response compatibility approached significance. However, as can be seen in the previous paragraph and in Chapter 2, the interaction between co-location and response compatibility in this experiment resembles that of Experiment 1, Chapter 2 in the patterns of the interaction, the significance of the pairwise comparisons, and the sizes of both effects of interest (the inhibitory effect on the passive objects: 6 ms in this experiment vs. 6 ms in Chapter 2, Experiment 1; the advantage of the active objects, 7 ms in this experiment vs, 8 ms in Chapter 2, Experiment 1). The marginally significant interaction in between-experiment comparison reported here has a very small effect size (η^2 = 0.06). It might be due to the difference in the orientation effects of active objects which was significant in this experiment but not in Experiment 1, Chapter 2. This finding is easily explained since the single object affordance might be more standing-out when the link between two objects is weaker. The familiarity of object pairings has been demonstrated to affect the affordance-based processing in certain tasks, as shown by other studies (see Discussion of this chapter). The between-experiment analysis here did not provide statistical evidence for any dissociation between the familiar and unfamiliar object pairs, which might be because the present experimental task, being irrelevant to action intention and functional knowledge, is insensitive to impact of object identity. However, this experiment does not aim at arguing against potential differences in affordance-based processing between familiar and unfamiliar objects pairs. Instead, the present study illustrates the similarity, though might be partial, in the patterns of affordance-based effects in these two categories of object pairs, which have been shown by respective pairwise comparisons.

Overall, these findings suggest that the familiarity of pairs, i.e. the identification of object pairs, is not critical in producing the effects of implied between-object actions, and is not the source of the dominance of the active objects, at least when the task does not require object identification or intention of object manipulation.

3.3 Experiment 2: Do the effects depend on the presence of active objects or action-related parts of the objects?

Experiment 1 illustrated that when the active objects were presented in unfamiliar object pairs, the interactions implied by their co-locations produced similar effects as those produced by familiar pairs. Experiment 2 intends to further examine whether the presence of some particular objects with high functional values, i.e. the active objects, evoked these effects. Experiment 2 paired larger and smaller objects previously used as passive objects (e.g. a bowl and a screw) and treated the larger one as “active”, thus formed a set of passive-passive object pairs as stimuli (see Figure 3-3 for examples). In the correct co-location condition, the objects were positioned in their respective orientations as in the correct co-location condition of previous experiments. The orientation of the “active”/larger objects in each pair was manipulated in the incorrect co-location condition.

Further, the “active”/larger passive objects used in Experiment 2 can be separated into two groups. For some objects, the grasping/ manipulation required in functional use is primarily afforded by a handle, e.g. a cup. For objects without handle, the manipulation requires grasping at the main body of the objects, e.g. a bowl. By comparing responses to with-handle and handle-less “active” objects, Experiment 2 examines whether, instead of the identification of active objects, it is the action-related object structures that produced the effects of implied between-object actions observed in Chapter 2. In addition, by assigning the larger objects as “active” objects in each pair, Experiment 2 also test whether size difference between active and passive objects acted as a confounding factor in Chapter 2.

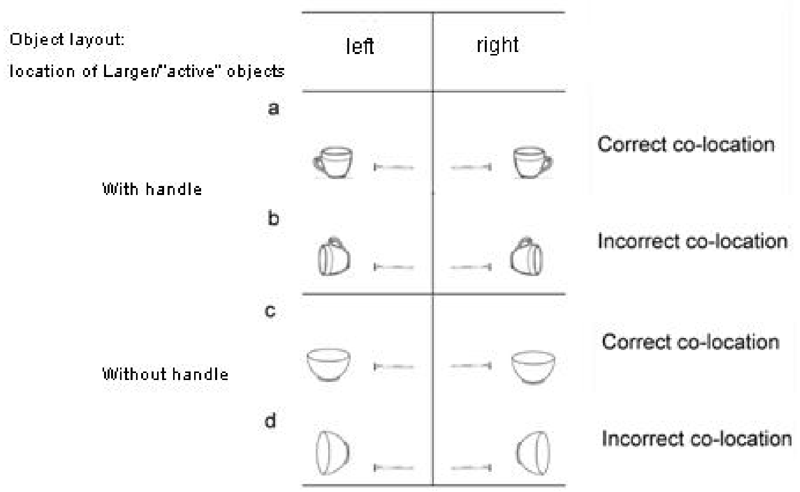

Figure 3-3. Example of the stimuli used in the Experiment 2.

3.3.1 Methods

A new sample of twenty healthy volunteers (two males, mean age 19 years, range: 18-23 yrs) from the University of Birmingham research participation scheme was recruited in Experiment 2. All participants are right-handed and have normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The procedure of Experiment 2 was the same as Experiment 1 except the stimuli presented. The stimuli in Experiment 2 consisted of 25 pairs of greyscale clip-art style images of objects on rectangle light grey background. Each pair consisted of two passive objects, one “active”/larger and one passive/smaller object. The two objects were functionally irrelevant (see Figure 3-3 for exemplary stimuli and Appendix 3-B for a complete list of object pairs used in Experiment 2). Some objects appeared in more than one object pairs, for instance a screw as a passive/smaller object in the glass-screw pair and the pan-screw pair. In total, five “active”/larger objects and five passive/smaller objects were used as stimuli. According to evaluation by separate groups of volunteers, the objects in each pair were not typically used together, and looked more like interacting with each other in the correct co-location condition compared to the incorrect co-location condition (detailed results see Appendix 3-C).

3.3.2 Results and Discussion

Participants were highly accurate, with accuracy between 96.5.2% - 99.3% in different conditions (mean 98.5%, mean RT = 425 ms, see Table 3-2).

To examine whether the overall RTs pattern replicated our earlier findings, mean RTs of each participant were entered into an ANOVA with SOA (240 ms and 400 ms), co-location (correct vs. incorrect), the layout of objects (the “active”/larger objects on the left side vs. on the right side) and response compatibility (aligned with the “active”/larger object vs. the passive/smaller object) as within-subjects factors.

There was a main effect of SOA, F (1, 19) = 82.16, p < .001, η^2 = 0.81, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 18 ms). There was a significant interaction between co-location and response compatibility, F (1, 19) = 10.14, p =.005, η^2 = 0.35, and an interaction between SOA, response compatibility and co-location, F (1, 19) = 8.38, p =.009, η^2 = 0.31. The analysis of the simple effects suggested that in the 240 ms SOA condition, the response aligned with the passive objects were marginally quicker in the incorrect co-location condition than in the correct co-location condition (p =.058, MD = 5 ms). In 400 ms SOA condition, this effect reached significant (p =.016, MD = 12 ms). In addition, in 240 ms, but not 400 ms, SOA condition, when the co-location was correct, responses aligned with the “active” objects were quicker than those aligned with the passive objects (p =.040, MD = 7 ms), while in 400 ms, but not 240 ms, SOA condition, when the co-location was incorrect, the response congruent with “active”/larger object (the manipulated objects) were slower than those congruent with the passive/smaller objects (those remained in its cardinal orientation, p =.010, MD = 11 ms). Hence, without differentiating “active” objects with and without handles, we did not fully replicate our earlier findings.

Handle vs. handle-less

To examine the role of action-related structural features in producing the effects of implied between-object actions, RT data were then entered into an ANOVA with an additional within-subject factor, the handle-ness of the “active”/larger object (the “active”/larger object in the object pair has a handle vs. does not have a handle). 14 of the 25 pairs of objects falls into the handled category and the rest the handle-less category.

There was a main effect of SOA, F (1, 19) = 78.45, p < .001, η^2 = 0.81, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 17 ms). There was a significant interaction between co-location and handle-ness, F (1, 19) = 12.88, p =.002, η^2 = 0.40, an interaction between response compatibility and handle-ness, F (1, 19) = 7.86, p =.011, η^2 = 0.29, and an interaction between co-location and response compatibility, F (1, 19) = 8.75, p =.008, η^2 = 0.32. Above all, the three-way interaction between handle-ness, co-location and response compatibility was significant, F (1, 19) = 5.24, p =.034, η^2 = 0.22 (see Figure 3-4). The analysis of simple effects suggested that for the pairs with a handle on the “active”/larger objects, the responses aligned with the passive/smaller objects were quicker in the incorrect co-location condition than in the correct co-location condition (p =.001, MD = 17 ms), but this effect does not exist for the object pairs when the “active”/larger objects did not possess handles (p > 0.2); the responses aligned with the passive/smaller objects were slower than those aligned with the “active”/larger objects in the correct co-location condition (p =.003, MD = 14 ms), but this effect did not exist for the object pairs when the “active”/larger objects did not possess handles (p > 0.1). In other words, the effects of implied between-object actions were replicated in “handle-ed” pairs, but not in the “handle-less” pairs.

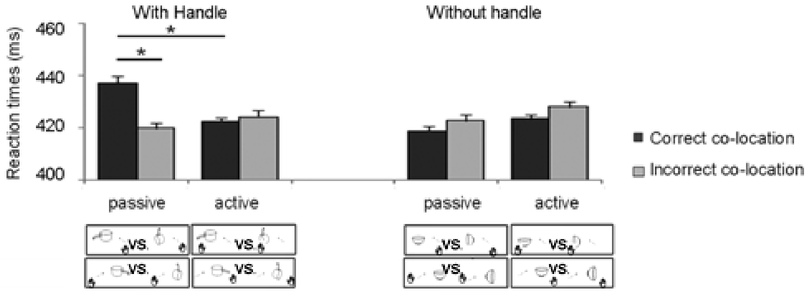

Figure 3-4. The three-way interaction between the presence of a handle, co-location and response compatibility. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

In addition, there was an interaction between handle-ness and response compatibility, *F* (1, 19) = 7.86, *p* =.011, η^2 = 0.29, and between handle-ness, SOA and response compatibility, *F* (1, 19) = 4.98, *p* =.038, η^2 = 0.21 (see Figure 3-5). Analysis of simple effect revealed that in 240 ms SOA condition, the responses aligned with the passive/smaller objects were slower when the ”active” objects had an handle, compared to when the ”active”/larger objects did not have a handle (*p* =.002, MD = 11 ms). The same effect was not significant for responses congruent with the “active”/larger objects (*p* > 0.1), or in 400 ms SOA condition (*F* < 1). Also, in 240 ms SOA condition, responses aligned with “active”/larger objects with a handle were quicker than those aligned with the passive/smaller objects (*p* =.002, MD = 11 ms). The same effect was not significant for pairs with handle-less “active”/larger object (*p* > 0.2), or in 400 ms SOA condition (*F* < 1). Note here this interaction reflected influences independent from co-location between objects. This interaction here might reflect a quick bottom-up attention orienting effect, in which attention was drawn to the object with a handle regardless of its orientation. There was also the significant interaction between SOA, co-location and response compatibility as reported in the first set of ANOVA two paragraphs earlier.

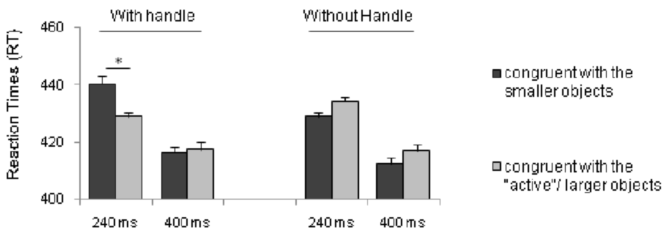

Figure 3-5. The three-way interaction between SOA, the presence of handle and response compatibility. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

3.3.3 Discussion

Without considering the handle-ness of the larger objects, the results of Experiment 2 only partially replicated the results of Experiment 1. The inhibitory effect on the passive objects reduced to marginally significant in 240 ms SOA condition, and the advantage for the active objects ceased to be significant in 400 ms condition. These changes suggest that the effects were not as clear-cut as in Experiment 1 or other experiments using active-passive object pairs. However when the handle-ness of the active/larger objects considered in the analysis, the results showed clear replication of our earlier findings in the object pairs with handle. Note that the effect of handle-ness was observed when the two objects in each pair do not afford familiar between-object actions. The effects of implied between-object actions and the advantage for “active” objects persisted in passive-passive object pairs as long as the “active”/larger objects have an action-related structure.

By replicating the effects of active-passive object pairs with certain passive-passive object pairs, Experiment 2 further suggested that the presence of the active objects (more of them are tools and are more likely to be actively used than the passive objects) was not indispensable for the affordance selection in implied action between objects. In addition, the handle-less pairs failed to replicate the effects observed in Chapter 2 even though there is a similar size difference between two objects in a given pair. This rules out size difference between active and passive objects as a potential confounding factor in previous experiments.

Table 3-2: Average accuracy and reaction times (RTs) of each condition in Experiment 2

SOA	Layout (“active” objects on the left or right)	Response compatibility (passive vs. “active” objects)	Accuracy	RTs (ms)
“Active”/larger objects have handles				
240 ms	Correct co-location			
	Left	Passive	.99	443
		“Active”	.98	437
	Right	Passive	.99	451
		“Active”	.99	423
	Incorrect co-location			
	Left	Passive	.98	431
		“Active”	.98	427
	Right	Passive	.99	437
		“Active”	.99	430
400 ms	Correct co-location			
	Left	Passive	.99	424
		“Active”	.98	419
	Right	Passive	.99	430
		“Active”	.99	412
	Incorrect co-location			
	Left	Passive	.99	404
		“Active”	.98	425
	Right	Passive	.97	407
		“Active”	.98	414
“Active”/larger objects have no handle				
240 ms	Correct co-location			
	Left	Passive	.98	417
		“Active”	.99	441
	Right	Passive	.98	433
		“Active”	.98	427
	Incorrect co-location			
	Left	Passive	.97	427
		“Active”	.99	437
	Right	Passive	.99	439
		“Active”	.97	433
400 ms	Correct co-location			
	Left	Passive	.98	407
		“Active”	.99	416
	Right	Passive	.99	419
		“Active”	.98	411
	Incorrect co-location			
	Left	Passive	.98	412
		“Active”	.99	425
	Right	Passive	.99	413
		“Active”	.99	416

3.4 Experiment 3: Do the effects depend on the activation of specific actions?

Experiment 2 suggested that action-related structures of the objects can play a key role in generating the effects of implied between-object actions. This opens another question, that is, what representation is activated by these stimuli. Recall Experiment 3 of Chapter 2 revealed that the effects of implied between-object actions may be generated by the activation of abstract action codes. However, is the activation of the exact action afforded by the objects also involved? Experiment 3 tested whether the specific action afforded by the objects is also activated in generating the observed effects. To do this, familiar active-passive objects were presented as stimuli and the participants were required to make left or right reaching and grasping responses (see Methods). This task should increase the size of the effects in question if the activation of specific action programme also contributes to the effects.

3.4.1 Methods

A new sample of twenty healthy volunteers (five males, mean age 19 years, range: 18-21 yrs) from the University of Birmingham research participation scheme was recruited. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

Experiment 3 used the same shape-discrimination task as in the previous experiments, but required the participants to release a keyboard key and to grasp one of two joysticks indicated by the shape of the target, mimicking a reaching and grasping response towards the object in action direction and effector hand.

Figure 3-6. The setting of joystick and keyboard for Experiment 3.

Two joysticks (Thrustmaster® USB joystick PC) were positioned between the keyboard and the screen, roughly between the j and f key and the left and right positions where the objects appeared. Participants held down the f and j keys with the index fingers of each hand (some used middle fingers of both hands). When the target was added to the screen, the participant had to release the key and to grasp the joystick positioned on the same side, mimicking a reaching and grasping response towards the object presented on the same side (see Figure 3-6 for the experiment setup). The time elapsed between the onset of the target and the releasing of the corresponding key was recorded as initiation time, and the time between key-releasing and joystick grasping was calculated as movement time.

Two variations of the incorrect co-location condition were included, one with the active objects changing orientation (as the incorrect co-location condition in Experiment 1 and 2), one with the passive objects changing orientation (as in Experiments 2, Chapter 2). The objects were task-irrelevant. Experiment 3 used the same stimuli set as in Experiment 2, Chapter 2 (See Appendix 2-B for a full list).

3.4.2 Results

Participants were highly accurate, with the average accuracy of each condition falling between 99.5% and 100% (mean 99.7%, mean Initiation time = 430 ms, mean Movement time = 517 ms, see Table 3-3).

RTs for the initiation and movement times were separately entered into an ANOVA each with SOA (240 ms and 400 ms), co-location (correct vs. incorrect with the active object manipulated vs. incorrect with the passive object manipulated), object layout (active-left vs. active-right) and response compatibility (active object vs. passive object) as within-subjects factors. We were particularly interested in two pairwise contrasts, which are the contrast between active and passive objects in the correct co-location condition and that between responses to passive objects in the correct and the incorrect-with-active-object-manipulated co-location conditions. Planned comparisons were made for these two contrasts when corresponding interactions or simple effects were not significant.

Initiation time. There was a main effect of SOA, F (1, 19) = 74.48, p < .001, η^2 = .80, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 15 ms).

The main effect of response compatibility was significant, F (1, 19) = 20.99, p < .001, η^2 = .53, with responses congruent with the active objects quicker than those congruent with the passive objects (MD = 7 ms). There was a significant interaction between co-location and response compatibility, F (2, 18) = 12.74, p < .001, η^2 = .59, see Figure 3-7. The analysis of simple effects revealed that, in the correct co-location condition, responses congruent with the passive objects were slower than those congruent with active objects, F(1,19) = 21.88, p < .001, η^2 = .54, MD = 11 ms. This effect replicated the advantage for the active objects reported in Chapter 2. In addition, when the co-location was incorrect due to the changed orientation of the passive object, responses congruent with the passive objects were slower than those congruent with the active objects, F(1,19) = 25.62, p < .001, η^2 = .57, MD = 13 ms. Co-location affected responses aligned with the active objects, F (2,18) = 7.56, p = .004, η^2 = .46, with the responses being longer when the co-location was incorrect with the active objects manipulated, compared with both the correct co-location condition (p = .007, MD = 8 ms) and the other incorrect co-location condition (when the passive objects were manipulated, p = .002, MD = 11 ms). The co-location effect on passive objects did not reach significance in the pairwise analysis, but it did yield a relatively large effect size, F (2,18) = 2.19, p = .14, η^2 = .20. The interested pairwise contrast between responses to passive objects in the correct and the incorrect-with-active-object-manipulated co-location conditions is marginally significant, MD = 6 ms, p = .078, showing a trend for the inhibitory effect on responses aligned with the passive objects.

Movement time. There was a significant interaction between the layout of the objects and response compatibility, F (1,19) = 15.62, p = .001, η^2 = .45. The analysis of simple effects revealed that this interaction was mainly driven by the quicker responses made by the dominant hand; the left-hand responses were slower than right-hand responses afforded by the same category of objects (for responses congruent with the active objects, F (1,19) =

15.01, p = .001, η^2 = .44, MD = 27 ms; for responses congruent with the passive objects, F (1,19) = 15.58, p = .001, η^2 = .45, MD = 26 ms, see Figure 3-8.

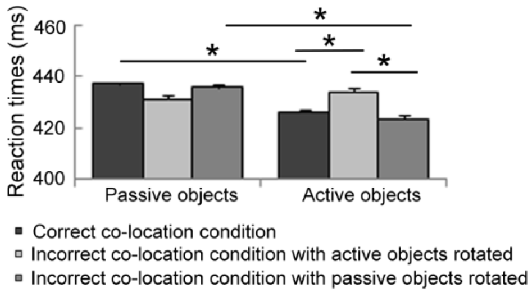

Figure 3-7. Initiation times in Experiment 3. In the correct co-location condition, RTs of responses compatible with the active objects were shorter than those compatible with the passive objects (the black bars). When the co-location was incorrect due to rotated passive object, mean RTs for responses congruent with the passive objects were longer than those congruent with the active objects (the dark grey bars). The mean RTs for responses congruent with the active objects were longer when their orientation were manipulated (light grey bar on the right cluster), compared with when they were not (both in the correct co-location condition, black bar in the right cluster, and the in co-location with rotated passive object condition, dark grey bar in the right cluster). The error bars indicate the standard error of each condition following method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

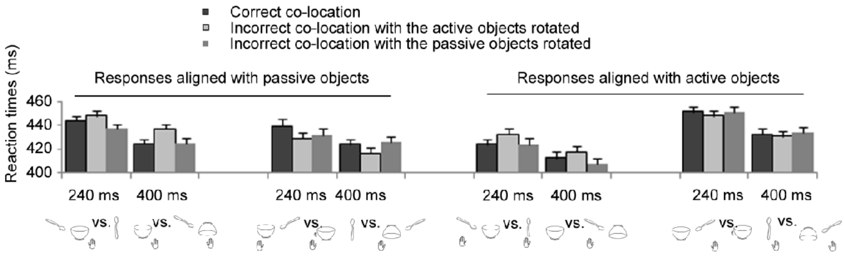

Figure 3-8. Movement time (time to release the key) in different conditions in Experiment 3.

The fact that the effect of implied actions appears in the initiation time rather than the movement time also suggests that the implied actions were registered before the actual response was made, which is natural because even if the observed effect comes from the activated motor program of the afforded action, the selection of the response hand, as required in our left-right selection task, must be made prior to the action being initiated. The absence of any effect in movement time suggests that the online motor control was not modulated by our manipulation.

Table 3-3: Average accuracy and reaction times (RTs) of each condition in Experiment 3

Layout (active objects on the left or right)	Response compatibility (passive vs. active objects)	Accuracy	Initiation time (ms)	Movement time (ms)
240 ms SOA				
Correct co-location				
Left	Passive	0.99	443	532
	Active	1.00	439	504
Right	Passive	1.00	424	504
	Active	0.99	452	528
Incorrect with the active object rotated				
Left	Passive	0.99	447	532
	Active	1.00	429	507
Right	Passive	1.00	431	507
	Active	1.00	447	531
Incorrect with the passive object rotated				
Left	Passive	1.00	437	535
	Active	1.00	431	505
Right	Passive	1.00	423	505
	Active	1.00	450	529
400 ms SOA				
Correct co-location				
Left	Passive	1.00	423	526
	Active	1.00	424	502
Right	Passive	1.00	412	502
	Active	1.00	432	530
Incorrect with the active object rotated				
Left	Passive	1.00	437	532
	Active	1.00	414	503
Right	Passive	1.00	417	507
	Active	1.00	431	531
Incorrect with the passive object rotated				
Left	Passive	1.00	425	529
	Active	1.00	424	503
Right	Passive	1.00	406	501
	Active	1.00	433	531

3.5 General Discussion

Chapter 2 found that implied actions between objects lead to an automatic prioritization of the active objects in action-related object pairs. Chapter 3 aimed to pinpoint the source of this advantage for active objects in implied between-object actions. The object pairs presented in Chapter 3 were either unlikely to be used together in functional action (in Experiment 1), or they did not include an active object at all (Experiment 2). The results suggested that the effects of implied between-object actions are insensitive to object pairing

(Experiment 1) and the presence of objects with high functional values (Experiment 2). The crucial factor might be the presence of action-related structures in objects (Experiment 2). Further, Experiment 3, together with Experiment 4 in Chapter 2, suggested that such action-related parts of objects evoke the observed effects by the activation of abstract action codes (see Chapter 2 for more discussion) instead of the activation of action programme specifically locked with particular effector hands (Experiment 3).

Linking back to the questions raised in the introduction part of this chapter, the results of Experiment 1-3 suggested that action-related structures of the objects can be the source of the automatic prioritization of the active objects in object pairs implying between-object actions (Chapter 2), and that responses to subsequent target stimuli are affected by the abstract response codes activated accordingly, e.g. correspondent to the primary action-related structures in a given scene. This will be discussed in details in the following.

3.5.1 The prioritization of the active objects might come from action-related object features

The reliance on the presence of action-related structures can accommodate the dominance of active objects easily, since the "active" objects according to our definition are the ones affording the major actions in object pairs. Even when paired with functional irrelevant passive objects, the active objects are still perceived as the one affording more substantial manipulation (as suggested by the results of stimuli evaluation, see Appendix 3-C).

The noticeable effect of handle-ness discovered in Experiment 2 raised a further question: Is the dominance of the active objects in Experiment 1 in Chapter 2 and Experiment 1 in the present chapter because of the handles of the active objects? To answer this question, the data of the respective experiments were reanalysed. In the reanalysis, object pairs were categorized according to whether the active object has a handle (e.g. a jug) or are generally grasped along the elongated axis (e.g. a bottle). There were less than 1/3 of object pairs with “handled” active objects (seven “handled” pairs and 16 “elongated” pairs in each experiment). This led to very few trials in some conditions. Therefore we excluded data of “handled” pairs from each experiment. If the handles of the active objects drove the effects we observed previously, by removing these pairs the effects of implied between-object actions should disappear. If the effects remain, then it is likely that handle is not the only possible source of these effects.

Each experiment was analysed separately. RT data were subjected to the same ANOVAs used in previous experiments, with SOA (240 ms and 400 ms), the co-location (correct vs. incorrect), the layout of paired objects (active-left vs. passive-left) and response compatibility (active-object vs. passive-object) as within-subjects factors (See Appendix 3-D and 3-E for detailed statistical report). The main finding is that in both experiments, both effects of implied between-object actions remained. Elongated, but handle-less, active objects also enjoys automatic prioritization in our paradigm, and the passive objects were inhibited when they are paired with these kinds of “active” objects. Interestingly, this is consistent with findings that elongation increases activation in tool sensitive areas including superior parietal lobe in the dorsal stream (Chen, Goodale, Culham, & Snow, 2014). Consequently, it is possible that handle is just one of many structures which create the dominance of active objects.

Regarding the real source of the dominance of active objects, it is possible that a class of action-related object features, e.g. elongation and handle, might all serve as a structural “cue” of between-object actions. Also, the objects with a handle are at the same time “asymmetric” in terms of affordance, affording manipulation mainly from the handle side and towards a direction typically opposite to the handle, which, in our bilateral presentation, is towards the other objects in the correct co-location condition. In this way, such asymmetry might also have created implication of an action relation between the two functionally irrelevant objects in the correct co-location condition of Experiment 2. Alternatively, it is possible that certain aspects of the semantic representation of the active objects (e.g. about its function and usage) denote the “activeness” of the active objects, and handle (and other action related structures) might only be influential when the object pair does not have apparent implication for familiar actions. The findings of the following chapter will shed more light on this issue, in favour of an affordance-based explanation over the semantic alternative. This will be further discussed in the general discussion of the present thesis.

3.5 2 The role of semantic knowledge about object functions

The findings of Experiment 1 and 2 suggest that functional familiarity of object pairing is not a prerequisite for the observed effects. Similarly, it has been found in a patient with Balint’s syndrome that for object identification task, the awareness-facilitation effect of action relation (illustrated in the contrast between the correct and the incorrect co-location conditions) was not reduced by object pairs affording feasible actions but of lower familiarity, compared to action-feasible-high-familiarity pairs (Humphreys, Riddoch & Fortt, 2006). This suggested that the awareness facilitation effect comes from the activated representation of a feasible, rather than typical, action relation independent from the semantic knowledge or experience of the presented object pairs. Moreover, in a functional magnetic resonance imaging (fMRI) study, Roberts and Humphreys (2010b) found that the activation of bilateral lateral occipital complex (LOC) was increased in the correct co-location compared to the incorrect co-location condition, and this effect exists regardless of the familiarity of the pair. These results, together with our results of Experiment 1 and 2, suggest that the identity of the object pairs is not crucial for implied between-object actions to affect responses. In addition, this lack of familiarity effect is in line with Gibson’s (1979) initial idea that affordances do not necessarily require the contribution from semantic knowledge.

However, some previous studies did report the influence from the familiarity of action relation/object pairing. For instance, Green and Hummel (2006) found that the correct co-location for interaction facilitated object identification, but this effect existed only when the two objects belonged to the same functional group (equivalent to familiar pairs in our study in Chapter 2), but not when they were functionally irrelevant (similar to our unfamiliar pairs in Chapter 3). Riddoch et al., (2003) found that in patients with extinction, identification was facilitated by the correct co-location when the presented objects were normally used together (e.g. bottle and glass), but not when the object pairings were not typical (bottle and bucket) or random (bottle and ball). Also, in an action observation study, Bach and colleagues (2005) reported that familiar/functional matched pairs of objects facilitated judgement of spatial relation (similar to correct vs. incorrect co-location in our experiments). We attribute the difference between these results and ours to the different experimental tasks. The semantic association between objects in these studies might have facilitated the retrieval of the semantic knowledge of the objects in the identification task or the functional/mechanical knowledge in the spatial judgement task, while in the present study the semantic-free task benefitted less from the semantic association between objects and relevant functional knowledge, but from the interacting co-locations of objects. The independence from the familiarity of the object pairing (Experiment 1) indicates that the implied actions between objects can be extracted without matching the object pair with semantic knowledge and experience. Instead, the extraction of the action relation is more of a "direct" nature. This "direct" nature can also be illustrated in the framework Riddoch et al.'s (2006) two-stage model for the perception of action relations for patients with extinction. At Stage 1, the action-related properties of the presented objects are registered preattentively, which affected attention allocation. Attention is more likely to be allocated across both objects when one object can be used upon the other and the objects are positioned correctly for their combined use, rendering the two objects a single unit in processing (Riddoch et al., 2003). Only at Stage 2 of Riddoch et al.'s, (2006) model, the initial bottom-up coding is subjected to influence of top-down modulation from knowledge and familiarity. In the present study, because the identities of objects were task-irrelevant, the influence of the second stage might have been weakened and the effect of familiarity absent.

The role of semantic knowledge was further questioned by the results of Experiment 2. The results of Experiment 2 indicated that both effects observed in Chapter 2 can be produced by any object pair given it possesses a salient action-related part, e.g. a handle. Chiming with this finding, the stimuli evaluation of Experiment 2 revealed that when the "active" objects had handles, they were rated more "active" compared to the objects without handle; the participants were more likely to choose these objects as the active object in a given pair, compared to the ones without handle.

Taken together, the results of Chapter 3 revealed that, instead of object identification, action-related structures of objects influence responses to paired objects.

Chapter 4

Ventral and dorsal stream contributions to responses to implied between-object actions: a TMS study

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Abstract: Xu, Humphreys and Heinke (2015) identified two effects of implied actions between objects on response selection: an inhibitory effect of on responses aligned with passive objects (e.g. a bowl) and a response advantage associated with responses aligned with the active objects (e.g. a spoon). The present study investigated the neurocognitive mechanisms behind these effects by examining the contributions from the ventral (perception) and the dorsal (action) visual streams, as defined in Goodale and Milner's (1992) two visual stream theory. Online transcranial magnetic stimulation (TMS) was applied during the presentation of each trial. The stimulation to the left anterior intraparietal sulcus (aIPS) reduced both the inhibitory effect of implied action on responses aligned with passive objects and the advantage of those aligned with the active objects, but only when the active objects were contralateral to the stimulation. TMS to the left lateral occipital areas (LO) did not affect the influence of implied actions. The results reveal that the dorsal visual stream and the affordance-based processing it undertakes are crucial in responding to implied actions between objects.

Keywords: Anterior intraparietal sulcus, Lateral occipital cortex, Transcranial magnetic stimulation, Implied action, Ventral and dorsal streams

In his seminal book, Gibson (1979) postulated that humans directly detect action possibilities (affordances) from the physical properties of objects in an automatic fashion. There is now substantial evidence for this claim (e.g. Bub, Masson, & Cree, 2008; Phillips & Ward, 2002; Riddoch, Edwards, Humphreys, West, & Heafield, 1998; Riddoch, Humphreys, Edwards, Baker, & Willson, 2003; Tucker & Ellis, 1998). For instance, despite being irrelevant to the task, responses are speeded when they are compatible with the grasping action afforded by a visual object, while those incompatible with the action are slowed down, (e.g. Ellis & Tucker, 2000; Phillips & Ward, 2002; Tucker & Ellis, 1998). Further studies revealed that the automatic extraction of action-related information is not confined to single objects, but extends to visual scenarios in which pairs of objects are presented (e.g. Humphreys, Wulff, Yoon & Riddoch, 2010; Humphreys, Yoon, et al., 2010; Riddoch, Humphreys, Edwards, Baker & Willson, 2003; Roberts & Humphreys, 2010a, b; 2011a, b; Xu, Humphreys & Heinke, 2015; Yoon, Riddoch & Humphreys, 2010). In these studies participants see object pairs where one object is “active” while the other object is “passive”. Active objects (e.g. a spoon in a spoon-bowl pair) are those items used in the action between the objects (e.g., grasping and scooping from the bowl), while the passive objects only need “stabilization” (e.g., the bowl in the spoon-bowl pair, see Figure 4-1). In a series of studies with such stimuli Riddoch and colleagues reported that, for patients with extinction, positioning objects for action enabled the patients to attend to both members of a pair, alleviating the impairment in detecting contralesional items (Riddoch, Humphreys, Edwards, Baker & Willson, 2003). Furthermore, there is a bias in patients to select the active objects, when the objects are correctly positioned for action, suggesting that attention to the object is modulated by the action related affordance (Riddoch et al., 2003). In normal observers, correctly co-locating objects for action, compared with when they are incorrectly co-located for action, facilitated object identification (Roberts & Humphreys, 2011a), and correctly co-located objects induce a larger bias towards identifying the active objects relative to the passive objects in each pair (Roberts & Humphreys, 2010a).

The present paper aims to follow up behavioral findings of the effects of pairing object for action on response preparation by Xu, Humphreys & Heinke (2015, and see Chapter 2 of the present thesis). Xu et al. (2015) presented pairs of action related objects, either correctly positioned for interaction or not (Figure 4-1). The objects were followed by a central target, and the participants were asked to make speeded left/right responses to indicate whether the target was a circle or triangle. The responses were aligned with either object in the object pair. Hence and in contrast to the previous studies, not only the implied action relationship but also the objects were task irrelevant. Nevertheless, Xu et al. (2015) found that the objects affected participants' responses. More specifically, they found that the responses aligned to the passive objects were slower when the two objects were presented as if in interaction, compared with when they were not in interaction. In contrast to this apparent inhibition effect responses were quicker if they are aligned with the active objects than with the passive objects—a facilitation effect— when the two objects were positioned as if in interaction. Xu et al. (2015) interpreted these findings as evidence for affordance effect on response selection (Cisek, 2007; Thill, Caligiore, Borghi, Ziemke, & Baldassarre, 2013): initially the affordances of both objects are extracted (e.g. handles and other action-relevant object parts) and subsequently are entered into a competition for motor action with the active object winning the competition. Such an affordance-based response processing may be linked to the dorsal stream, as proposed by theories distinguishing vision for action (through the dorsal stream) from vision for perception (through the ventral stream, for reviews, see Goodale & Milner, 1992; Milner & Goodale, 2006, 2008; see also Riddoch, Humphreys & Price, 1989; Yoon, Heinke & Humphreys, 2002). According to this dual-stream account, on-line motor responses to visual stimuli should be modulated by the dorsal stream. However it is also possible that processes in the ventral stream also contribute to the behavioural findings. Roberts and Humphreys (2010b), for example, reported enhanced activation in ventral visual stream including the lateral occipital complex and fusiform gyrus, for pairs of objects that were correctly positioned for action compared with objects incorrectly positioned for action. Roberts and Humphreys argued that action-positioned objects could trigger a visual recognition response within the ventral stream, facilitating the grouping of action-related objects. Whether such effects extend to the activation of motor related responses, indexed by compatibility effects in Xu et al (2015), is a moot point.

To examine the contribution of the two streams, the present study conducted an online transcranial magnetic stimulation (TMS) to induce a “virtual lesion” to representative areas of each stream, the left anterior intraparietal sulcus (aIPS) and left lateral occipital area (LO) for the dorsal and the ventral pathway respectively. As a representative region within human ventral visual stream, LO has been reported to be activated in human neuroimaging studies across a range of object perception and recognition tasks (for review see Grill-Spector, Kourtzi, & Kanwisher, 2001). TMS to LO (Brodmann’s area 37) slows subjects’ reactions for object naming (Stewart, Meyer, Frith, & Rothwell, 2001) and shape discrimination (Ellison & Cowey, 2006). The left LO was also activated by action-related objects in Roberts and Humphreys (2010b). As a representative region within the human dorsal visual stream, aIPS has been proposed to mediate online control of object-directed grasping (Binkofski et al., 1998; Culham et al., 2003; Frey et al., 2005; Rice et al., 2007; Tunik et al., 2005). Further, a left-lateralized network of brain regions including aIPS was identified (i) during studies in which there was increased activation for tools compared to other objects (Chao & Martin 2000; Chouinard & Goodale 2012; Mruczek, von Loga, & Kastner, 2013; Valyear, Cavina-Pratesi, Stiglick, & Culham, 2007) and (ii) during viewing, hearing, executing, planning, and pantomiming tool use (Lewis, 2006), in which tool use actions are preferred compared to control conditions. TMS on left aIPS has also been reported to affect online grasping (Cohen, et al., 2009).

4.1 Methods

4.1.1 Design

The experiment followed a 2 (co-location: correct vs. incorrect) × 2 (the layout of paired objects: Active-left vs. active-right) × 2 (response compatibility: Active object vs. passive object) × 3 (Stimulation site: Cz, left aIPS & left LO) within-subject factorial design.

4.1.2 Participants

Sixteen healthy volunteers (2 females, age range 18-25 years) with no previous history of neurological problems participated. All participants had normal or corrected-to-normal vision and were right handed. Participants gave informed consent and received monetary compensation for their time.

4.1.3 Apparatus

The experiment was run on a Windows PC with a 1GMHZ Pentium III processor, using a Philips 109S monitor (1280 × 1024 at 75 Hz). Matlab7 (The MathWorks Inc., Natick, MA, USA) with Psychtoolbox 3 was used to display the stimuli and record RTs.

4.1.4 Stimuli

The stimuli consisted of 23 pairs of greyscale clip-art style images of objects on a light grey (200, 200, 200 RGB) background. Each pair included an active object and a passive object commonly used together in actions (see Figure 4-1 for an example and Appendix 4-A for a complete list of the object pairs used). Some stimuli appeared in more than one object pair. For instance a jug appeared in a jug-cup pair and a jug-glass pair. In total, 16 active objects and 15 passive objects were used as stimuli. Each object image subtended 3.2°×3.2°

of visual angle. The relative sizes of the objects within each pair matched their relative sizes in real life. Other stimuli included a fixation cross subtending 0.8°×0.8° of visual angle and two blue (0, 121, 212 RGB) response targets (a triangle or a circular disk), both subtended 0.6°×0.6° of visual angle.

The stimuli were rated by two different participant groups with respect to (a) whether the action relations between the objects were familiar and apparent, (b) whether, by changing the orientation of the active objects in the incorrect co-location condition we effectively manipulated the implied actions between objects, (c) whether the objects always afford actions by the hand aligned with their location, and d) the appropriateness of our assignment of active and passive objects. The results revealed that the stimuli satisfied these criteria. A detailed description of the procedure and the results of the stimulus evaluation process can be found in Appendix 2-D.

4.1.5 Procedure

The participants were seated in a comfortable chair, with their chins resting on a chin rest, and the index and middle finger of their right hand resting on the j and k keys respectively. Each test session consisted of one practice block and five experimental blocks. The practice block consisted of 64 trials, randomly assigned to different conditions. Each experimental block consisted of 64 trials following one warm-up trial. The experimental trials were evenly assigned to different conditions and were presented in a pseudo-randomized order, with no more than three consecutive trials from the same condition. Each warm-up trial was randomly assigned to a condition. The testing of each participant was divided into three days. On each day the participants took part in one TMS stimulation condition. The order of stimulation sites was counterbalanced across participants.

In each trial, line-drawings of a pair of objects were presented on the screen. On half of the trials (in the correct co-location condition), the pair of objects were co-located appropriately for interaction (Figure 4-1a). On the other half of the trials (the incorrect co-location condition), the active object was positioned in an orientation inappropriate to interact with the corresponding passive object, while the orientation of the passive object was maintained relative to the correct co-location condition (Figure 4-1b). In the active-left condition, the active objects were presented on the left side of the screen, while the passive objects appeared on the right side. In the active-right condition, the whole presentation was horizontally flipped from the corresponding active-left presentation. Though previous studies in our group did not find effects of object layout, we included object layout into analysis to account for any potential impact from the lateralized stimulation as well as the contralateral preferences of the stimulated cortical areas.

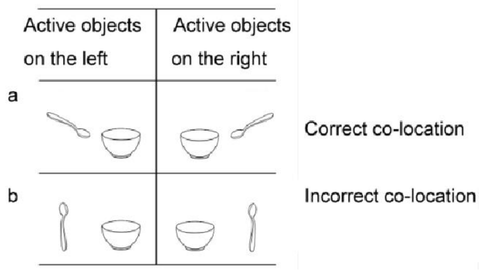

Figure 4-1. Example of the stimuli used in the experiments

At the beginning of each trial, a fixation point was presented at the centre of the screen for 400 ms. After this the fixation cross disappeared and the object pair appeared. After 240ms or 400ms a central circle or triangle target was presented (see Figure 4-2). The majority of the trials (75% of all) were with a 240ms SOA. The number of trials with 400ms SOA was reduced compared to the original procedure (Xu et al., 2015) in order to shorten the length of sessions while at the same time mimicking the variation of SOA, as in our previous experiments. The 400 ms SOA trials were treated as filler trials.

The target and the object pair remained on the screen until the participants made a response or for 1600 ms without response. Participants indicated whether the target was a triangle or a circle by using their left or right index finger to press the f or j key on a QWERTY keyboard. The stimulus–response mapping was counter-balanced across subjects. The participants were required to respond as quickly and accurately as possible, and feedback was given immediately when they failed to make responses within 1600ms after the target's onset or an incorrect response was made. Single hand responses were used here to ensure any interference from the TMS stimulation will be comparable to both effectors, since TMS were only delivered to the left hemisphere.

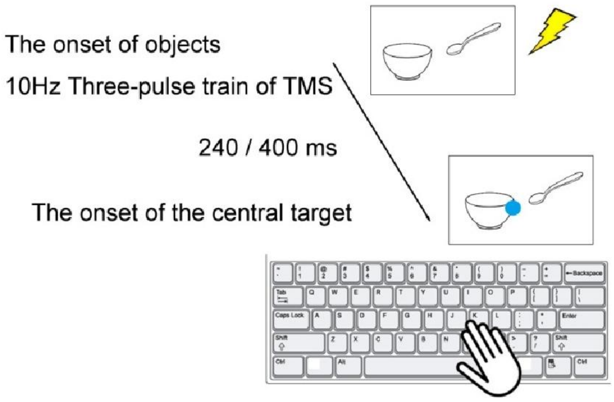

Figure 4-2. The procedure of a typical trial. The participants were required to make speeded key-press responses with the left or right index finger, according to the shape of the central target (in display 2). The responses made by the finger on the same side with the active objects (middle finger response in this figure) were considered aligned with the active objects and responses on the other side (index finger response in this figure) were aligned with the passive objects.

As in our previous study, we assessed the effects of implied between-object actions by comparing the correct co-location condition with the incorrect co-location condition (baseline). For example, take the correct co-location condition when the active objects were presented on the left side (left panel in Figure 4-1a). Here a right response to the shape would be aligned with a response afforded by the passive object (the bowl). Whether the implied between-object actions modulated this response was tested by comparing responses against a baseline when a right response was required and the orientation of the active object (the spoon) was incorrect for any interaction between the objects (left panel, Figure 4-1b).

In the present study, we always presented passive objects in their typical orientation, but varied the orientation of the active objects to manipulate the co-location between objects. The contrast across the co-location conditions on the response aligned with the passive objects (slowed down in the correct co-location condition) provides robust evidence for the inhibitory effects of the interacting objects on responses evoked by the passive objects (Xu et al., 2015). This inhibitory effect, and the advantage of active objects in the correct co-location condition compared to the passive objects, are the contrasts of interest in the present study.

4.1.6 TMS Procedure

A Magstim Rapid2 stimulator (MagStim, Whitland, UK) with a 70-mm figure of 8 coil was used to deliver TMS to three cortical sites: (1) the most anterior region of the IPS in the left hemisphere (aIPS) (2) the lateral occipital complex (LOC) in the left hemisphere, and (3) Vertex as a control site. A high-resolution three-dimensional volumetric structural magnetic resonance image (MRI) was obtained for each subject (3 T magnetic resonance imaging scanner; Philips, Aachen, Germany), and the cortical surface was displayed as a three-dimensional representation using Brainsight Frameless Stereotaxic software (Rogue Research, Montreal, Quebec, Canada). aIPS and LOC, defined for each participants separately as described below, was demarcated on his or her three dimensional image using the same software. The position of the coil and the subject’s head were monitored using a Polaris Optical Tracking System (Northern Digital, Waterloo, Ontario, Canada). Positional data for both rigid bodies were registered in real time to a common frame of reference and were superimposed onto the reconstructed three-dimensional MRI of the subject using the Brainsight software (Rogue Research). Thus, the center of the coil (the stimulation locus) was continuously monitored to be over the site of interest. For all sites, the TMS coil was held tangential to the surface of the skull. An adjustable frame was used to hold the TMS coil firmly in place, while the participants rested their head on a chin rests. Head movements were monitored constantly by Brainsight and were negligible.

Stimulation intensity was set at 60% of the maximum intensity of the stimulator. On each trial, the participants received a 10-Hz train of three pulses simultaneous with the onset of the object pair. Previous studies have shown that this protocol is successful for showing interfering effects (e.g., Mevorach, Hodsoll, Allen, Shalev & Humphreys, 2010). The train of

TMS pulses is not delayed according to the afferent delay (the latency between stimuli onset and the information reaching corresponding neurons) for the object pairs, so that all three pulses can be fitted into the 240 ms SOA, and will not temporally overlap with the onset of the target. Such synchronization between stimuli onset and TMS stimulation has been found effective in generating interference effects in parietal areas (Chang, Mevorach, Kourtzi, & Welchman, 2014).

4.1.7 Localization of brain sites for TMS

LOC A full-brain high-resolution anatomical image along with a region of interest localiser imaging data for the participants were acquired for each participant at the Birmingham University Imaging Centre using a 3-tesla Philips MRI scanner with an eight-channel head coil. Blood oxygen level–dependent signals were measured with an echo-planar sequence (TE 35 ms; TR 2000 ms; 2.5 × 2.5 × 3 mm, 32 slices). fMRI data were analysed with BrainVoyager QX (BrainInnovation, B.V.). For each participant, we transformed the anatomical data into Talairach space. Functional data were preprocessed using three-dimensional motion correction, slice time correction, spatial smoothing (5 mm), linear trend removal and high-pass filtering (three cycles per run cut-off). The lateral occipital complex (LOC) was defined using standard procedures that have been described elsewhere (Preston, Kourtzi & Welchman, 2009). The average Talairach coordinates of LO was [-43, -66, -4], with 95% CI [-45, -41], [-69, -63], and [-6, -2], respectively.

aIPS We localized aIPS by structural landmarks, i.e. the junction between the anterior extent of the IPS and the inferior postcentral sulcus, on individual anatomical images. This was shown to be effective in defining aIPS (Rice et al., 2006, Davare et al., 2010, Cohen et al., 2009). Stimulation loci were superimposed onto the reconstructed three-dimensional MRI image of each subject using the Brainsight software. The average Talairach coordinates of the aIPS were Talairach coordination [-37, -39, 41], with 95% CI [-39, -35], [-42, -37], and [38, 44], respectively. This is within the confidence range of the left aIPS collated from recent fMRI studies which reported activation in aIPS in action/grasping related tasks (Frey et al., 2005).

Cz Cz was defined individually by the point of the same distance to left and right pre-auriculars, and of the same distance to the nasion and Inion.

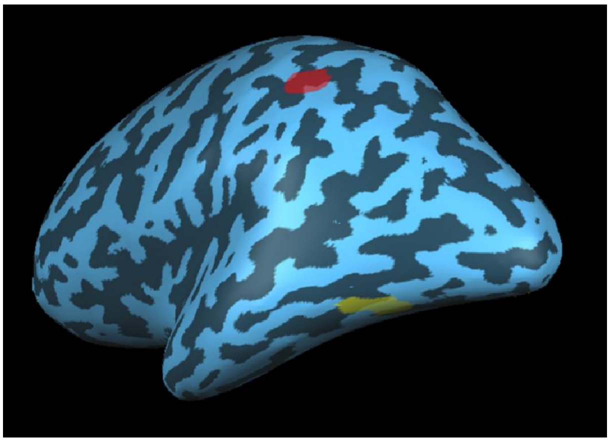

Figure 4-3. Stimulation sites. A three dimensional inflated rendering of one subject's structural MRI in BrainVoyager QX, illustrating the cortical sites chosen for stimulation. Red area: left aIPS. Yellow area: left LO.

4.2 Results

Participants were highly accurate, with the average accuracy of the different conditions between 97.75% and 99.65% (mean 98.64%, mean RT = 387 ms, see Table 1). RTs were initially trimmed to remove responses quicker than 100 ms. RTs more than 2.5 standard deviations from the mean of each participant were then discarded in a non-recursive manner. Discarded trials were fewer than 2% of the total trials.

The RT data were initially entered into an analysis of variance (ANOVA) with co-location (correct vs. incorrect), object layout (active-left vs. passive-left), response compatibility (with active objects vs. passive objects) and TMS location (Cz, aIPS and LO) as within-subjects factors. Besides the standard analysis of RT data, we were particularly interested in two contrasts. They are (a) responses aligned with passive objects in the correct vs. the incorrect co-location conditions, and (b) responses aligned with active objects vs. with passive object in the correct co-location condition. Xu et al (2015) found that the responses aligned with the passive objects in the correct co-location condition were slower than in incorrect co-location condition, and that responses aligned with active objects were quicker than those aligned with the passive objects in correct co-location condition. In the present study, we examine whether these two contrasts were affected in each stimulation condition.

There was a significant main effect of response compatibility, $F(1,15) = 15.88$, $p = .001$, $\eta^2 = 0.51$, and a marginally significant main effect of co-location, $F(1,15) = 3.45$, $p = .083$, $\eta^2 = 0.19$. There was a interaction between co-location and response compatibility, $F(1,15) = 11.33$, $p = .004$, $\eta^2 = 0.43$, a interaction between object layout and stimulation site, $F(2,14) = 4.29$, $p = .035$, $\eta^2 = 0.38$, a marginally significant interaction between co-location and stimulation site, $F(2,14) = 3.19$, $p = .072$, $\eta^2 = 0.31$, and a significant four-way interaction (TMS location, co-location, layout and response compatibility), $F(2,14) = 4.11$, $p = .039$, $\eta^2 = 0.37$. The three-way interaction of interest between TMS location, co-location, and response compatibility was not significant, $p = 0.158$. None of other main effects or interaction was significant.

Table 4-1: Average accuracy and reaction times (RTs) of each condition

Stimulation site	Layout (active objects on the left or right)	Response compatibility (passive vs. active objects)	Accuracy	RTs (ms)
Cz	Correct co-location			
	Left	Passive	0.98	397
		Active	0.99	386
	Right	Passive	0.98	386
		Active	0.99	381
	Incorrect co-location			
	Left	Passive	0.98	394
		Active	0.98	384
	Right	Passive	0.98	383
		Active	0.99	389
aIPS	Correct co-location			
	Left	Passive	0.98	395
		Active	0.98	378
	Right	Passive	0.98	386
		Active	0.99	387
	Incorrect co-location			
	Left	Passive	0.99	386
		Active	0.99	386
	Right	Passive	0.98	386
		Active	0.98	385
LO	Correct co-location			
	Left	Passive	0.99	393
		Active	1.00	386
	Right	Passive	0.99	391
		Active	0.99	387
	Incorrect co-location			
	Left	Passive	0.98	388
		Active	0.99	383
	Right	Passive	0.99	386
		Active	0.99	387

To examine the overall interaction, we conducted a separated three-way ANOVA for each TMS location.

Cz condition

In the Cz condition, the main effect of layout was significant, $F(1,15) = 10.44$, $p = .006$, $\eta^2 = .410$. Responses were quicker when the active objects were presented on the right side (MD = 5 ms). The main effect of response compatibility was also significant, $F(1,15) = 7.89$, $p = .013$, $\eta^2 = .35$. Responses aligned with the active objects were quicker than those aligned with the passive objects (MD = 5 ms). There was a significant interaction between co-location and response compatibility, $F(1,15) = 4.94$, $p = .042$, $\eta^2 = .25$. None of other interactions was significant. Analysis of simple effect revealed that there was a marginally significant inhibitory effect of correct co-location on responses aligned with the passive objects ($RT_{correct\ co\text{-}location} > RT_{incorrect\ co\text{-}location}$, MD = 3 ms, $p = .055$), while the difference between the correct and the incorrect co-location conditions was not significant for responses aligned with the active objects ($p = .18$). In addition, in the correct co-location condition, responses aligned with the active objects were quicker than those aligned with the passive objects (MD = 8 ms, $p = .002$), while the effect of response compatibility was not significant when the co-location was incorrect ($p = .32$). The interaction between co-location, response compatibility and object layout was not significant ($p = .20$). Hence, the results in the Cz condition replicated the findings by Xu et al. (2015).

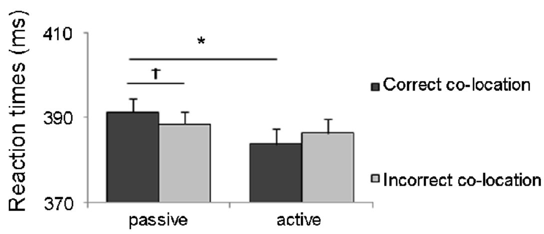

Figure 4-4. Results of Cz condition. Responses aligned with the passive objects were slower in correct co-location condition than in incorrect co-location condition. Responses aligned with active objects were quicker than those aligned with passive objects in the correct co-location condition. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

aIPS condition

For the aIPS condition, the main effect of response compatibility was significant, $F(1,15) = 10.62$, $p = .005$, $\eta^2 = .42$. Responses aligned with the active objects were quicker than those aligned with passive objects (MD = 5 ms). There was an interaction between co-location and response compatibility, $F(1,15) = 15.54$, $p = .001$, $\eta^2 = .51$, and an interaction between co-location, response compatibility and layout, $F(1,15) = 8.31$, $p = .011$, $\eta^2 = .36$.

None of other interaction was significant. A simple effect analysis revealed a significant inhibitory effect of co-location on responses aligned with the passive objects when the active objects were presented on the left side, ipsilateral to the stimulation ($RT_{correct\ co\text{-}location} > RT_{incorrect\ co\text{-}location}$, MD = 10 ms, p = .003), but not when the active objects were presented contralateral to the stimulation (p = . 74). Meanwhile, responses aligned with active objects ipsilateral to the stimulation were quicker in correct co-location condition than in incorrect co-location condition (MD = 8 ms, p = .024, η^2 = .30), but this effect was absent when the active objects were presented contralateral to the stimulation (p = 0.46). In addition, the advantage of active objects over passive objects in the correct co-location condition was only evident when the active objects were presented ipsilateral to the stimulation (MD = 12 ms, p = .002), and was absent when the active objects were contralateral to the stimulation (p = .22), or when the co-location was incorrect (p = .23 for ipsilateral active objects and p = .11 for contralateral active objects). Hence, when active objects were presented ipsilateral to the stimulation we replicated Xu et al.'s (2015) findings, but when the stimulation was contralateral to the active objects, both effects of implied between-object actions disappeared (see Figure. 4-5).

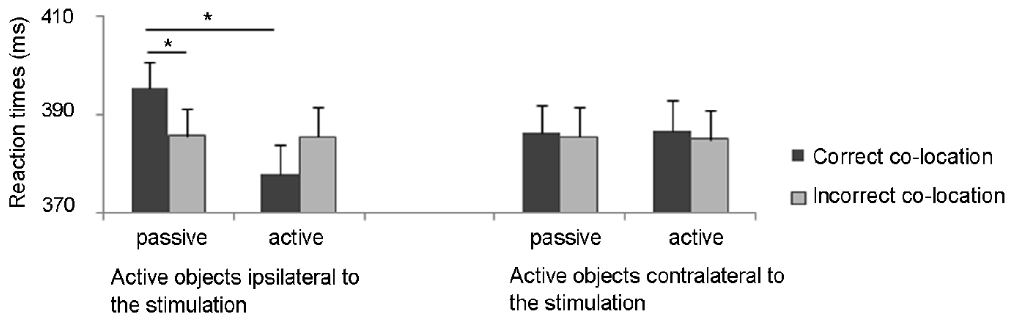

Figure 4-5. Results of the aIPS stimulation condition. When the active objects were presented ipsilateral to the stimulation, there was an inhibitory effect of implied action over responses aligned with passive objects (slower RTs in correct co-location condition than in incorrect co-location condition when the response were compatible with the passive objects), and an advantage of responses aligned with active objects over passive objects in correct co-location condition (shorter RTs when the responses were compatible with active objects than those compatible with passive objects in correct co-location condition). However both effects were absent when the active objects were presented contralateral to the stimulation. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

LO stimulation

For LO stimulation, the main effect of layout was not significant (p = .68). However, the main effect of response compatibility was significant, $F(1,15) = 5.20$, $p = .038$, $\eta^2 = .26$. Responses aligned with the active objects were quicker than those aligned with the passive objects (MD = 4 ms). The main effect of co-location was significant, $F(1,15) = 6.21$, $p = .025$, $\eta^2 = .29$, responses in correct co-location condition were slower than in incorrect co-location condition (MD = 3 ms). The interaction between co-location and response compatibility was not significant (p = .29), nor was the interaction between co-location, response compatibility and object layout (p = .45). However, because of the pre-defined contrasts of interest, we still conducted one-tailed pairwise comparisons between the conditions of interest. There was an inhibitory effect over responses aligned with passive objects; responses aligned with passive objects were slower in the correct co-location condition than in the incorrect co-location condition (MD = 5 ms, p = .032), and this effect was significant or marginally significant regardless whether the active object was ipsilateral (MD = 5 ms, p = .042) or contralateral

(MD = 5 ms, *p* = .054) to the stimulation. In addition, there was an advantage for responses aligned with active relative to those with passive objects; responses aligned with the active objects were quicker than those aligned with passive objects (MD = 6 ms, *p* = .016) in the correct co-location condition. We also evaluated whether layout modulated the advantage for active objects under LO stimulation. However, the advantage of active objects in the correct co-location condition was not significant (*p* = .14 when the active objects were ipsilateral to the stimulation and *p* = .23 in the other layout condition). In summary, the effects of implied between-object actions persist under the LO stimulation condition.

Further, to examine whether the layout effect observed with aIPS stimulation also existed with LO stimulation, we separately tested the contrasts of interest in different object layouts (when the active objects were presented contralateral or ipsilateral to the stimulation) in LO data, though layout was not involved in the interaction between co-location and response compatibility in LO analysis. We found that the inhibitory effect on passive objects was significant or marginally significant when the active object was ipsilateral (MD = 5 ms, p = .042) and contralateral (MD = 5 ms, p = .054) to the stimulation (Figure 7). However, the advantage of the active objects in the correct co-location condition was not significant when the active objects were ipsilateral to the stimulation (p = .14) or contralateral to stimulation (p = .23; Figure 4-7), probably due to the reduced number of trials in each condition. This illustrates the different pattern of responses in LO and aIPS stimulation condition, and might be an important source of the four-way interaction reported in the overall analysis (p.78).

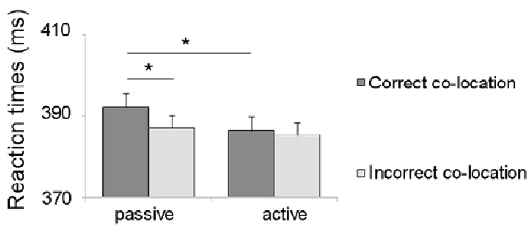

Figure 4-6. Results of LO condition. Revealed by planned contrasts, there was an inhibitory effect of implied action over responses aligned with passive objects (slower RTs in the correct co-location condition than in the incorrect co-location condition when the responses were compatible with the passive objects), and there was an advantage for responses aligned with active objects over passive objects in the correct co-location condition (shorter RTs when the responses were compatible with active objects than when they were compatible with passive objects in the correct co-location condition). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pre-planned pairwise one-tailed comparisons is denoted on the figure (a = .05).

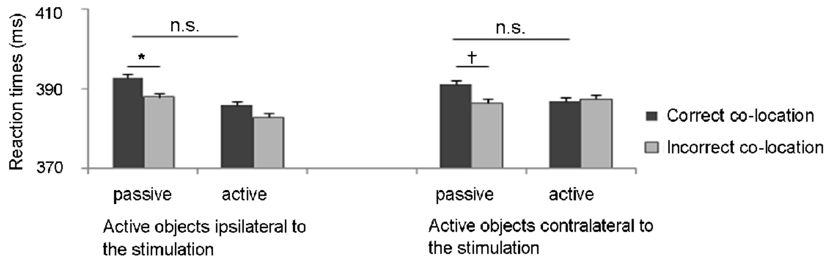

Figure 4-7. Though there is no evidence of layout effect, to examine whether the layout effect observed with aIPS stimulation existed with LO stimulation, we conducted planned pairwise analysis of the LO stimulation condition for each layout condition. For the active objects ipsilateral as well as contralateral to the stimulation, there was an inhibitory effect of implied action over responses aligned with the passive objects (slower RTs in the correct co-location condition than in the incorrect co-location condition when the response were compatible with the passive objects). In addition, in both layout conditions, there was a trend (but not statistically significant) of the advantage of responses aligned with the active objects over the passive objects in the correct co-location condition (shorter RTs when the responses were compatible with the active objects than those compatible with the passive objects in the correct co-location condition). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significances were obtained in one-tailed pairwise comparisons (a = .05, † indicates .05 < p < .10).

The dissociation between impact of LO and aIPS stimulation was apparent in the different patterns reported above. Further, it was confirmed by a combined analysis including data from both stimulation conditions. The four-way interaction between TMS location, co-location, object layout and response compatibility was significant, $F(1, 15) = 7.40$, $p = .016$. $\eta^2 = .33$.

4.3 Discussion

We investigated the influence from the ventral and the dorsal visual streams on the processing of implied between-object actions. As in a previous study (Xu et al., 2015) we found that responses to passive objects, as indexed by following discrimination RTs, were inhibited when objects were positioned correctly for action relative to when they were not correctly positioned for action. This is consistent with competition taking place between the affordances offered by the stimuli, and with the affordance to the passive object (incompatible with the action to the object pair) being suppressed by the competition. Effects of stimulating the dorsal (aIPS) or ventral visual stream (LOC) were examined. A dissociation was found whereby TMS to the aIPS, but not the LOC, reduced the effects of affordance set up by paired objects implying interactions, indexed by following discrimination RTs. Note that the aIPS stimulation only affected the effect when the active objects were presented contralateral to the stimulation. Our results suggest that aIPS plays an important role in generating the effects of implied actions on response selection with object pairs.

4.3.1 The Role of Ventral Stream

In contrast to the evidence for dorsal stream involvement, the present study did not provide strong evidence for a contribution of ventral-pathway processing to the response selection effect with paired objects. The absence of LOC stimulation effect in our study appears to be at variance with previous findings reporting activation change in LO during processing of implied actions between objects (e.g. Kim & Biederman, 2010; Kim, Biederman & Juan, 2011; Roberts & Humphreys, 2010b). However, in those studies the participants were engaged in tasks relevant to the identification of objects (repetition judgements, Kim & Biederman, 2010; object categorization, Roberts and Humphreys, 2010b; and object identification, Kim, Biederman & Juan, 2011). These tasks require the retrieval of semantic knowledge of the objects to different degrees, which might have engaged the ventral pathway to a greater extent than tasks such as ours where performance on the imperative task was determined by response compatibility with the objects. This might have "weighted" the task towards activation within the dorsal stream.

4.3.2 Dorsal contribution to the processing of implied actions

We found that TMS to aIPS reduced the effects of affordance of paired objects, as indexed by following discrimination RTs, on responses to paired objects. This is consistent with most known functions of aIPS. aIPS is thought to play a critical role in action-oriented object processing, including online control of object-directed grasping (Binkofski et al., 1998; Culham et al., 2003; Frey et al., 2005; Rice, Tunik, et al., 2006; Rice et al., 2007; Tunik et al., 2005), action observation (Shmuelof & Zohary, 2005), and passive viewing and naming manipulable compared to non-manipulable objects (Chao & Martin 2000; Chouinard & Goodale 2012; Mruczek, von Loga, and Kastner, 2013; Valyear, Cavina-Pratesi, Stiglick, & Culham, 2007). In addition to processing the affordance of a given object and planning simple prehensile actions, it has also been proposed that aIPS represents the goals of actions (Shmuelof & Zohary, 2005), and hosts context-specific information for action planning and execution (Tunik et al., 2007).

Of particular relevance to our research question about implied between-object actions, aIPS is reported to be involved in the execution of learned/skilful actions, including complex tool-use behaviours (for review see Johnson-Frey 2004; Lewis 2006). It is suggested that aIPS represents learned knowledge about how to "act with" tools (e.g., Buxbaum, 2001; Johnson-Frey & Grafton 2003, Valyear at al., 2007), as well as information about the hand postures and the critical structures of objects that are relevant to tool use (Buxbaum et al. 2003, 2006; Creem & Proffitt 2001; Daprati & Sirigu 2006; Goodale & Humphrey, 1998). For example, an increase in activation for familiar tools was observed relative to other graspable objects in aIPS and surrounding areas when participants were required to execute tool use actions (e.g., Fridman et al., 2006; Johnson-Frey et al., 2005); increased activation in aIPS has also been found when the participants make judgements regarding whether objects are co-located for action (see Bach, Peelen & Tipper, 2010). These results indicate that aIPS, and the surrounding areas, are involved in object utilization (Daprati & Sirigu, 2006; Buxbaum & Kalénine, 2010). In particular, Mruzek et al. (2013) reported that the left anterior IPS, which strongly prefers tools to animals and graspable objects, is isolated from the previous defined human parietal grasping region (hPGR). This suggests that the anterior aIPS represents information including experience-dependent knowledge of action associations, functions, and potential goals, over and above the mechanical graspability of objects.

The established functional role of aIPS in extracting affordance and representing skilled actions is consistent with Xu et al.'s (2015) hypothesis that the effects of implied between-object actions is based on the direct extraction of affordances of visually presented objects. aIPS stimulation might have interfered with affordance perception of the contralateral active objects, thus removing the advantage for active objects over passive objects, as well as the inhibition on passive objects in the correct co-location condition.

Admittedly, besides its involvement in processes related to actions, aIPS is also closely involved in salience-based selective attention. Activation in aIPS has been shown to be modulated by the relative perceptual salience of the target and non-target stimuli, reflecting the degree to which attention shifts away from a target because of a perceptually salient non-target, rather than by the top-down allocation of spatial attention (Geng & Mangun, 2009). The aIPS identified in Geng and Mangun's study (Talairach coordinations: [-32, -44, 45]) is slightly more posterior, dorsal and medial than our stimulation site (Talairach coordinations: [-37, -39, 41]). Thus our study and Geng and Manguan's might simply report functions of different areas, given the fine scale function topology of aIPS (Mruzek et al., 2013). Admittedly, this argument should be treated with caution due to the limited spatial resolution of TMS, and further study is needed to directly test the role of attention of the selection of paired-object affordance. However, the functional role of the aIPS in salience selection may not contradict our interpretation. The active object might have higher salience because of its strong affordance for action, and aIPS might respond to the implied between-object actions by extracting the unbalanced salience in the pairs of objects. This conjecture would fit with data on temporal order judgements, where the active member of an object pair tends to gain 'prior entry' (Roberts & Humphreys, 2010a).

Whichever the case, we maintain that the effects of implied between-object actions require the processing of affordance-based, information, and are not pure attentional effects produced by size differences and location differences between the active and the passive objects. This is because the size and location differences between active and passive objects were maintained across the correct and incorrect co-location conditions. Consequently, if these factors were critical, there should not be the inhibitory effect of implied action we observed here and in a previous study (Xu et al., 2015).

4.3.3 Distinction between Active and Passive objects

An interesting aspect of the aIPS stimulation effect here is that performance was modulated by the relative location of the active objects and the stimulation site; the interference from aIPS stimulation was only apparent when the active objects were presented contralateral to the stimulation. We consider the position of the active objects critical, because previous studies have found that the left aIPS has a preference to contralateral hand-object interactions in action observation (Shmuelof & Zohary, 2006), and that each aIPS shows a preference to contralateral acting hands during grasping (Binkofski et al., 1998; Culham et al., 2003; Johnson-Frey et al., 2005). In our paradigm, responses aligned with both active and passive objects were actually made by the same hand. However, in the correct co-location condition, the contralateral objects afford a response made by the hand contralateral to the stimulation, and so in the dominant visual field of the stimulated aIPS. Our results show that when there are contralateral active objects, the effects of implied actions were reduced, suggesting that the processing of the active objects is critical for the implied between-object actions to affect affordance selection. When the processing of the active objects is disrupted, the effects of the implied actions disappear.

The particular importance of active objects in generating the effects of implied between-object actions is consistent with the explanation of our previous studies (Xu et al., 2015). We suggested that there was suppression of the affordance to the passive object in order to support the preparation of the between-object actions, with the active object affording a more critical role in these actions, compared with the passive objects. By disturbing the processing of the active objects, this suppression in affordance selection disappears. The dominance of the active objects is also in line with previous conclusions drawn from studies looking at the effect of implied between-object actions on object identification, in which "a bias towards the active objects in an action context" (Roberts & Humphreys, 2011a) was reported. For instance, Riddoch et al. (2003) found that in those trials when extinction patients were only able to report one of the objects in the pairs, patients tended to report the active objects when the functionally related object pair was positioned for interaction.

4.3.4 The automaticity of the processing of implied action

One striking property of the effects of implied action is the contrast between the automaticity of the effect and the learnedness of the implied actions. These actions to objects are closely associated with specific function and abstract action intention, and they tend to be learned at a relatively late developmental stage. In the present study, all the object pairs involve man-made objects, and the functional action associated with the active objects are likely learned. However, once they are learned, not only the procedure and kinematic routine of the action is internalized, the capability of recognizing possibilities of these actions seems to be automated as well. We consider that reliance on the dorsal pathway for activation of the motor response to the objects might provide the foundation of this automaticity. The dorsal pathway has been speculated as less dependent on intentional modulation and visual awareness than the ventral pathway (Goodale & Westwood, 2004; Norman, 2002; Pisella et al., 2000; Schindler, Rice, McIntosh, Rossetti, Vighetto & Milner, 2004), and capable of carrying out skilled actions automatically. However, the present study does not address how the skilled tool-use actions are internalized, or the exact mechanism behind this automaticity. Further investigation is needed in this aspect.

4.4 Conclusion

The present study examined the contribution of the ventral and the dorsal visual streams to automatic prioritization of active over passive objects in response to implied between-object actions (Xu et al., 2015). We demonstrated that aIPS is crucial for implied between-object actions to affect response selection. We found that online TMS to the left aIPS reduced both the inhibitory effect on responses aligned with passive objects and the advantage for responses aligned with the active objects. These reductions only occurred when the active objects were contralateral to the stimulation. Stimulation of the left LO did not produce any distinctive effect. The results reinforced the suggestion that the effects of implied actions were based on competition between affordance to the objects.

Chapter 5

Knowing is not enough: newly learned interactions between manipulable objects do not affect affordance selection

Abstract

Prior evidence indicates that correctly positioning objects for interaction leads to two effects in affordance selection (Xu, Humphreys, & Heinke, 2015): (a) When the objects were positioned correctly for interaction, responses aligned with the “active” object (e.g. the spoon) were quicker than those aligned with the “passive” object (e.g. the bowl). (b) Presenting objects in the correct co-locations slowed down responses compatible with passive, but not active, objects. These results illustrated the striking automaticity of the extraction of implied action relations between objects. The present study examined how this automaticity develops. The participants learned new interactions between novel objects by either (a) observation (Experiment 1 - 3) or (b) observation and practice (Experiment 4). We compared the performance before and after training in (a) subjective judgment of action relations (Experiment 1), and (b) a response compatibility paradigm used in Chapter 2-4 (Experiment 2 and 4). Though change in subjective judgment task suggested that the participants were able to grasp the action relations between novel objects after observational learning, we did not find evidence of learning in the manual responses to the between-object actions implied by pairs of novel objects (Experiment 2 and 4), or to the affordance of single novel active objects (Experiment 3). The results revealed dissociation between the establishment of declarative knowledge and procedural knowledge of action relations between objects.

5.1 Introduction

One defining intellectual capability of human is the manufacture and using of complex tools (Ambrose, 2001). Tool use is a category of actions in which "the external employment of an unattached or manipulable attached environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself" (Beck, 1980). By definition, using a tool requires not only the knowledge and proficiency in tool manipulation, but also a comprehension of the tool's function and its interaction with other objects. Note that by defining the objects being used upon the other (e.g. a spoon in a spoon-bowl pair) as active objects and the other (e.g. the bowl) the passive objects, the relation between active and passive objects in paired-object studies resembles that between tools and their objects, and the active objects in a given object pair generally take the role of the tool, the passive its object. In this chapter we will examine the learning of tool-use behaviours by examining the establishment of novel interactions between unfamiliar active and passive objects. Previous studies suggest that human are remarkably sensitive to visual cues of actions between manipulable objects, such as those between tools and their objects. Riddoch and colleagues reported that visual extinction was reduced when patients were presented with a pair of objects correctly positioned for interacting in the form of one being used upon the other, relative to when the objects were positioned in co-locations preventing interaction (Riddoch et al., 2003). In neurologically intact observers, correctly co-locating active and passive objects (e.g. tools and their objects) for action improves the identification of briefly-presented objects, compared to when the objects are positioned incorrectly for interaction (Roberts & Humphreys, 2011a).

Chapter 2 revealed two effects of implied between-object actions in a response compatibility paradigm: an advantage for active objects when the two objects were presented as if in interaction, and an inhibitory effect on responses to the passive objects from a co-location conducive to interaction. Both effects suggest automatic prioritization of the active over the passive objects. One remarkable feature of these effects is their automaticity. The automaticity lies in two senses. First, the objects used as stimuli were completely task-irrelevant. The extraction of the implied between-object actions is done without task-related intention. In this sense the automaticity might be explained by the direct, involuntary manner of affordance extraction as suggested by Gibson (1979) and the previous observation of automatic effect of graspable objects in visuomotor areas (Chao & Martin, 2000; Grezes & Decety, 2002; Phillps & Ward, 2002; Tucker & Ellis, 1998). The more intriguing point comes with the fact the automaticity is achieved despite the learned nature of involved actions. All the object pairs used as stimuli in Chapter 2 consists of man-made objects, and none of the functional action associated with the active objects exists widely in the behavioural repertoire of untrained non-human animals (with a few exceptions, e.g. hammering resembles cracking with a stone, and a spoon might be used in a way kinetically similar to the chimpanzees' famous ant-fishing activity). The automatic effects on response selection found in Chapter 2 suggested that for these highly man-made objects and completely acquired actions, not only the procedure and the kinematic routine of the actions are internalized, the capability of recognizing possibilities of these actions seems to be automated as well, not requiring voluntary guidance and effortful retrieval. It is still not clear how such knowledge is internalized and automated, and the present study aims to answer this question.

In the present study, we examine whether action relations between objects can be learned by observational learning. Observational learning is a prevalent and effective way to learn new tool-use actions, in which the individual learns by watching an action being demonstrated, deliberately or not, by another individual. The evidence of observational learning in tool use, e.g. activation changes brought forth by observing the use of novel tools, has been observed in multiple brain areas involved in the representation of familiar tools. For instance, Weisberg, van Turennout, and Martin (2007) found that observing the usage of novel tools changes activity in areas representing various information about familiar tools:

their affordance (left intraparietal sulcus and premotor cortex), visual appearance (fusiform gyrus) and action understanding (middle temporal gyrus). These areas largely overlap with the neural network for skilled tool use (Chao & Martin, 2000; Johnson-Frey, 2004; Lewis, 2006). These results suggested observation as an effective training method to gain the previously novel objects "the conceptual status of 'tools'" (Weisberg, van Turennout & Martin, 2007). Converging results comes from Menz, Blangero, Kunze, and Binkofski (2010). They pushed the test of the efficiency of observational learning in tool use to a more extreme extent, by reducing the amount of training to merely watching a 3.7s video showing the functional use of novel tools. Still, they found change in activation in a left-lateralized network involving prefrontal, inferotemporal and parietal areas, as well as high accuracy in explaining the newly learned tool use action after training.

Though existing research provided valuable insight into the learning of novel tool-use actions, none of them directly examined whether and how the learning of tool functionality automates the extraction of action possibilities between tools and their correspondent objects. For instance, in both Weisberg et al. (2007) and Menz et al. (2010), the novel tools were presented with their objects during the learning of its functional use, however the effect of learning was assessed by contrasting the difference between viewing the videos of novel tool-use vs. familiar tool-use, both subtracted by a baseline in which the tools were presented in isolation. This contrast is appropriate for their respective research objective, which is to examine the neural activity associated with "tool understanding". However it cannot directly assess the difference between perception of action potentials between objects before and after the participants acquire the understanding of the potential actions between the objects. Moreover, in these studies the participants were usually required to deliberately process the visually presented tools to certain degree (object matching between different views in Weisberg, van Turennout, & Martin, 2007, and action understanding judgement in Menz et al., 2010). Consequently, the effect they reported might not be entirely spontaneous, unlike the automatic effects reported in Chapter 2, when the objects and their action relations were task irrelevant. Important for the purpose of the current chapter, it remains unclear how learning will affect the automatic processing of action potentials suggested by tools and their objects.

Another purpose of the present study is to examine the relation between the automatic extraction of implied actions and the mental representation of objects. It is well established that tools are represented not only by its visual features and conceptual identity, but also properties related to their functions and manipulation, the former being suggested by the change in BOLD signal in temporo-occipital category-specific areas when viewing tools, while the later is revealed by tool-specific activations in the frontal and posterior parietal cortex (Boronat, Buxbaum, Coslett, Tang, Saffran, Kimberg, & Detre, 2005; Canessa, Borgo, Cappa, Perani, Falini, Buccino & Shallice, 2008; Chao and Martin, 2000; Kellenbach Brett & Patterson, 2003; Lewis, 2006; Martin, Wiggs, Ungerleider & Haxby, 1996; Peran, Schnur, Tettamanti, Cappa & Fazio, 1999). The question follows as whether it is the conceptual representation or the action-related representation that supports the automated extraction of action relation between tools and its objects?

Worth noticing, the speeds of establishing the conceptual and action-related representations are different. Menz and colleagues (2010) found that the acquisition of visual/conceptual representation of tools is quick and highly efficient. They reported that after only one demonstration changes at the neural level is reflected in regions associated closely with the visual processing and semantic knowledge of tools (prefrontal and mediotemporal areas). In contrast, studies reporting learning-associated changes in regions more closely related to motor processes always involved longer training (3 training sessions with 5 – 10 mins in each session for each novel tool in Bellebaum, Tettamanti, Marchetta, Della Rosa, Rizzo, Daum & Cappa, 2013; 16 one-hour sessions for 64 novel shapes in Kiefer, Sim, Liebich, Hauk & Tanaka, 2007 and Weisberg et al., 2007; days to months in studies reporting modulation of tool use experience on mirror neuron systems, e.g. Arbib, Bonaiuto, Jacobs & Frey, 2009 and Ferrari, Rozzi & Fogassi, 2005). The current study will make use of the different speeds in building conceptual and motor representation of new tool-use actions. By limiting the training to almost the minimum level, we would like to address the following question: is the automaticity an emergent property of conceptual knowledge of the action, or an effect requiring not only the relative quick-to-learn declarative knowledge but also longer-term consolidation?

In the present study, we created 11 novel pairs of objects (see Appendix 5-B for a full list), each consisting of a tool-like active object and a passive object upon which the active object can be used to carry out one of the pre-designed functions: rotating, lifting, pushing and fitting in. In training, we showed participants videos of interactions being carried out with these object pairs. Before and after the training, the participants completed either a judgement task regarding the functional relation between the novel objects (Experiment 1), or Xu, Humphreys, and Heinke (2015)'s response compatibility task (Experiment 2 - 4). We compared task performance before and after the training sessions to see the effect of learning. We also contrasted familiar objects to novel objects to highlight any difference brought by long-term experience. We first examined whether after the training the participants can acquire declarative knowledge of the designed actions between the novel active and passive objects (Experiment 1). This serves also as a validation for the appropriateness of stimuli design and the effectiveness of our training sessions in conveying the idea of the designed between-object actions. Having established the validity of stimuli and the training method, we examined the influence of learning on affordance selection to paired novel objects (Experiment 2 and 4), and on the affordance extraction to the active objects alone (Experiment 3). We also explored the effect of hands-on experience on learning of novel tool-use actions (Experiment 4).

5.2 Experiment 1: Learning the actions by passive viewing

The first experiment examined the possibility of learning the conceptual knowledge of actions between novel manipulable objects by near-minimum amount of observation. The experiment includes a pre-training session, two 20 min-training sessions, and a post-training session.

In the pre- and post-training sessions we manipulated the correctness of co-location (correct vs. incorrect) and the object layout (active objects in the left and passive objects in the right visual field vs. vice versa), and created four conditions comparable to previous studies in which the effects of implied actions on affordance selection were established (Chapter 2). In the incorrect co-location condition, the orientation of the active objects was manipulated while the orientation of the passive object was maintained relative to the correct co-location condition. Examples of the stimuli are shown in Figure 2-1. To produce robust effects of implied between-object actions, in this chapter we only manipulated the orientation of the active, not the passive, objects in the incorrect co-location condition, same as in Chapter 3 and 4. The task in the pre- and post- training sessions was similar to the material evaluation in our previous study (supplementary materials of Chapter 2). In both the pre- and post-training sessions, the participants rated pairs of novel and familiar objects regarding (a) whether the action relations between the objects were familiar and apparent, and (b) whether, by changing orientation of the active objects in the incorrect co-location condition we effectively manipulated the implied actions between objects, (c) whether the objects presented on the left side reliably afford left hand responses and those on the right side right hand responses, and (d) the appropriateness of our assignment of active and passive objects.

In the training sessions only the novel object pairs were used. The participants watched videos showing the active objects being used upon the passive objects. A recognition test followed each video, making sure that the participants paid attention to the videos and they could associate the line drawings of the objects (to be used in the pre- and post-training sessions) to corresponding video representations.

We compared the ratings in the pre- and post-training sessions to examine whether the participants managed to learn the possible interactions between the novel objects by viewing video demonstrations. We were mainly interested in: (a) whether the action relations between novel objects were rated more familiar and apparent in post-training session relative to the pre-training session, (b) in post-training rating, whether, by changing orientation of the active objects in the incorrect co-location condition we effectively manipulated the perceived readiness of the actions between novel objects as we did between familiar objects, and (c) after the training, whether the participants were more likely to identify the active novel objects as “active” in each pair.

5.2.1 Methods

5.2.1.1 Participants

A group of volunteers (one male and 11 females, age range: 18-25y) from the University of Birmingham research participation scheme participated in Experiment 1. All participants are right-handed and have normal or corrected-to-normal vision. Participants gave informed consent and received course credits for their time.

5.2.1.2 Materials and Procedure

In Experiment 1, greyscale clip-art style images of 12 pairs of familiar objects and 11 pairs (originally 12, one discarded because the rating in Question 5 [see below] indicates its inappropriateness. See Appendix 5-C for details of itemwise analysis of the novel objects) of novel objects constructed for the present study. All object images were presented on a light grey background (240, 240, 240 RGB). Each object images subtended 3.2°×3.2° of visual angle. The relative sizes of the objects within each pair matched their relative sizes in real life.

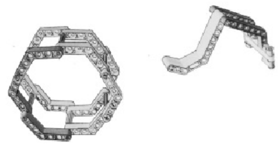

Figure 5-1. An exemplar pair of novel objects, the object on the right is the active object. It is used to rotate the passive objects.

The familiar objects had been used in previous chapters and had been found effective in evoking automatic prioritization of active over passive objects in the paradigm used in following experiments (for a full list, see Appendix 5-A). The novel objects were constructed with Lego blocks and plasticine. They were designed as pairs, with one (active) object designed to be used upon the other (passive) one to carry out one of the four possible functions: rotating, lifting, pushing and fitting in (See Figure 5-1 for exemplar objects, and see Appendix 5-B for a full list). The spatial extent of the novel objects was similar to that of the familiar objects (average size of the objects by pixels: familiar objects: 63×49; novel: 60×55), and for both categories of object pairs their centres overlapped with the centre of the screen.

The pre- and the post-training sessions were conducted on different days, separated by 0-2 days. Each session consisted of five blocks. In each of the first four blocks each object pair was presented in four variations (as shown in Figure 5-1), and each variation was evaluated in one trial, resulting in 96 trials per block. The variations were generated by manipulating orthogonally the object layout (active-left and active-right) and the co-location (correct and incorrect co-location condition). In this way, we replicated all the possible displays of a given pair in the response compatibility task in Experiment 2 and 4. In each trial, the object pair was presented at exactly the same location and of the same size as they would be in Experiment 2 and 4, and the questions were presented below the images. The participants were asked to answer the questions on a five-point scale, ranging from "*1: definitely No*" to "*5: definitely Yes*". In the last block, the objects were presented always in the correct co-location. Consequently each object pair was presented only twice, once with the active object on the left side and once on the right side of the screen. The participants evaluated the distinction between active and passive objects in each object pair by indicating which one is more likely to be used upon the other one, and the responses were coded as 1 for the left object and 2 for the right object. Through all five blocks, the object pair, the question and the choices remained on the screen until a response was made.

In each block the participants evaluated all object pairs and their variations according to a same question. The order of the questions was constant, but the order of object pairs within each block varied across blocks and participants.

The five questions served four main purposes:

a. **Familiarity of the action relation** Regarding whether the objects in each pair are typically involved in certain action relation, and whether the action relations between objects were recognized in the incorrect co-location condition :

   Are these objects typically used together?

   This question was for block 1.

b. **Readiness of interaction** Regarding whether the co-location between objects is appropriate for an implied between-object action in the correct co-location condition but not in the incorrect co-location condition:

   Are these objects appeared to be currently used together? Or, are they positioned properly or likely to be used together?

   This question was for block 2.

c. **Object affordance** Regarding whether the assumption is valid that objects presented on the left side afford left-hand responses while objects presented on the right side afford right-hand responses:

   When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?

When the pair of objects are located in the way they are located on the screen, and you are going to use them together, which hand are you going to use if you are going to handle the object on the left side of the screen?

These two questions were for block 3 and 4 respectively.

d. **Distinction between active and passive objects** regarding which object in each pair was active. The question was presented as:

When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right one, and press 2 if the right object is going to be used upon the left one.

Each question was verbally explained to the participants and the participants only began answering the questions after they confirmed that they understood each question clearly. Especially, for Question b, it was explained to the participants that the question asked whether they perceive the co-location between objects were conducive to interaction or not, and the "Or," in Question b leads an alternative expression for the same question rather than a different question.

The two training sessions were identical, with the order of trials varied. In the training sessions the participants watched videos, each depicting a pair of novel objects showing the active object being used upon the passive object when they were presented correctly, or a video showing the objects being picked up and then put down without any interaction between them when the two objects were incorrectly co-located. The participants were informed that a recognition test will follow each video, in which they need to identify which two objects were just presented. Each pair of novel objects was presented four times in each training session, the layout of the objects and their co-location manipulated orthogonally. The average length of videos is 16.7s (SD = 2.1). After each video, four line drawings (consisting of the two objects in the previous video and two novel objects randomly picked from the pool) will be presented on the screen and the participants were required to pick which two just appeared. The participants would receive immediate feedback when the choice was wrong, which rarely happened. One training session will be conducted immediately after the pre-training session and the other one immediately before the post-training session, separated by brief breaks.

5.3.2 Results and Discussion

Considering the nature of our data, we conducted median based non-parametric analysis to test our main hypotheses, i.e. (a) whether the action relations between novel objects will be rated more familiar and apparent in post-training relative to pre-training session, (b) in post-training rating, whether, by changing orientation of the active objects in the incorrect co-location condition we effectively manipulated the implied actions between novel objects as we did between familiar objects, (c) whether the participants reliably consider the objects afford actions by the hand spatially aligned with them, and (d) after training, whether the participants were more likely to identify the active novel objects as "active" in each pair.

Additionally, we used mean-based parametric (ANOVA) methods to investigate the interaction between factors. The application of parametric method on data from Likert scale has been suggested acceptable (Norman, 2010).

Familiarity of the action relation The familiar objects were evaluated as typically involved in interaction, and this perception persisted when the two objects were presented in the incorrect co-location, while the evaluation of the novel objects did not show such conviction in either co-location condition. In response to the question "*Are these objects typically used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the median of response score to the correctly and incorrectly co-located familiar object pairs significantly diverted from the mid-point, in both pre- and post-training sessions. In contrast, for the novel objects, the ratings only significantly differed from the mid-point after training (shown in both non-parametric and parametric tests. For detail and exact statistics, see Table 5-1). For the familiar objects, the rating for the correct and the incorrect co-location conditions did not differ from each other in both pre- and post-training sessions. For the novel objects, both correctly and incorrectly positioned object pairs were rated higher in the post-training session than the pre-training session (shown in both non-parametric and parametric tests, for detail and exact statistics, see Table 5-3). To illustrate the distinct patterns of training on the familiar and novel object pairs, we used repeated-measures ANOVA on the ratings of this question. The mean rating scores in each condition of each participant were entered into the analysis, with object type (familiar vs. novel), session (pre- vs. post-training) and co-location (correct vs. incorrect) as within subject factors. We found that there was a main effect of object type, F (1, 11) = 39.00, p < .001, η^2= .78, rating for the familiar objects being higher than for novel objects (MD = 0.91). There was a main effect of session, F (1, 11) = 46.91, p < .001, η^2 = .81, rating in post-training session being higher than in pre-training session (MD = 0.91). There was a main effect of co-location, F (1, 11) = 5.21, p = .043, η^2 = .32, rating for the correct co-location being higher than the incorrect co-location (MD = 0.05). The interaction between object type and session was significant, F (1, 11) = 29.13, p < .001, η^2 = .73. Simple effect analysis suggested that the difference between pre- and post-training sessions existed only in the rating of novel objects (MD = 1.31, p < .001), but not in those of familiar objects (p = .13). The interaction was illustrated in Figure 5-2.

Table 5-1*:* The median ratings for familiarity of action relations

		Mean	SD	Median	Wilcoxon rank test: difference between 3 (mid-point of the scale)
Familiar objects					
Pre-training	Correct co-location	4.87	0.15	5.00	>.001
	Incorrect co-location	4.80	0.25	5.00	>.001
Post-training	Correct co-location	4.93	0.13	5.00	>.001
	Incorrect co-location	4.95	0.13	5.00	>.001
Novel objects					
Pre-training	Correct co-location	3.45	0.66	3.25	.070
	Incorrect co-location	3.36	0.71	3.00	.111
Post-training	Correct co-location	4.56	0.55	5.00	.002
	Incorrect co-location	4.51	0.55	5.00	.002

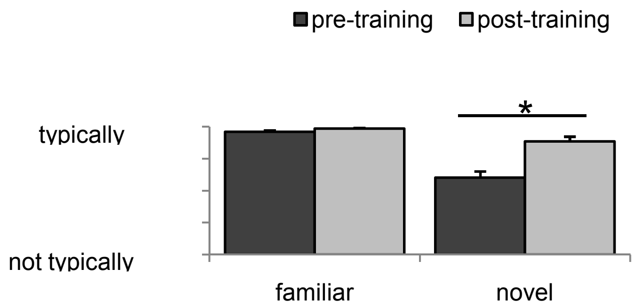

Figure 5-2. Rating on action familiarity in Experiment 1. The rating of action relation familiarity increased for novel objects after training, and remained high in both pre- and post-training sessions for familiar objects. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

Readiness of interaction Manipulating the orientation of active objects significantly affected the perception of implied interaction for familiar objects in both pre- and post-training sessions and for novel objects in post-training sessions. In response to the question "*Are these objects appeared to be currently used together? Or, are they positioned properly or likely to be used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the median of response score to the correctly co-located familiar object pairs significantly diverted from the mid-point to the direction of *Yes*, while for the incorrectly co-located familiar object pairs the responses significantly diverted from the mid-point to *No*, in both pre- and post-training sessions (Table 5-2). In contrast, for the novel objects, the rating did not significantly divert from the mid-point when the objects were presented correctly in pre-training session, but significantly diverted to the *No* direction when incorrectly presented. In the post-training sessions, novel objects in the correct co-location condition were rated significantly different from mid-point towards the direction of *Yes*, while for the incorrectly co-located object pairs the responses significantly diverted from the mid-point to *No*, replicating the rating pattern of familiar objects (shown in both non-parametric and parametric tests, for detail and exact statistics, see Table 5-2). Paired comparison confirmed that the training sessions increased the interaction-readiness rating for novel objects when they were presented in the correct co-location, but not when they were in the incorrect co-location. Though the novel objects were rated more likely to imply interactions in the correct than in the incorrect co-location condition both before and after training, the mean difference was larger in post-training session than in pre-training session. Training did not affect the ratings of familiar objects in either co-location condition, or in either session (shown in both non-parametric and parametric tests, for detail and exact statistics, see Table 5-2). To illustrate the distinct patterns of training effects on the familiar and novel object pairs, we applied repeated-measures ANOVA on the ratings of this question. The mean rating scores in each condition of each participant were entered into the analysis, with object type (familiar vs. novel), session (pre- vs. post-training) and co-location (correct vs. incorrect) as within subject factors. We found a main effect of object type, F (1, 11) = 36.20, p < .001, η^2 = .77, rating for the familiar objects being higher than for novel objects (MD = 0.58). There was a main effect of session, F (1, 11) = 10.63, p = .009, η^2 = .49, rating in the post-training session being higher than in pre-training session (MD = 0.37). There was a main effect of co-location, F (1, 11) = 121.33, p < .001, η^2 = .92, rating for the correct co-location being higher than the incorrect co-location (MD = 1.20). The interactions were significant between object type and session, F (1, 11) = 10.25, p = .008, η^2 = .48, object type and co-location, F (1, 11) = 114.48, p < .001, η^2 = .91, session and co-location, F (1, 11) = 5.55, p = 038, η^2 = .34, and all three factors, F (1, 11) = 12.16, p = .005, η^2 = .53. Simple effect analysis suggested that the difference between pre- and post-training sessions existed only in the ratings of novel objects when their co-locations were correct, with training increasing the rating of interaction readiness (MD = 1.10, p = .003), but not that of familiar objects, or novel objects in the incorrect co-location condition (ps >.066). In addition, the interaction between object type and session was significant in the correct co-location condition, F (1, 11) = 15.72, p = .002, η^2 = .59, but not in the incorrect co-location condition (p = .18), suggesting training selectively affected the perception of implied actions in novel object pairs in the correct co-location condition. The interactions were illustrated in Figure 5-3.

*Object affordance***.** The association between object location and its affordance was evident across all conditions. In response to the question "*When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?*" on a five-point scale ranging from "*1: definitely left" to "5: definitely right"*, the overall likelihood of using the left hand for the object presented on the left side of the screen was significantly larger than for the objects presented on the right side of the screen, and the dissociation persisted in both the correct and the incorrect co-location conditions. The difference between ratings in the correct and the incorrect co-location conditions was not significant regardless of whether the objects were on the left or right side of the screen. The results were replicated by Chi-Square test (See Table 5-4 for detailed statistics).

Table 5-2: The median ratings for readiness for interaction

		Mean	SD	Median	Wilcoxon rank test: difference between 3 (mid-point of the scale)
Familiar objects					
Pre-training	Correct co-location	4.69	0.25	5.00	.001
	Incorrect co-location	1.84	0.45	1.50	.002
Post-training	Correct co-location	4.77	0.22	5.00	.001
	Incorrect co-location	2.11	0.63	2.00	.018
Novel objects					
Pre-training	Correct co-location	2.84	0.50	2.75	0.187
	Incorrect co-location	2.14	0.46	2.00	0.008
Post-training	Correct co-location	3.94	0.83	4.50	.012
	Incorrect co-location	2.17	0.70	2.00	.012

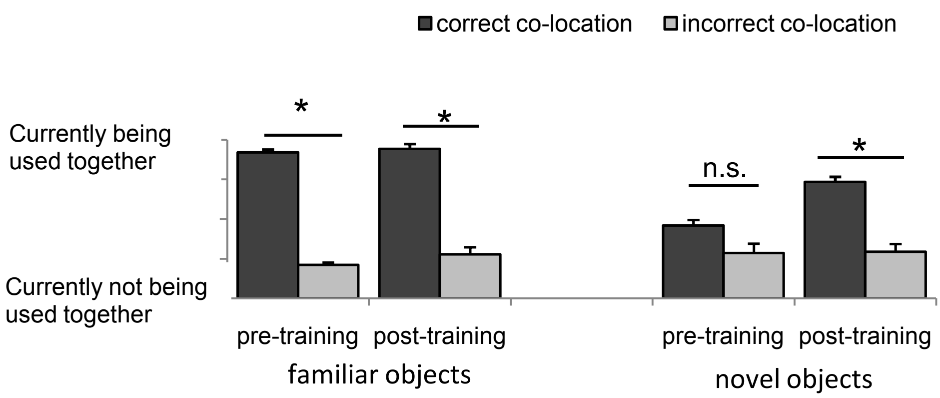

Figure 5-3. Rating of perceived readiness of interaction in Experiment 1: Training increased the perceived readiness of interaction between novel objects in the correct co-location condition. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

Table 5-3: Pairwise comparison between median ratings for familiarity of action relations and readiness for interaction

		t	df	Sig. (2-tailed)	Related sample Wilcoxon sign rank
Familiarity of action relations: effect of co-location					
Familiar objects	Pre-training	1.10	11	.295	1
	Post-training	-0.97	11	.352	1
Novel objects	Pre-training	1.70	11	.117	.157
	Post-training	0.91	11	.380	.655
Familiarity of action relations: effect of learning					
Familiar objects	Correct co-location	1.10	11	.295	1
	Incorrect co-location	-0.97	11	.352	1
Novel objects	Correct co-location	-5.95	11	>.001	.006
	Incorrect co-location	-6.71	11	>.001	.004
Readiness for interaction: effect of co-location					
Familiar objects	Pre-training	20.85	11	>.001	.002
	Post-training	14.25	11	>.001	.003
Novel objects	Pre-training	8.36	11	>.001	.024
	Post-training	4.44	11	.001	.011
Readiness for interaction: effect of learning					
Familiar objects	Pre-training	-1.49	11	.165	1
	Post-training	-2.04	11	.066	.109
Novel objects	Pre-training	-4.06	11	.002	.011
	Post-training	-0.16	11	.879	.655

Table 5-4: Pairwise comparison between mean ratings of object affordance

Affordance rating	t	df	Sig. (2-tailed)	Chi-Square significance (2-tailed)
Left vs. Right objects				
Overall	2.53	11	.028	.050
Correct co-location	2.55	11	.027	.026
Incorrect co-location	2.43	11	.027	.026
Correct vs. Incorrect co-location				
Object on the left side	1.71	11	.115	.109
Object on the right side	1.22	11	.248	.317

Active-passive distinction. The active-passive distinction between objects was evident for both familiar and novel objects, in both pre-training and post-training sessions. One sample t-test suggested that when the designed active objects were presented on the left side the participants tended to report that the left objects were active, while in swapped object layout the participants tended to report that the right objects were active objects in both pre- and post-training sessions for both familiar and novel objects. In response to the question "*When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right, and press 2 if the right object is going to be used upon the left one.* ", the median response when the active objects were on the left side was 1.07, SD = 0.05, when the active objects were on the right side 1.98, SD = 0.04. One sample t-test suggested that the ratings in each condition differed from mid-point towards the designed active objects in the pair, ps<.01 (see Table 5-5). According to our design the effect of learning should be shown by a larger difference in rating between different layout conditions in the post- than in the pre-training session. To examine this interaction, we subjected the rating into repeated-measures ANOVA on the ratings of this question. The mean scores in each condition of each participant were entered into the analysis, with object type (familiar vs. novel), session (pre- vs. post-training), object layout (active object on the left vs. active objects on the right), and co-location (correct vs. incorrect) as within subject factors. We found a main effect of object layout, F (1, 11) = 74.72, p < .001, η^2 = .78, rating for the object pairs with the active object on the left side being significantly lower than those with the active objects presented on the right side of the screen (MD = 0.78). The interactions were significant between object type and session, F (1, 11) = 10.59, p = .008, η^2 = .49 and between object type, session and object layout, F (1, 11) = 12.69, p = .004, η^2 = .54. None of other main effects and interactions reached significance (ps > .06). To break down the three-way interaction, and to examine separately whether the interested interaction between session and object layout existed for familiar and novel objects, we submitted mean ratings data of familiar and novel objects into separate two-way repeated-measure ANOVAs, with object layout and session as within-subject factors. The results suggested that for familiar objects, the interaction between object layout and session was not significant (p = .47), but the main effect of object layout was significant, F (1, 11) = 89.07, p < .001, η^2 = .89, with the rating lower when the active objects were on the left side than when they were on the right side (MD = 0.85). For novel objects, the results suggested that besides a significant main effect of object layout, F (1, 11) = 56.99, p < .001, η^2 = .84, active-on-the-left condition being rated lower than active-on-the-right condition (MD = 0.72), there was an interaction between object layout and session, F (1, 11) = 11.47, p = .006, η^2 = .51 (see Figure 5-4). Simple effect analysis suggested that the difference between object layouts was significant in both sessions (ps <.001), but the difference was bigger in post- than in pre-training session (MD = 0.63 in the pre-training session, and MD = 0.83 in the post-training session).

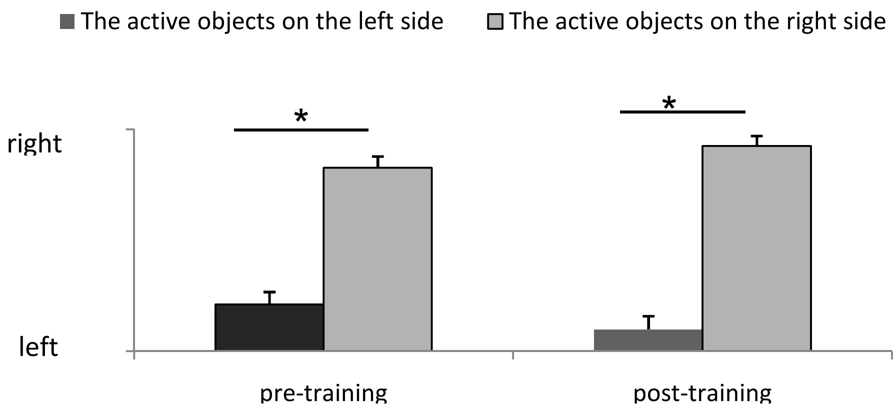

Figure 5-4. Rating of active-passive dissociation in Experiment 1. When the active objects were presented on the left side the choice of active objects were significantly biased towards the left objects, while the choice was biased towards the right object when the active objects were presented on the right side. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

The results of Experiment 1 suggested that by observing the designed actions, the participants managed to understand and remember the designed interaction between novel objects till the post-training test session. After training, their rating of novel objects regarding the appropriateness of between-object action and the readiness of interaction in the correct co-location, as well as the perception of the distinction between active and passive objects in each pair, resembled the perception of familiar, well-learnt object pairs. This suggested that the training was successful in conveying the declarative knowledge of novel action relations between novel objects.

Experiment 2 further studied whether the effect of learning can be reflected in affordance selection. The participants would make speeded left and right responses to an imperative central target, which was added on to task-irrelevant object pairs. Experiment 2 would compare participants' response to familiar and novel object pairs, and examine the effect of training (observing the designed action between novel objects) on the responses to novel object pairs.

Table 5-5: The choice of active objects in different conditions and the results of one-sample t-test of ratings in each condition with mid-point (1.5)

	Where is the active objects	Mean	SD	t	df	Sig (2-tailed)
Familiar objects						
Pre-training	Left	1.08	0.14	-10.54	11	< .001
	Right	1.94	0.12	12.15	11	< .001
Post-training	Left	1.12	0.21	-6.17	11	< .001
	Right	1.95	0.17	9.24	11	< .001
Novel objects						
Pre-training	Left	1.21	0.20	6.45	11	< .001
	Right	1.83	0.18	-6.71	11	< .001
Post-training	Left	1.10	0.21	9.18	11	< .001
	Right	1.92	0.16	-10.54	11	< .001

5.3 Experiment 2: Can the learned implied action affect response selection?

The paradigm we used to capture the effect of implied actions on response selection is the same as that used in Chapter 2. This task revealed two effects of actions with familiar action-related objects, i.e. the advantage for the active objects and the inhibitory on the passive objects. These effects were replicated in Chapter 3 and 4. In Experiment 2, we would use these two effects as an index of the establishment/acquisition of new actions afforded by the novel object pair. We were interested in a) whether the effects would be replicated by the familiar object pairs in both pre- and post-training sessions, and b) whether the training, i.e. observing the designed novel action twice, would produce similar effects for pairs of novel objects. The training sessions were the same as in Experiment 1, which has been demonstrated effective in establishing declarative knowledge of action relation between novel objects.

5.3.1 Methods

5.3.1.1 Participants

Fourteen healthy volunteers (two males, mean age 19 years) from the University of Birmingham research participation scheme were recruited in Experiment 2. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credits for their time.

5.3.1.2 Materials

The same images and videos of object pairs were used in Experiment 2 as in Experiment 1. In the pre- and post-training session, the line-drawings of a pair of objects were presented on the screen. In half of the trials (in the correct co-location condition), the pair of objects were co-located appropriately for interaction. On the other half of the trials (the incorrect co-location condition), the active object was positioned in an orientation inappropriate to interact with the corresponding passive object. In the active-left condition, the active objects were presented on the left side of the screen, while the passive objects appeared on the right side. In the active-right condition, the whole presentation was horizontally flipped from the corresponding active-left presentation. The spatial and color parameters of the stimuli were the same as in Experiment 1.

Other stimuli included a fixation cross subtending 0.8°×0.8° of visual angle and two response targets (a blue [0, 121, 212 RGB] triangle or a circular disk), both subtended 0.6°×0.6° of visual angle.

The materials used in the training sessions were the same as in Experiment 1.

5.3.1.3 Procedure

Participants took part individually in Experiment 2. The pre- and the post-training sessions were conducted on different days, separated by 0-2 days. A training session followed pre-training session immediately, and the other preceded the post-training session immediately, separated by a brief break.

Each of the pre- and post-training sessions consisted of one practice block and six experimental blocks. The practice block consisted of 40 trials, randomly assigned to different conditions. Each experimental block consisted of 128 trials following 5 warm-up trials. The experimental trials were evenly assigned to different conditions and were presented in a pseudo-randomized order, with no more than 3 consecutive trials from the same condition. Each warm-up trial was randomly assigned to a condition. Several participants were required to repeat the practice block because they failed to meet the accuracy criteria (see below) in the first practice block. The accuracy criteria were the same for practice and formal blocks.

The procedure of each trial and the task were the same to Experiment 1 in Chapter 2, i.e. the participants made speeded bi-manual key pressing responses according to the shape of the target added on the object pair (see Figure 2-2).

The two training sessions were the same as in Experiment 1.

5.3.2 Results and Discussion

Participants were highly accurate, with the average accuracy of different conditions between 95.4% and 100% (mean 98.16%, mean RT = 439 ms, see Table 5-6). RTs were initially trimmed to remove responses quicker than 100 ms. RTs more than 2.5 standard deviations from the mean of each participant were then discarded in a non-recursive manner. Discarded trials were fewer than 2% of the total trials. The same data outlier removal procedure was done for data of Experiment 3 and 4, and won’t be repeated in corresponding sections.

The mean RT of each participant in each condition were calculated and entered into an ANOVA with SOA (240 ms vs.400 ms), co-location (correct vs. incorrect), object layout (active-left vs. passive-left), response compatibility (with active objects vs. passive objects), object familiarity (familiar vs. novel) and session (pre- vs. post- training) as within-subject factors. There was a main effect of SOA, F (1, 13) = 84.57, p < .001, η^2 = .87, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 21 ms). The main effect of co-location was significant, F (1, 13) = 10.77, p = .006, η^2 = .45, with responses in the correct co-location condition being slower than in the incorrect co-location condition (MD = 3 ms). In addition, several interactions reached significance, including that between co-location, response compatibility and object familiarity, F (1, 13) = 11.31, p = .005, η^2 = .47 (see Figure 5-5), between object layout and response compatibility, F (1, 13) = 5.21, p = .039, η^2 = .29, between object familiarity and session, F (1, 13) = 7.61, p = .016, η^2 = .37, and between response compatibility, object familiarity and session, F (1, 13) = 6.69, p = .023, η^2 = .34.

Table 5-6: Average accuracy and reaction times (RTs) of each condition in Experiment 2

Layout (active objects on the left or right)	Response compatibility (passive vs. active objects)	Object novelty	Sessions	Accuracy	RTs (ms)
240 ms SOA					
Correct co-location					
Left	Passive	familiar	Pre-training	1.00	457
			Post-training	.98	439
		novel	Pre-training	.98	448
			Post-training	.99	452
	Active	familiar	Pre-training	.98	459
			Post-training	.98	451
		novel	Pre-training	1.00	455
			Post-training	.97	453
right	Passive	familiar	Pre-training	.99	465
			Post-training	.98	454
		novel	Pre-training	.99	463
			Post-training	.98	443
	Active	familiar	Pre-training	.96	451
			Post-training	.99	439
		novel	Pre-training	.98	453
			Post-training	.99	446
Incorrect co-location					
Left	Passive	familiar	Pre-training	.99	443
			Post-training	.99	430
		novel	Pre-training	.99	445

				Post-training	.98	442
		Active	familiar	Pre-training	.98	469
				Post-training	.98	449
			novel	Pre-training	.98	455
				Post-training	.99	450
	right	Passive	familiar	Pre-training	.98	453
				Post-training	.97	450
			novel	Pre-training	.97	449
				Post-training	.97	447
		Active	familiar	Pre-training	.99	453
				Post-training	.99	433
			novel	Pre-training	.98	443
				Post-training	.98	442
400 ms SOA						
Correct co-location						
	Left	Passive	familiar	Pre-training	.99	431
				Post-training	.99	424
			novel	Pre-training	.98	422
				Post-training	.99	416
		Active	familiar	Pre-training	.97	444
				Post-training	.98	421
			novel	Pre-training	1.00	439
				Post-training	.98	430
	right	Passive	familiar	Pre-training	.97	441
				Post-training	.97	436
			novel	Pre-training	.98	440
				Post-training	.98	426
		Active	familiar	Pre-training	.98	422
				Post-training	.96	418
			novel	Pre-training	.98	429
				Post-training	.99	418
Incorrect co-location						
	Left	Passive	familiar	Pre-training	.98	417
				Post-training	.99	421
			novel	Pre-training	.95	429
				Post-training	.98	417
		Active	familiar	Pre-training	.98	443
				Post-training	.98	437
			novel	Pre-training	.98	435
				Post-training	.98	425
	right	Passive	familiar	Pre-training	.99	439
				Post-training	.99	427
			novel	Pre-training	.98	436
				Post-training	.99	437
		Active	familiar	Pre-training	.98	430
				Post-training	.99	416
			novel	Pre-training	.98	415
				Post-training	.98	419

To examine the interactions, we analyzed familiar object pairs and novel object pairs separately. RTs for each kind of object pairs were subjected to an ANOVA with SOA (240 ms vs.400 ms), co-location (correct vs. incorrect), object layout (active-left vs. passive-left), response compatibility (with active objects vs. passive objects), and session (pre- vs. post-training) as within-subject factors.

Familiar objects

For the familiar objects, there was a main effect of SOA, F (1, 13) = 66.45, p < .001, η^2 = .84, RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 21 ms). There was an interaction between co-location and response compatibility, F (1, 13) = 11.50, p = .005, η^2 = .47 (see Figure 5-5). The analysis of simple effects replicated previous findings of effects of implied actions. Responses aligned with the passive objects were slower in the correct co-location condition than in the incorrect co-location condition (MD = 9 ms, p = .003, but not when they are aligned with the active objects, p = .14), suggesting the inhibitory effect of the correct co-location on passive objects. There was an advantage for active objects comparing with passive objects in the correct co-location condition, i.e. responses aligned with active objects were quicker than those aligned with passive objects (MD = 5 ms, p = .045), and in the incorrect co-location condition, responses on the side of passive objects were quicker than those on the side of active objects (MD = 6 ms, p = .020). Training did not affect this interaction, as the three way interaction between training, responses side and co-location was not significant (p = .15), nor other interactions involving these three factors (ps > .21). Pairwise analysis revealed that the advantage for active objects in the correct co-location condition remained of a similar size in pre- and post-sessions (MD ~ 5ms). The inhibitory effect on passive-side responses was larger in the pre-training session than in post-training session by value (MD = 10 ms, p = .014 vs. MD = 6 ms, p = .067). Additionally, there was an interaction between object layout and response compatibility, F (1, 13) = 6.60, p = .034, η^2 = .30. Analysis of simple effects revealed that this interaction was probably driven by an advantage for the dominant hand. When the active objects were presented on the right side, responses aligned with the active objects were marginally quicker than those aligned with the passive ones (MD = 13 ms, p = .063), while those aligned with the passive objects were quicker than those aligned with the active objects when the layout of object pairs were reversed (MD = 14 ms, p = .023).

Novel object pairs

For novel object pairs, there was a main effect of SOA, F (1, 13) = 76.99, p < .001, η^2 = .86, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 22 ms). However, the interaction between response compatibility and co-location was not significant (p = .27, η^2 = .09, see Figure 5-6), neither the interaction between response compatibility, co-location and training (p = .89, η^2 = .01). To examine the effects of implied action, i.e. the inhibitory effect of co-location on passive objects and the advantage for active objects in the correct co-location condition, we conducted planned pairwise comparison a) between the correct and the incorrect co-location conditions for responses aligned with the novel passive objects, and b) between the responses aligned with the active and passive novel objects in the correct co-location condition, both separately for pre- and post-training sessions. We did not find any sign of the inhibitory effect of implied action on responses aligned with passive objects or the advantage for active objects (ps> .3).

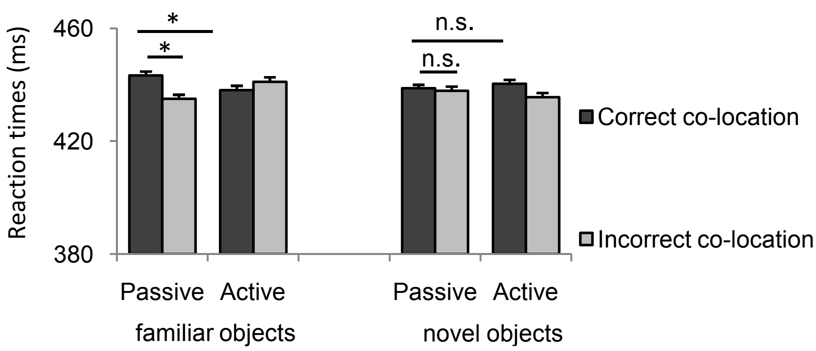

Figure 5-5. Experiment 2: The Reaction times across sessions in Experiment 2. The effects of implied between-object action shown in familiar object pairs (left bars) were absent in novel object pairs (right bars). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

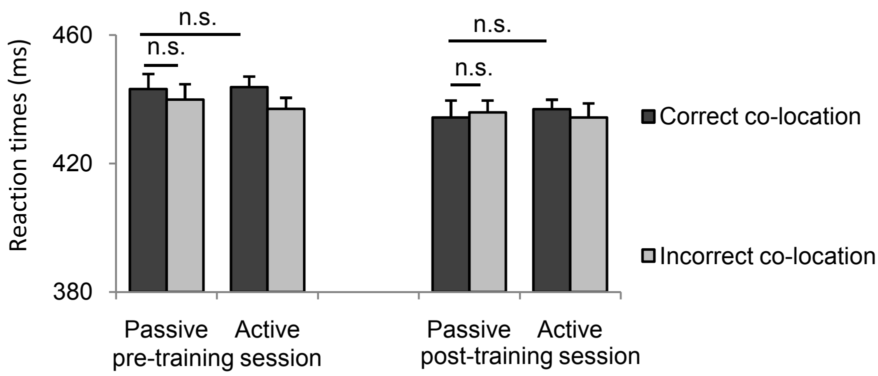

Figure 5-6. Lack of learning effect in Experiment 2. Reaction times of responses to novel objects did not show effects of implied between-object action in either the pre- (left bars) or the (post-) training session. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

Experiment 2 failed to find any evidence for effect of the newly-learned action relations between novel objects. These results suggested that the effects of implied actions cannot be learned as easily as declarative knowledge regarding unfamiliar between-object actions. We wondered whether this was because the participants failed to pick up the affordance of the active objects, which, as suggested by our previous studies (as in Chapter 4 when aIPS is interfered by TMS stimulation) can be the driving factor behind the absence of implied between-object actions effects. We examined this possibility in Experiment 3.

5.4 Experiment 3: Can the affordance of single objects be learned?

In Experiment 3 we trained the participants in the same way as in Experiment 1 and 2, but presented only the active objects on the centre of the screen preceding the imperative central cue in the pre- and post-training sessions. The paradigm of the key-pressing task was the same to which used to by Phillips and Ward (2002) to reveal the affordance-based compatibility effect of single object. We planned to compare the affordance-based compatibility effect between the familiar and novel active objects, and to examine how the training affects the affordance-based compatibility effect of the novel active objects. Our logic was, if during the training the participants learned to extract the affordance of the novel active objects in a manner similar to how the affordance of the familiar active objects were extracted, the compatibility effect of novel objects in the post-training session should resemble that of the familiar objects to a larger extent than in pre-training session.

5.4.1 Methods

A new sample of sixteen volunteers (one male, mean age 19 years, range: 18-20 yrs) from the University of Birmingham research participation scheme was recruited. All the participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The procedure of Experiment 3 was the same of Experiment 2, except that in the pre- and post-training sessions only the active objects in each pair was presented before the imperative central cue. We labelled the responses made by the hand on the same side with the graspable part of the objects compatible responses, and those by the other hand incompatible. In addition, the active objects were presented at the centre of the screen, instead of on one side of it, and were always shown in the same orientation as in the correct co-location condition in Experiment 2. Each session consisted of one practice block and five formal blocks. In Experiment 3 the active objects in the pre- and post-training sessions will always be in the functional orientation (as if in the correct co-location condition of Experiment 1 and 2). Our main interest was whether the responses required by the imperative central cue would be quicker when compatible with the affordance of the active objects than not.

5.4.2 Results and Discussion

Participants were highly accurate, with the average accuracy of different conditions between 97.4% and 99.6% (mean 98.8%, mean RT = 413 ms, see Table 5-7).

Mean RT data of each participant in each condition were entered into an ANOVA with SOA (240 ms and 400 ms), affordance of active objects (left vs. right), object type (familiar vs.

novel), response compatibility (compatible with vs. incompatible) and session (pre- vs. post-training) as within-subject factors.

There was a main effect of SOA, F (1, 15) = 80.61, p < .001, η^2 = .84, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 23 ms). The main effect of response compatibility was significant, F (1, 15) = 34.18, p < .001, η^2 = .70, with responses quicker when congruent than incongruent with the affordance of the active objects (MD = 6 ms). There was a main effect of object familiarity, F (1, 15) = 18.17, p = .001, η^2 = .55, with responses made to familiar objects being quicker than to novel objects (MD = 5 ms). The main effect of training was also significant, F (1, 15) = 12.55, p = .003, η^2 = .46, with the responses in the post-training session being quicker than in the pre-training session (MD = 19 ms). There was an interaction between affordance of active objects and responses compatibility, F (1, 15) = 22.48, p <.001, η^2 = .60 (see Figure 5-7). The analysis of simple effects revealed that this interaction was probably driven by handedness. When the active objects afforded left responses, incompatible responses were quicker than compatible response (MD = 15 ms, p = .005). When the active objects afforded right responses, the compatible responses were quicker than the incompatible ones (MD = 28 ms, p < .001). In addition, there was an interaction between response compatibility and object familiarity, F (1, 15) = 16.94, p = .001, η^2 = .53 (see Figure 5-8). Analysis of simple effects revealed that, counter-intuitively, there was an compatibility effect for novel objects, i.e. responses compatible with the active objects were quicker than the incompatible ones (MD = 11 ms, p < .001). In contrast, there was no evidence for compatibility effects for familiar objects (MD = 2, p = .23). The interaction between response compatibility, object familiarity and training was not significant (p = .53). Additionally, there was a significant interaction between SOA and training, F (1, 15) = 7.49, p = .015, η^2 = .33, and between object familiarity and session, F (1, 15) = 6.62, p = .021, η^2 = .31. Analysis of simple effects suggested that in the post-training session, responses to the familiar objects were quicker than those to the novel objects (MD =

7 ms, *p* < .001) while in the pre-training session this difference was smaller (MD = 3 ms, *p* = .047). The RTs differences between pre- and post-training sessions were significant in both SOA conditions, but numerically larger in the 240ms SOA condition (MD = 22 ms vs. 17 ms, *p*s < .01).

To examine directly the hypothesized effect of training on the affordance-based compatibility effect to novel objects, we submitted RTs of compatible and incompatible responses of the novel objects in each session to planned pairwise analysis. The compatibility effects were significant in both sessions, but numerically larger in pre-training session (MD = 13 ms and 9 ms respectively, *p*s < .001, see Figure 5-9). We also examined the interaction between training and compatibility for responses to the novel objects. The interaction was not significant ($p = .23$, $\eta^2 = .10$). We likewise examined the pairwise analysis between congruent and incongruent responses to familiar objects in each session, and found that the compatibility effect was not significant in either session (*p*s> .3).

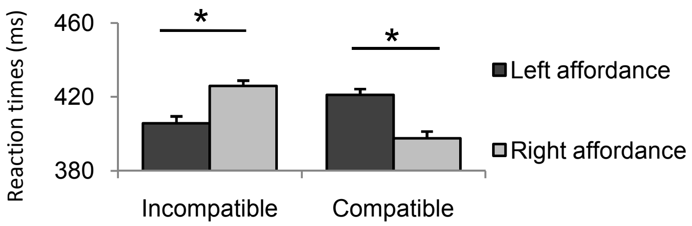

Figure 5-7. Dominant hand effect in Experiment 3. The responses made by the right hand (incompatible with left affordance, light grey bar on the left, and compatible with the right affordance, dark grey bar on the right) were always quicker than those made by the left hand (dark grey bar on the left and light grey bar on the right). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

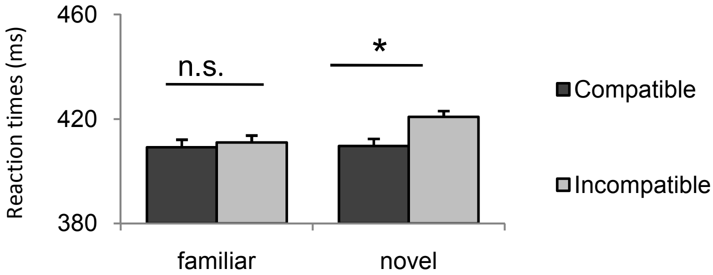

Figure 5-8. Compatibility effect in Experiment 3. Across sessions, incongruent responses were slower than congruent responses to the novel objects, but this compatibility effect is not significant for responses to familiar objects. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

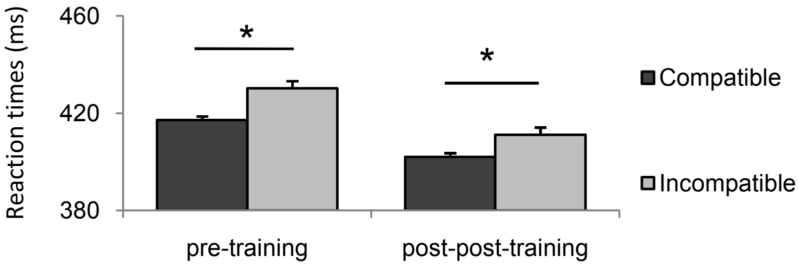

Figure 5-9. Compatibility effect of novel objects in Experiment 3.The responses congruent with the affordance of novel active objects were quicker than the incongruent ones (the compatibility effect) in both pre- and post- training sessions, but it is numerically smaller in post- than pre- training session. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

The results of Experiment 3 were counter-intuitive in the sense that we found significant compatibility effect for the novel, but not the familiar objects. However, previous studies found that the affordance-based compatibility effect of single manipulable objects is sensitive to task context (e.g. Cho & Proctor, 2010; Symes et al., 2005; Tipper et al., 2006), and can be confounded with other compatibility effect. For instance, it was found that two independent types of compatibility effects exist for visually presented tool-like objects, one associated with the functional portion of the tool, e.g. the spout of a kettle, and the other with the affordance and the graspable part of the object, e.g. the handle of a kettle (Cho & Proctor, 2011; Pellicano et al., 2010). Given that the functional and the graspable part of the objects were typically separated in space, two effects often predict results of opposite directions. It was found that which of the two effects dominates in a given context is sensitive to task requirement (Pellicano et al., 2010) and the relative saliency of the graspable and the functional part of the objects (Cho & Proctor, 2011). Pellicano and colleagues (2010) found that the compatibility effect associated with the graspable part of the objects emerged when the task required extraction of action related visual information (object orientation), while the compatibility effect associated with the functional part of the objects emerged when the task required extraction of perceptual information (colour of objects). Cho and Proctor (2011) considered the critical factor to be the coding of relative location of each part of the objects and argued that the compatibility effect is always associated with the relatively salient part. The reason that we did not find the compatibility effect for familiar object might be that a similar competition exists between the handle side and the functional side of the objects. Due to the knowledge of their functional use, the functional part of a familiar active object might have competed strongly with the graspable part, and cancelled out the compatibility effect associated with object affordance. In contrast, we did find a compatibility effect of the novel active objects. This might be because their functions had not been learned, therefore the participants were not skilled in picking out the functional parts of these novel objects. Consequently, without competition from the functional part, the graspable parts evoked an apparent compatibility effect.

We would like to point out that the lack of affordance-based compatibility effect in the familiar objects does not necessarily conflict with the conclusion drawn from previous chapters. In Chapter 3 and 4, based on direct manipulation of the structural feature of objects and the processing of the active objects, it has been revealed that action-related structures and /or the stronger affordance of the active objects is crucial in producing the effect of implied between-object action. The lack of affordance compatibility effect here is observed in a single object scenario. In this scenario configural information (e.g. the co-location between objects implying interaction) is not available as in the paired-object presentations (Chapter 3 and 4). The configural information of object pairs might steer processing towards the structural features of the objects which afford the manipulation of the whole pair of objects. In contrast, the single objects might not be subjected to such modulation, thus the affordance compatibility effect might be subjected to stronger competition from compatibility effect associated with other features. The qualitative difference between response selection effect for single- and paired- object presentation has been demonstrated in Chapter 2. The result of the present experiment reinforced this dissociation.

Worth noticing, the compatibility effect of novel active objects was not affected by learning. It reached significance before the participants learned by observation how the novel objects could be grasped. After the learning sessions, in which the participants saw and learned how the active objects were to be grasped, the effects persisted, though numerically reduced. It suggested that the responses to the graspable part of the objects were rather spontaneous, independent from the declarative knowledge of the functionality of the objects. Admittedly, the lack of influence from learning on the compatibility effect might be due to the relative short learning format, which further suggested the difficulty in affecting the affordance-related compatibility effect by limited observational learning.

Table 5-7: Average accuracy of each condition in Experiment 3

	Affordance of active objects	Response compatibility (passive vs. active objects)	session	Accuracy	RTs (ms)
Familiar objects 240 ms SOA					
	Left	Passive	Pre-training	0.99	423
			Post-training	0.97	401
		Active	Pre-training	0.99	443
			Post-training	0.98	418
	Right	Passive	Pre-training	0.99	420
			Post-training	0.98	397
		Active	Pre-training	0.99	443
			Post-training	0.99	419
400 ms SOA					
	Left	Passive	Pre-training	0.99	402
			Post-training	0.99	382
		Active	Pre-training	0.98	421
			Post-training	0.99	398
	Right	Passive	Pre-training	0.98	396
			Post-training	0.99	379
		Active	Pre-training	0.99	419
			Post-training	0.99	399
Novel objects 240 ms SOA					
	Left	Passive	Pre-training	0.99	435
			Post-training	0.99	410
		Active	Pre-training	0.99	442
			Post-training	0.99	427
	Right	Passive	Pre-training	1.00	419
			Post-training	0.99	401
		Active	Pre-training	0.99	456
			Post-training	1.00	432
400 ms SOA					
	Left	Passive	Pre-training	0.98	404
			Post-training	0.98	390
		Active	Pre-training	1.00	415
			Post-training	0.99	405
	Right	Passive	Pre-training	0.99	393
			Post-training	0.99	376
		Active	Pre-training	0.99	426
			Post-training	0.99	414

5.5 Experiment 4: The Effect of learning by imitation

Experiment 1 suggested that the declarative knowledge about action relations between novel manipulable objects can be learned by observational learning, while Experiment 2 and 3 suggested that learning by limited observation in a short period of time is not sufficient, or is not efficient, enough in to enable the novel object pairs affect affordance selection to comparable extent as objects affording well-established, skilled between-object actions. To examine whether a more powerful training method can make a difference, Experiment 4 examined the possibility of acquiring such action “knowledge” by physical experience with the designed interaction, i.e. by imitating the designed interaction in the learning sessions.

Previous research suggests that physical experience with novel manipulable objects affects the representation of the novel objects, and this influence is dissociable from that of visual familiarity of the objects. For instance, Bellebaum and colleagues (2013) assigned functions to two sets of novel objects, trained participants by either visually exploring the objects or actively manipulating the objects, and compared the neural correlates of each set of objects with unlearned novel objects. They found that training by manipulation changed activation in left inferior/middle frontal gyrus and the left posterior inferior parietal lobule to a larger extent than visual training, in addition to the change in frontal-parietal cortex shared by both types of training. Further, dynamic causal modelling of effective connectivity between the regions showing enhanced post-training activity revealed that training by manual exploration strengthened the connectivity between regions activated by visual training, while visual training reduced connectivity for regions selectively responding to manual manipulation training. Converging, Kiefer et al. (2007) reported that only when participants were trained by pantomiming the actions afforded by novel objects, learning effect was reflected in the event-related potentials early in the frontal motor regions and later in occipito-parietal visual-motor regions, but this learning effect was absent when the participants were trained instead by pointing to the same novel object. Both studies demonstrated that learning via practicing generates unique effect, comparing with learning without experience of manipulation. Consequently, in Experiment 4 we gave the participants a pair of novel objects, and asked them to actually imitate the observed tool-use action, thus to allow them the opportunity to gain manual experience during training. We hypothesized that imitation, comparing with passive observation, would strengthen the learning effect and lead to similar response patterns for the novel and familiar object pairs in the post-training session.

5.5.1 Method

A new sample of twenty-two healthy volunteers (one males, mean age 19 years, range: 18-21 yrs) from the University of Birmingham research participation scheme was recruited. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received course credit for their time.

The design and procedure of Experiment 4 were almost the same as Experiment 2, the only difference being that during the training session, the participants were given the objects after each video and required to imitate the action, instead of choosing the line-drawings of the presented objects out of four alternatives.

5.5.2 Results and Discussion

Participants were highly accurate, with the average accuracy of each condition falling between 95.9% and 99.4% (mean 98.3%, mean RT = 405 ms). There was no evidence of a speed-accuracy trade-off (see Table 5-8).

Table 5-8: Average accuracy and reaction times (RTs) of each condition in Experiment 4

	Layout (active objects on the left vs. right)	Response compatibility (passive vs. active objects)	Sessions	Accuracy	RTs (ms)
Familiar objects					
240 ms SOA					
Correct co-location	Left	passive	Pre-training	1	420
			Post-training	0.98	409
		active	Pre-training	0.98	416
			Post-training	0.99	412
	Right	passive	Pre-training	0.98	431
			Post-training	0.98	415
		active	Pre-training	1	416
			Post-training	0.97	398
Incorrect co-location	Left	passive	Pre-training	0.99	414
			Post-training	0.98	400
		active	Pre-training	0.99	433
			Post-training	0.98	417
	Right	passive	Pre-training	0.96	423
			Post-training	0.99	414
		active	Pre-training	0.98	419
			Post-training	0.99	400
400 ms SOA					
Correct co-location	Left	passive	Pre-training	0.99	400
			Post-training	0.99	390
		active	Pre-training	0.99	406
			Post-training	0.98	396

	Right	passive	Pre-training	0.98	408
			Post-training	0.98	399
		active	Pre-training	0.98	399
			Post-training	0.99	378
Incorrect co-location	Left	familiar	Pre-training	0.98	396
			Post-training	0.97	376
		novel	Pre-training	0.97	414
			Post-training	0.97	397
	Right	familiar	Pre-training	0.99	411
			Post-training	0.99	398
		novel	Pre-training	0.98	402
			Post-training	0.98	382
Novel objects					
240 ms SOA					
Correct co-location	Left	familiar	Pre-training	0.99	412
			Post-training	0.99	401
		novel	Pre-training	0.98	432
			Post-training	0.99	414
	Right	familiar	Pre-training	0.97	426
			Post-training	0.98	414
		novel	Pre-training	1	417
			Post-training	0.98	406
Incorrect co-location	Left	familiar	Pre-training	0.97	421
			Post-training	0.97	402
		novel	Pre-training	0.98	424
			Post-training	0.98	411
	Right	familiar	Pre-training	0.98	428
			Post-training	0.96	416
		novel	Pre-training	0.98	415
			Post-training	0.99	405
400 ms SOA					
Correct co-location	Passive	familiar	Pre-training	0.98	392
			Post-training	0.99	390
		novel	Pre-training	0.95	409
			Post-training	0.98	397
	Active	familiar	Pre-training	0.98	400
			Post-training	0.98	392
		novel	Pre-training	0.98	394
			Post-training	0.98	386
Incorrect co-location	Passive	familiar	Pre-training	0.99	398
			Post-training	0.99	385
		novel	Pre-training	0.98	405
			Post-training	0.99	389
	Active	familiar	Pre-training	0.98	402
			Post-training	0.99	393
		novel	Pre-training	0.98	390
			Post-training	0.98	382

Mean RTs of each participants in each condition were entered into an ANOVA with SOA (240 ms vs.400 ms), co-location (correct vs. incorrect), object layout (active-left vs. passive-left), response compatibility (with active objects vs. passive objects), object familiarity (familiar vs. novel) and session (pre- vs. post- training) as within-subject factors. There was a main effect of SOA, F (1, 21) = 196.87, p < .001, η^2 = .90, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 19 ms). The main effect of training was significant, *F* (1, 21) = 9.56, *p* = .006, η^2 = .31, with responses in pre-training session being slower than in post-training session (MD = 13 ms). In addition, several interaction reached significance, including those between co-location, response compatibility and object familiarity, *F* (1, 21) = 16.03, *p* = .001, η^2 = .44 (see Figure 5-10), between object layout and response compatibility, *F* (1, 21) = 8.97, *p* = .007, η^2 = .30, between co-location, object layout and object familiarity, *F* (1, 21) = 13.38, *p* = .001, η^2 = .39, and between object layout, response compatibility, and object familiarity, *F* (1, 21) = 4.75, *p* = .041, η^2 = .19. The interaction between training, co-location, response compatibility and object familiarity was not significant (*p* = .29).

To examine the interactions, we analyzed familiar object pairs and novel object pairs separately. RTs for each kind of object pairs were subjected to ANOVA with SOA (240 ms vs.400 ms), co-location (correct vs. incorrect), object layout (active-left vs. passive-left), response compatibility (with active objects vs. passive objects), and session (pre- vs. post-training) as within-subject factors.

For the familiar objects, there was a main effect of SOA, *F* (1, 21) = 151.22, *p* < .001, η^2 = .88, with RTs in the 240 ms SOA condition being longer than in the 400 ms SOA condition (MD = 18 ms). The main effect of training was significant, *F* (1, 21) = 10.16, *p* = .004, η^2 = .33, with responses in pre-training session being slower than in post-training session (MD = 14 ms). There was an interaction between co-location and response compatibility, *F* (1, 21) = 28.90, *p* < .001, η^2 = .58 (see Figure 5-10). The analysis of simple effects replicated previous findings in Chapter 2. Responses aligned with the passive objects were slower in the correct co-location condition than in the incorrect co-location condition (MD = 5 ms, *p* = .003), while for responses aligned with the active objects, responses were quicker in the correct than in the incorrect co-location condition (MD = 5 ms, *p* = .004), revealing an inhibitory effect of the correct co-location on responses aligned with the passive objects and an orientation effect for active objects. There was an advantage for active objects comparing with passive objects in the correct co-location condition, i.e. responses aligned with active objects were quicker than those aligned with passive objects (MD = 6 ms, $p < .001$), and in the incorrect co-location condition, responses on the side of passive objects were quicker than those on the side of active objects ($p = .016$, MD = 4 ms). A three-way interaction between object compatibility, co-location and object layout was also significant, F (1, 21) = 9.34, $p = .006$, $\eta^2 = .31$. Simple effect analysis suggested that the inhibitory effect of co-location on passive objects were prominent when the passive objects were presented on the right side and thus aligned with right hand responses (MD = 8 ms, $p = .001$), but not significant for left hand responses ($p = .22$). Also, the advantage for active objects in the correct co-location condition were only significant when the active objects were presented on the right hand side (MD = 16 ms, $p = .003$), but disappeared when the active objects were presented on the left side ($p = .48$). This might be because the effect of the handedness overwrote the advantage for the active objects, as the hypothesized advantage for active objects relative to passive objects requires quicker responses made by the left hand than the right hand responses when the active objects were presented on the left side, which is against the handedness of our right handed participants. Additionally, there was an interaction between object layout and response compatibility, F (1, 21) = 9.62, $p = .005$, $\eta^2 = .31$. Analysis of simple effect revealed that this interaction was probably driven by an advantage for the dominant hand. When the active objects were presented on the right side, responses aligned with the active objects were quicker than those aligned with the passive ones (MD = 11 ms, $p = .013$), while those aligned with the passive objects were quicker than those aligned with the active objects when the layout of object pairs were reversed (MD = 13 ms, $p = .004$).

For novel object pairs, there was a main effect of SOA, F (1, 21) = 140.27, $p < .001$, $\eta^2 = .87$, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 21 ms). However, the interaction between response compatibility and co-location was only marginally significant (p = .06, η^2 = .16), and the interaction between response compatibility, co-location and training was not significant (p = .30, η^2 = .05, see Figure 5-11). To examine the inhibitory effect of co-location on passive objects and the advantage for active objects in the correct co-location condition, we conducted planned pairwise comparison between the correct and the incorrect co-location conditions for responses aligned with the novel passive objects in each session separately, and we compared the responses aligned with the active and passive objects in the correct co-location condition, separately for pre- and post-training sessions. We did not find evidence of either the inhibitory effect of implied action on responses aligned with passive objects or the advantage for active objects (*p*s> .1, see Figure 5-11). Additionally, there was an interaction between object layout and response compatibility, F (1, 21) = 7.45, p = .013, η^2 = .26. Analysis of simple effect revealed that this interaction was driven by an advantage for the dominant hand. When the active objects were presented on the right side, responses aligned with the active objects were quicker than those aligned with the passive ones (MD = 10 ms, p = .017), while those aligned with the passive objects were quicker than those aligned with the active objects when the layout of object pairs were reversed (MD = 10 ms, p = .026).

The results of Experiment 4 resembled those of Experiment 2, suggesting that in our paradigm integrating explicit, manual imitation in the learning stage still cannot capture the effect of the newly-learned action relations between novel objects.

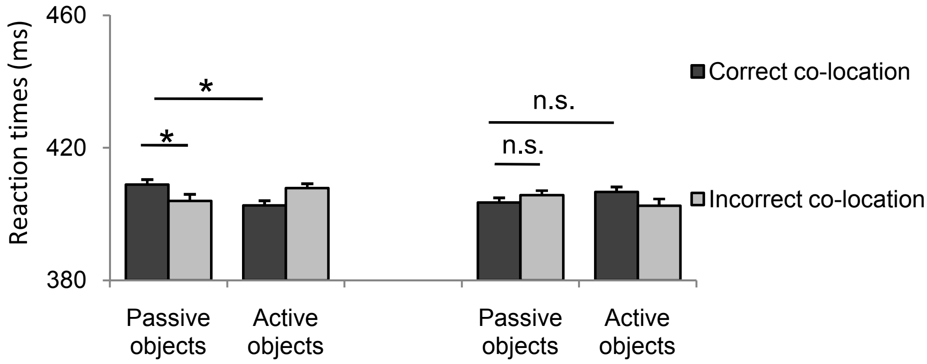

Figure 5-10. Results of Experiment 4 across testing sessions. The effects of implied actions were apparent for familiar objects (left), but not for novel objects (right). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

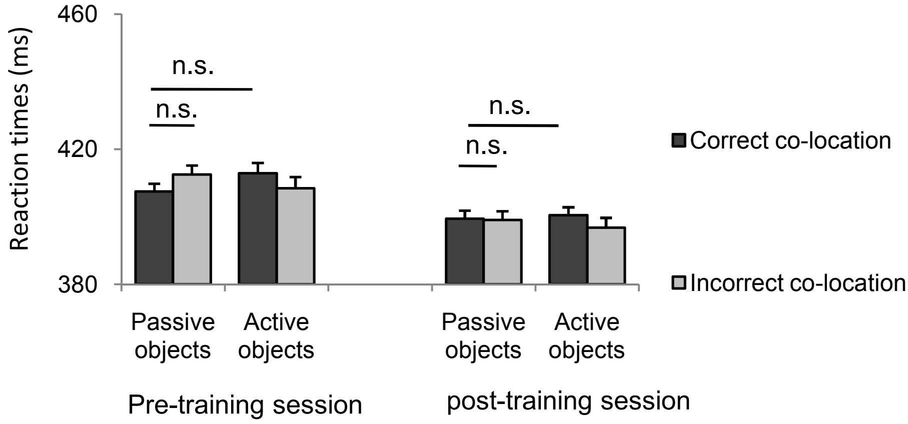

Figure 5-11. Lack of learning effect of novel objects in Experiment 4. The effects of implied actions were absent in both pre- (left) and post-training sessions (right) for novel objects. The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05).

5.6 General Discussion

5.6.1 Summary of results

The present study examined whether the automatic extraction of implied between-object actions can be acquired by observational learning. We examined whether novel between-object actions can be learned, and whether the learned novel objects would resemble the familiar objects affording well established actions in informing function judgement and affordance selection. We found that even though the participants learned the action relations between novel objects on a conceptual level, as reflected in the action-relation judgement task (Experiment 1), the learned action relations cannot be reflected in the affordance selection, as shown in Experiment 2 and 4. In addition, the results of Experiment 3 suggested that the compatibility effect based on single-object affordance exists before learning the functional usage of the novel active objects, and observational learning failed to render such effect to a pattern resembling that of familiar objects.

5.6.2 Lack of learning effect in affordance selection: Dissociated representations and learning mechanisms

Our results do not support the hypothesis that newly learned action relations between objects affect affordance selection (Experiment 2 – 4). This is in sharp contrast with the learning effect in function judgment task (Experiment 1). Such dissociation is in line with the sensory/functional theory of object representation, which stresses that knowledge about tools is organized in multiple distributed subsystems (Warrington & Shallice, 1984), and should reflect the history of sensory experience with a given object (Warrington & McCarthy, 1987). Accordingly, the representation of familiar tools would be based on properties related not only to their identities, but also to their function and manipulation. This idea is supported by evidence from functional magnetic resonance imaging (fMRI) studies, which have consistently shown tool-specific activations in visual and category-specific areas as well as the frontal-parietal regions overlapping with those involved in active tool use (Boronat et al., 2005; Canessa et al., 2008; Chao & Martin, 2000; Kellenbach et al., 2003; Lewis, 2006; Martin et al., 1996; Perani et al., 1999). The dissociated learning effects in our study can be considered as an evidence of the dissociated representation of between-object actions, which includes a declarative component as well as a visuomotor component.

Our results suggest that the representations are not established simultaneously. This is consistent with the dissociation between parallel learning processes behind the acquisition of tool-use behaviours. It has been suggested that there is dissociation between the learning processes behind acquiring (a) skills for dexterous tool use, i.e. the proficiency, and (b) semantic knowledge about functionality (Menz et al, 2010). Menz and colleagues (2010) found that the acquisition of conceptual representation of tool is quick and highly efficient. They reported that after only one demonstration the participants can understand the designed function of a novel tool and its interaction with recipient objects, while changes at the neural level has been reflected in regions believed to be associated closely with the visual processing and semantic knowledge of tools (prefrontal and mediotemporal areas). In contrast, learning-associated changes in regions believed to be related to motor processes were produced by longer training programmes (4 weekly 1h session in Stout & Chaminade, 2007; 3 training sessions with 5 – 10 mins in each session for each novel tool in Bellebaum et al., 2013; 16 one hour sessions for 64 novel shapes in Kiefer et al., 2007, and Weisberg et al., 2007; and days to months in studies reporting modulation of tool use experience on mirror neuron systems, e.g. Arbib et al., 2009 and Ferrari et al., 2005). In our study, the participants only watched the designed interaction between objects four times, two for each object layouts, throughout the training sessions, and the post-training session was almost immediately after the second training session. It is natural to speculate that the training might be too short to produce impact in motor-related area and thus failed to affect affordance selection. Extending the literature regarding dissociated learning processes behind tool-use learning, our results suggest that, at least on the behavioural level, influence from brief observational learning differs for the conceptual and affordance related components of representations. The conceptual aspect is sensitive to limited exposure to demonstration of novel tool-use actions, while the extraction of action possibilities between tools and their objects might be less vulnerable to such impact.

Previous literature suggests distinct mechanisms for motion learning, which are the fast associative mechanism, and the slow visuomotor mechanism. For instance, a framework (Hikosaka, Nakamura, Sakai & Nakahara, 2002; Lohse, Wadden, Boyd & Hodges. 2014) was proposed that two cortico-striatal-cerebellar loops underlie motor learning. In an initial stage, performance improves rapidly, with changes being driven by an "associative" loop consisting frontal, parietal and premotor cortical regions, the caudate, and associative cerebellar regions. After this initial rapid learning stage, a "motor" loop produces gradual improvement, receiving a contribution from cortical motor areas, putamen, and cerebellum. The idea of a time-consuming component in motor learning is also supported from a memory perspective. It was suggested that the quick and slow components in the motor learning is associated with the quick formation of declarative memory and the slow component the time-consuming and long-lasting formation of procedural memory (Karni, Meyer, Rey-Hipolito, Jezzard, Adams, Turner, et al., 1998). To accommodate the time requirement of the slow learning component, Kantak and Winston (2012) stressed the importance of including a delayed post-training session to capture the learning effect coming from consolidation. The fact that we arranged the post-training session right after the second training session might have prevented the long-term learning effect to appear. We speculate that our training sessions only managed to achieve the formation of the associative representation or the declarative memory of the between-object interaction, that is, engaging the rapid associative loop, but failed to sustain the "motor" loop which internalizes the novel between-object actions.

However, we still consider it is possible that the functionality of tools can be learned on visuomotor level. For instance, Ferrari and colleagues (2005) found that after long-term action observation, mirror neurons in premotor area started exhibiting higher activation when an action was performed with a tool (the one they have been observed extensively in training), than when the action was performed by an biological effector, e.g. hand or mouth (see also Cook, Dickinson, & Heyes, 2012; Arbib et al., 2009). Mirror neurons are believed to be involved in representing the sensorimotor associations in object manipulation (for review, see Hickok, 2009). Other regions in premotor and motor areas also exhibited learning effect after extensive tool-use observation (e.g. Bellebaum et al., 2013; Kiefer et al., 2007; Stout &

Chaminade, 2007; Weisberg et al., 2007). Consequently, we conjecture that by extending the training or/and consolation time the current paradigm might still be able to capture the visuomotor effect of tool use observation. Worth noticing, same as in other studies reporting learning effect in dorsal areas, the learning session in Ferrari and colleagues' (2005) study is much longer than ours, being approximately 2 months. This might have given neurons in parietal areas and premotor cortex enough time to shape synapse accordingly, and thus influences the visuomotor responses.

The dissociation between learning effect in function judgment (Experiment 1) and response compatibility paradigm (Experiment 2 - 4) answered the question we raised in the introduction: is the automatic extraction of action relations between manipulable objects acquired as an emergent property of declarative knowledge of the between-object interaction? We demonstrated that though the declarative knowledge of tool use can be learned rather quickly, automatic visuomotor responses to the implied actions between newly learned tools and their objects could not be acquired in the same progress, suggesting that the effects of implied between-object actions on affordance selection are not by-products of declarative knowledge. Our learning effect in function judgement task replicated Menz and colleagues (2010)'s finding about the transient understanding of tool function, and we speculate that the absence of affordance selection effect in our study might be associated instead with the motor proficiency factor mentioned by Menz and colleagues. Our previous TMS study suggested aIPS and the dorsal stream plays a central role in generating the effects of implied between-object action (Chapter 4). Therefore we speculate that the slow consolidation of new visuomotor representation might be carried out as a trial-by-trial slow modulation in aIPS (Della-Maggiore, Malfait, Ostry, & Paus, 2004; Hardy, Tipper, Borg, Grafton, & Gazzaniga, 2006). Further study is needed to explore the exact mode and amount of consolidation required to produce the visuomotor effects, and to allow newly learned tool use actions being assimilated to an extent comparable to familiar objects.

In summary, though we failed to find short-term learning effect in affordance selection in the present study, the subjective judgment task in Experiment 1 revealed that the effect of short-term learning about novel objects and their interactions can be observed in declarative knowledge. Furthermore, the dissociation in learning effects supports the notion of dissociated mechanisms behind the functional/conceptual representation of the objects and the visuomotor representation associated with tools (e.g. Johnson-Frey, 2004).

5.6.3 Dissociation between single object affordance and effect of implied actions

Another interesting finding of the present study is the compatibility effect in responses to single tool-like objects (Experiment 3). The absence of a compatibility effect based on the handle-orientation is in line with results suggesting the weakening effect of another salient protrusion on the compatibility effect associated with the handle of manipulable objects (e.g. Cho & Proctor, 2011). The fact that such weakening in handle-based compatibility effect can only be found for familiar active objects, but not for the novel objects after training suggest that such weakening, similar to the effects of implied action between paired objects, cannot be produced by limited observational learning. We do not have direct evidence suggesting whether this weakening effect is acquirable. However, the dissociation between familiar and novel objects in this effect suggests this possibility. Our results suggested that, if such learning effect exists, it cannot be achieved by the limited exposure as in our study, as we did not find difference in the post- and pre-training sessions for the novel active objects.

Another potential reason for the weakening of handle-based compatibility effect might be directly related to the motor experience with these objects (Hardy et al., 2006). Hardy and colleagues found that though the participants have no experience in grasping certain climbing tools, these objects generated reliable activation in several visuomotor-related cortical regions—including left PMv and left AIP. In contrast, the familiar graspable objects (the door knobs in their study) did not evoke activity in any motor related regions. Hardy and colleagues (2006) suggest that this might reflect a negative correlation between motor experience and activation in motor-related cortex in response to a manipulable object. It will be interesting if this speculation is confirmed, because if it is the case, the affordance-based effect, which is closely associated with the manipulation of the objects, reduces with motor experience, but the affordance selection favouring the tools increases with motor experience (as shown by the dissociation between novel and familiar objects in the present study). Further research is needed in testing this explanation and the counterintuitive potential dissociation it predicted.

Nonetheless, the fact that novel active objects already potentiate lateralized responses echoes the core notion behind the concept of affordance, which suggests that the action possibilities afforded by objects, as long as being affordable to the agent (as in the case of our healthy adult participants), are picked up imperatively and are not necessarily accompanied by the analysis of functionality and meaning of the objects (Gibson 1979). The automatic facilitation on the side of the graspable part of the novel objects is consistent with this automaticity and its independence from semantic knowledge.

Chapter 6

Damaged selective attention and response inhibition alter the effects of implied between-object actions

Abstract

Previous chapters suggest dissociation between active and passive objects, and a bias towards the affordance of active objects in response to implied between-object actions. This implies an inhibitory component in affordances selection evoked by paired objects. Though inhibitory mechanism has been conjectured by previous theories about affordance selection in single object scenarios, it is not clear how it applies to multi-object scenario, as in the paradigm used in previous chapters. It remains an open question whether the observed inhibitory effect reflects attention selection or response inhibition based on the perception of the shared affordance of object pairs. To answer this question, the present chapter reported two case studies of patients with lesion-induced deficits in either domain, as well as older healthy control participants. We found that lesion-induced and aging-related changes in executive functions alter the responses to implied between-object actions. The results were discussed in relation to the role of executive functions in affordance selection and the potential impact of aging.

6.1 Introduction

Previous chapters established that implied between-object actions affect affordance selection for neurologically intact participants. In Chapter 2 we identified two effects of implied between-object actions. Both suggested selection between objects: the inhibitory effects on responses aligned with the passive objects and the advantage for active objects.

The results suggest that when faced with pairs of objects positioned as if in interaction observers select the affordance of the active objects over that of the passive objects. This notion is further supported by the findings in Chapters 3-5. The present chapter asks what the cognitive mechanism of such selection is by examining the performance of two patients. Each patient has lesion-induced deficit in a process potentially crucial for affordance selection.

Theories and hypotheses have been proposed regarding the mechanism of affordance selection (for a review, see Thill et al., 2013). Cisek (2007) considered single object scenarios and proposed that the brain specifies several currently available action possibilities in parallel, and these potential actions compete with each other under modulation from top-down control. However, what happens when one faces a loosely structured scene, in which the affordance of each object was constrained by their functional and spatial relation with other objects? Linking to the results of previous chapters, what is the neurocognitive mechanism behind the selection in response to implied between-object actions?

Here we consider two candidates, selective attention and response inhibition. Even though selective attention and response inhibition are strongly related, they are dissociable both functionally and anatomically (Barch, 2013; Tian, Liang, & Yao, 2014). The two processes are operationalized and measured by distinct behavioural tasks. To investigate selective attention, endogenous (e.g. Stroop task) and exogenous attention tasks (e.g. peripheral cueing paradigm) are used, while the capability of response inhibition is often examined with Go/No-go task and Stop-Signal task. Anatomically, selective attention is typically linked with the fronto-parietal network (Barch, 2013; Braver, Barch, Gray, Molfese, & Snyder, 2001; Corbetta & Shulman, 2002). In this network, the intraparietal cortex and the superior frontal cortex are involved in top-down attentional modulation, while areas including the temporoparietal cortex and the inferior frontal cortex are specialized for bottom-up attentional selection (Corbetta & Shulman, 2002). On the other hand, response inhibition is assumed to rely on a different network, the cingulo-opercular network (Barch, 2013; Dosenbach, Fair, Cohen, Schlaggar & Petersen, 2008; Petersen & Posner, 2012; Tian et al, 2014). This response inhibition network stops or interrupts unwanted or irrelevant motor responses (Tian et al, 2014) and maintains stable goal-related functional set (Dosenbach et al., 2008). It consists of the midline frontal/anterior cingulate cortex, the dorsolateral prefrontal cortex (dlPFC), the dorsomedial frontal cortex (pre-SMA), as well as subcortical regions including the basal ganglia (Dosenbach et al, 2008; Petersen & Posner, 2012; Tian et al, 2014). Specifically, the anterior cingulated cortex (ACC) is associated with the facilitation of appropriate responses (Bench et al., 1992; Corbetta, Miezin, Dobmeyer, Shulman & Petersen, 1991; Paus, Petrides, Evans & Meyer, 1993), inhibition of the inappropriate ones (Paus et al, 1993), error detection (Carter et al., 1998; Gemba, Sasaki & Brooks, 1986), and conflict monitoring (Botvinick , Barch, Carter & Cohen, 2001), while lesion in the frontal cortex leads to severe deficit in behavioural inhibition (Drewe, 1975a,b; Stanley & Jaynes,1949).

Take the effects observed in Chapter 2 and 3, it is possible to explain the automatic prioritization of active over passive objects with the function of either network. It might be that the active object gains an advantage via selective attention, which facilitates processing and generates stronger codes of its affordance compared with the passive object (the advantage effect). Besides, the stronger codes associated with the active object might act as a strong competitor with the affordance of the passive object when the two were presented as if in interaction, and the competition might slow down the response aligned with the passive object in that condition (the inhibitory effect). Alternatively, the competitive processes might happen at a later stage, in the form of response inhibition. Affordances of both objects might be extracted and the responses corresponding to both (sets of) affordances active, until one response is chosen and the others are inhibited. In this case, one can expect that the response inhibition network plays a significant role in affordance selection. However, the two networks interact intensively in real life, which makes it difficult to examine the relative contribution from these two functional modules in healthy participants.

Consequently, this chapter tries to dissociate their contributions by examining the performance of two patients whose lesions affect either of the two networks. The patient GA suffers from dysexecutive syndrome, and magnetic resonance imaging (MRI) results (see Figure 6-2) revealed lesion in his medial frontal cortex including the ACC, a critical structure in the response inhibition network. The medial frontal cortex and the ACC have been suggested to play central roles in monitoring potential conflict (Carter et al., 1998; Mostofsky, & Simmonds, 2008) and maintaining constant task-related modulation (Dosenbach et al., 2008). The other patient, PF, has lesions in bilateral superior parietal areas and the intraparietal sulcus (See Figure 6-1). Both areas are crucial structures in the frontoparietal attention selection network. These areas are assumed to carry out top-down attention control and its integration with bottom-up attention selection (Corbetta & Shulman, 2002; Yantis & Serences, 2003; Petersen & Posner, 2012). PF displayed syndromes of deficit in selective attention in the form of mild simultanagnosia and extinction (in left visual field). In sum, the lesion sites and symptoms of GA and PF are linked to selective attention and response inhibition respectively. Here we tested the performance of these two patients, using the same paradigm as in our previous studies (Chapter 2). We aim to examine whether the deficit of either networks eliminates the effects of implied between-object actions, and hope the results would inform the discussion of the neurocognitive mechanisms of affordance selection in multi-object scenarios.

As in Chapter 2, we required participants to respond to a central shape which was preceded by a pair of objects. We examined the effects of the implied between-object actions on responses to the target shape. Out of the same consideration as in Chapter 3-5, we manipulated the orientation of active objects to manipulate implied between-object actions. The present chapter examines how deficits in selective attention and response inhibition affect the two effects of implied between-object actions (see Chapter 2) respectively. The link between performance and lesion will inform the neurocognitive mechanism behind the responses to implied actions. Besides the two patients, we tested older healthy participants who provided a baseline for change in the interested processes induced by healthy aging.

6.2 Methods

6.2.1 Case report

PF (dob 4.2.48, female)

PF was 65 years old at the time of testing. She suffered bilateral lesions to the posterior parietal cortices including the superior parietal lobe and the intraparietal sulcus, extending more inferiorly in the left hemisphere (Figure 6-1), caused by two strokes. PF has deficit in attentional selection, especially for stimuli presented in the left visual field, while the right visual field is her "good side", comparatively. PF presented with a mild case of simultanagnosia and left visual extinction with brief visual displays. Both are demonstration of her attentional deficits (Kinsbourne & Warrington, 1962; Soto, Mannan, Malhotra, Rzeskiewicz, & Humphreys, 2011; Vancleef, Wagemans, & Humphreys, 2013; Wulff & Humphreys, 2013). For bilateral letter presentations shorter than 200 ms, she consistently made errors by failing to report the item in her left visual field (Braet & Humphreys, 2007). PF did not show particular deficits in motor-related tasks, as shown in the tests of multistep object use and gesture production of Birmingham Cognitive Screen (Bcos, Humphreys, Bickerton, Samson, & Riddoch, 2012). Data of the present study were collected in 2014.

Figure 6-1. Lesion transcriptions for PF (Humphreys & Bedford, 2011)

GA (dob 23.5.54, male)

GA was 59 years old at the time of testing. He suffered bilateral damage to the middle and anterior temporal lobe and damage in the frontal lobes (particularly on the left), including ACC (Telling, Meyer & Humphreys, 2010, see Figure 6-2). His lesion was caused by herpes simplex encephalitis infection. He has severe amnesia, and shows signs of surface dyslexia and dysgraphia, and a deficit in object identification, which was most pronounced for living things, but not for inanimate stimuli (Humphreys & Riddoch, 2003). GA showed reduced suppression for saccade towards distractors (Telling, Meyer & Humphreys, 2010). GA also showed evidence of dysexecutive syndrome in tests including the Wisconsin Card Sort Task, the Hayling test of the frontal lobe and the Stroop test, but achieved average score in the Brixton test of frontal lobe function. GA shows no evidence of any low-level perceptual deficit (Humphreys & Riddoch, 2003). His dysexecutive syndrome is of most interest to the present study. Data were collected between 2011 and 2012.

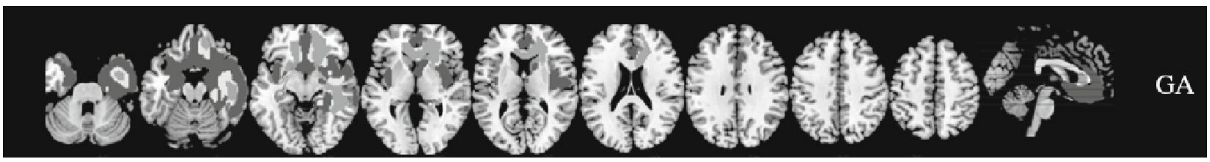

Figure 6-2. Lesion transcriptions for GA (Humphreys & Bedford, 2011)

Age-matched healthy older adult participants

Eight healthy volunteers (three males, mean age 63.9 years) from the research volunteer pool of School of Psychology, University of Birmingham were recruited in the experiment. All participants have normal or corrected-to-normal vision. Participants gave informed consent and received monetary compensation for their time.

6.2.2 Stimuli and Procedure

The stimuli used in Chapter 6 were the same as in Chapter 4, consisting of 23 pairs of greyscale clip-art style images of objects on a light grey (200, 200, 200 RGB) background. Each pair included an active object and a passive object routinely used together in common actions (see Figure 2-1 for an example and Appendix 2-A for a complete list of the object pairs used). Stimuli evaluation by a separate group of participants revealed that the stimuli are appropriate. The detailed description of the procedure and the results can be found in Chapter 2, Appendix 2-C. The presentation parameters were the same to that in Chapter 2-5. Matlab7 (The MathWorks Inc., Natick, MA, USA) with Psychtoolbox 3 installed on a Windows XP computer was used to display the stimuli and record RTs.

The experiment follows a 2 (SOA: 240 ms vs. 400 ms) × 2 (co-location: correct vs. incorrect) × 2 (the layout of paired objects: Active-left vs. active-right) × 2 (response compatibility: Active object vs. passive object) within-subject factorial design. Though previous studies in this thesis did not find any effect of object layout in the young participants without experimental interference, the factor of layout was still included in the present study in order to capture any potential impact of the lateralized attentional capability of PF. SOA was retained as a factor in case any slower effect might emerge for older adults, since they rely on slower and controlled processes more than younger adults (Davis et al., 2008; Heuninckx, Wenderoth, Debaere, Peeters, & Swinnen, 2005; Park & Reuter-Lorenz, 2008). The patients and older healthy participants all took part individually in the experiment in a dimly lighted room, with their upper arms resting on the table and index fingers of their left and right hands resting on the f and j keys respectively. A detailed description with illustration of each trial can be found in the method part of Chapter 2 (and Figure 2-2). For GA, the experiment consisted of 10 sessions, proximately one hour each. Each session consists of 5-

14 blocks. Each block contains 32-64 experimental trials and four warm-up trials, lasting for 3-6 minutes. The number and the length of the blocks were adjusted according to the patient's concentration status at that moment. The adjustment led to a total number between 15-30 trials per condition in each session. For PF, the experiment consisted of 6 sessions, one hour each. Each session consists of 8-9 blocks. Each block contains 52-84 experimental trials and four warm-up trials, lasting for 4-6 minutes. The number and length of the blocks were adjusted according to the patient's concentration at that moment. The adjustment led to a total number between 29-47 trials per condition in each session. For the older healthy participants, the experiment consists of ten blocks. Each block consisted of 64 experimental trials following 4 warm-up trials. This led to a total of 40 trials per condition in each session.

The experimental trials were evenly assigned to different conditions in each session and cross sessions. They were presented with pseudo-randomized order, which ensured no more than three consecutive trials belonged to the same condition. Each warm-up trial was randomly assigned to a condition. For GA, each trial was manually started by the experimenter; for PF and the older healthy participants, trials were automatically triggered by key response to the target in the preceding trial. Brief breaks were arranged between blocks.

No accuracy criterion was imposed, however a feedback messages was presented immediately after any error.

6.3 Results

Both patients and healthy older adult participants were highly accurate, with the average accuracy of different conditions between 99% and 100% (mean RTs: PF: 661 ms, GA: 524 ms, healthy older adults: 506 ms. see Table 6-1). RTs were initially trimmed to remove responses quicker than 100 ms. RTs more than 2.5 standard deviations from the mean of each participant were then discarded in a non-recursive manner. Discarded trials were fewer than 2% of the total trials.

The analysis of RTs was based on median RTs of correct trials for each condition. We followed Hulleman and Humphreys' (2007) approach in dealing with single case data. We treated the median RTs in each single one-hour session as a single entry (i.e. as a "participant") in ANOVA, while the healthy older adult participants only participated in one session, and their data were treated in standard method (but with median rather than mean RTs), same to how data from young adult participants were treated in previous chapters. In addition, considering the lack of comparability between the two patients and between both and healthy older adult participants in terms of basic response speed and cognitive capability, we subjected their median RT data separately to an ANOVA with SOA (240ms and 400 ms), co-location (correct vs. incorrect), the layout of objects (active object on the left side vs. on the right side) and response compatibility (with active object and with passive object) as within-subjects factors. In addition to the standard ANOVA, we conducted planned pairwise contrasts between responses aligned with passive objects in the correct and the incorrect co-location conditions (for the hypothesized inhibitory effect of co-location on passive objects) and that between responses aligned with the active and the passive objects in the correct co-location condition (for the hypothesized advantage for active objects over passive objects in the correct co-location condition). The planned pairwise contrasts were designed to examine the effects of implied between-object action identified in previous chapters.

Table 6-1: Average accuracy and reaction times (RTs) of each condition

Participants		**Layout (active objects on the left or right)**	**Response compatibility (passive vs. active objects)**	**Accuracy**	**RTs (ms)**
PF	**240 ms SOA**				
	Correct co-location				
		Left	Passive	0.99	652
			Active	0.99	719
		Right	Passive	1.00	713
			Active	1.00	630
	Incorrect co-location				
		Left	Passive	1.00	650
			Active	1.00	699
		Right	Passive	1.00	722
			Active	0.99	658
	400 ms SOA				
	Correct co-location				
		Left	Passive	1.00	627
			Active	1.00	658

		Right	Passive	1.00	670
			Active	0.99	595
	Incorrect co-location				
		Left	Passive	0.99	616
			Active	0.99	667
		Right	Passive	1.00	664
			Active	1.00	640
GA	**240 ms SOA**				
	Correct co-location				
		Left	Passive	1.00	516
			Active	1.00	549
		Right	Passive	1.00	540
			Active	1.00	554
	Incorrect co-location				
		Left	Passive	1.00	529
			Active	1.00	540
		Right	Passive	1.00	596
			Active	1.00	497
	400 ms SOA				
	Correct co-location				
		Left	Passive	1.00	479
			Active	1.00	518
		Right	Passive	0.99	488
			Active	1.00	512
	Incorrect co-location				
		Left	Passive	1.00	506
			Active	1.00	505
		Right	Passive	1.00	537
			Active	1.00	521
Healthy older adult participants	**240 ms SOA**				
	Correct co-location				
		Left	Passive	0.99	515
			Active	0.99	521
		Right	Passive	1.00	519
			Active	1.00	495
	Incorrect co-location				
		Left	Passive	1.00	507
			Active	1.00	505
		Right	Passive	1.00	533
			Active	0.99	506
	400ms SOA				
	Correct co-location				
		Left	Passive	1.00	492
			Active	1.00	508
		Right	Passive	1.00	518
			Active	1.00	485
	Incorrect co-location				
		Left	Passive	0.99	495
			Active	1.00	495
		Right	Passive	0.99	515
			Active	1.00	481

PF

There was a main effect of SOA, F (1, 5) = 162.23, $p < .001$, $\eta^2 = 0.97$, with RTs in the 240 ms SOA condition being longer than 400 ms SOA condition (MD = 38 ms). The main effect of response compatibility was not significant (p = .43). The interaction between co-location and response compatibility was not significant (p = .22). However, the interaction between SOA, co-location and response compatibility was significant, F (1, 5) = 34.16, p = .002, η^2 = 0.87 (see Figure 6-3), as well as the interaction between co-location and object layout, F (1, 5) = 7.59, p = .04, η^2 = 0.60, and between object layout and response compatibility, F (1, 5) = 17.53, p = .009, η^2 = 0.78 (see Figure 6-4).

Simple effect analysis revealed that the interaction between object layout and response compatibility was driven by consistently quicker responses made by the right hand compared to the left hand: when the active objects were presented on the right side, the responses aligned with the active objects (right hand responses) were quicker than those aligned with the passive objects (left hand responses, MD = 49 ms, p = .048), and when the active objects were presented on the left side, the responses aligned with the active objects (left hand responses) were slower than those aligned with the passive objects (right hand responses, MD = 62 ms, p = .001).

For the interaction between co-location and object layout, simple effect analysis revealed that when the active object was presented on the right side (the “good” side of PF), general response times (i.e. averaged across responses aligned with the active and the passive objects) in the correct co-location condition were shorter than in the incorrect co-location condition (MD = 19 ms, p = .049), and there was no effect of co-location when the active objects were presented on the left side (PF’s “bad” side, p = .24). In other words, the orientation of the active objects affected responses without being modulated by response compatibility when the active object was presented in PF’s “good” side.

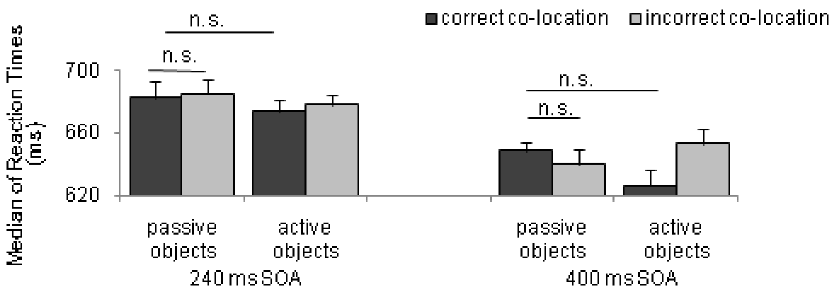

Figure 6-3. PF. Illustration of the three-way interaction. In both SOA conditions there was no sign of inhibitory effect from the correct co-location on responses compatible with passive objects (compared to the incorrect co-location condition) or of advantage for active over passive objects in the correct co-location condition.

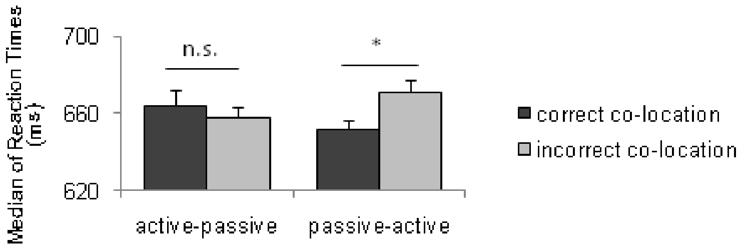

Figure 6-4. PF. Interaction between co-location and object layout. When the active objects were presented on the right side, the responses were quicker in the correct, than the incorrect, co-location condition (bars on the right side), and this contrast was not significant when the active objects were presented on the left side (bars on the left). The error bars indicate the standard error of each condition following the method proposed by Cousineau (2005). The significance of pairwise comparisons is denoted on the figure (a = .05). The same applies to all the bar charts in this chapter.

To examine the three-way interaction between SOA, co-location, and response compatibility, we separately analysed the data in 240 ms SOA condition and in 400 ms SOA condition. We found that the interaction between co-location and response compatibility reached significance in neither SOA condition (240 ms SOA: p = .13, $\eta^2 = 0.39$; 400 ms SOA: p = .072, $\eta^2 = 0.51$). However, we still carried out planned comparison for the inhibitory effect on passive objects and the advantage for active objects. The results suggested that none of the planned comparisons was significant (ps > .16). There was no statistical evidence of inhibitory effect on responses aligned with passive objects in either SOA condition, or of the advantage for responses aligned with active objects, though by visual inspection of Figure 6-3 one can see a pattern similar to the interaction reported in study of young healthy participants. This might suggest that with longer SOA or more sufficient exposure to the stimuli PF can process affordance-related information, and the null effect observed here might be due to the limited power of reduced trial numbers. However, the noticeable weakening of any effects of paired-object affordance suggested already the impact of parietal lesion of PF's responses to paired object affordances.

GA

There was a main effect of SOA, F (1, 9) = 7.25, p = .025, η^2 = 0.45, with RTs in the 240 ms longer than 400 ms condition (MD = 32 ms). The main effect of response compatibility was not significant (p > .96). The interaction between co-location and response compatibility was significant, F (1, 9) = 10.19, p = .011, η^2 = 0.53 (see Figure 6-5). Analysis of simple effects indicated that the responses aligned with the passive objects were quicker in the correct than in the incorrect co-location condition (MD = 35 ms, p = .014), while this effect was not significant for responses aligned with active objects (p = .24). In addition, when the co-location between objects was correct, responses aligned with passive objects were marginally quicker than those aligned with active objects (MD = 27 ms, p =.06), and significantly slower when the co-location was incorrect (MD = 26 ms, p = .041).

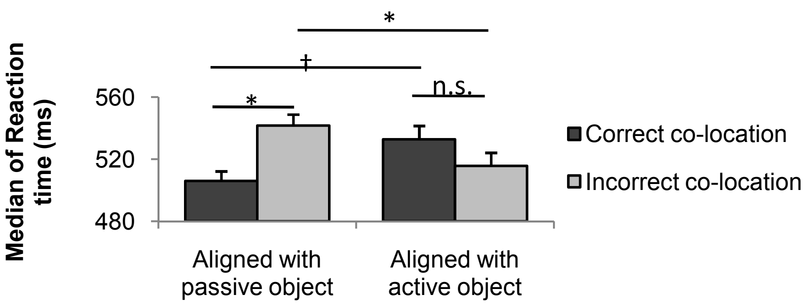

Figure 6-5. GA. Illustration of the interaction between response compatibility and co-location. The responses compatible with the passive objects were quicker in the correct than the incorrect co-location condition (left bars). When the co-location between objects was correct, responses aligned with passive objects were marginally quicker than those aligned with active object (dark bars, denoted by †, p = .10). When the co-location was incorrect, responses aligned with the passive objects were slower than those aligned with the active objects (light grey bars).

Healthy Older Adult Participants

None of the main effect and interaction was significant except the main effect of response compatibility, F (1, 7) = 6.76, p = .035, η^2 = 0.49, with responses aligned with the active objects quicker than those compatible with the passive objects (MD = 12 ms). The interaction between response compatibility and co-location was not significant (p = .20, see Figure 6-6). We still carried out planned contrasts to examine the previously established effects of implied between-object actions. The results of planned contrasts revealed that the inhibitory effect of co-location on responses aligned with the passive objects was not evident (p = .69). The advantage for the active objects in the correct co-location condition was not significant either (p = .11). We also examined the possibility that the current sample size was too small for the effects in question to reach significant. We conducted power analysis for required sample size in pairwise comparison for the inhibitory effect on passive objects, based on the current mean and standard deviation in the two conditions involved. It turned out that a sample of around 500 participants would be needed for this effect to reach significance. This number is beyond practicality and suggested how small is this effect, if it is real. A similar power analysis revealed that a sample of around 7 or 8 participants should have a power of 0.95 for the advantage effect of the active objects to reach significance in one-tail pairwise comparison. This corresponds with the results reported above, where a significant difference between active and passive objects emerged, though across co-location conditions. Consequently, though with limited power, we believe the results would not change qualitatively even if the sample sizes of this experiment were matched with the young-adult experiments reported in previous chapters.

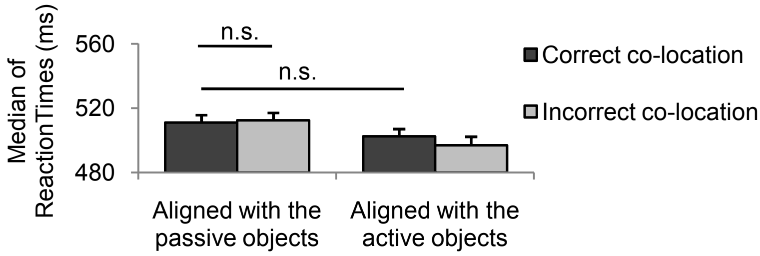

Figure 6-6. Healthy older adult participants. Illustration of the non-significant interaction between response compatibility and co-location. There is no sign of inhibitory effect of co-location on responses aligned with the passive objects (left bars). There is no sign of advantage for active objects in the correct co-location either (dark bars).

6.4 Discussion

We found that lesion-induced and aging-related deficits in both selective attention and response inhibition altered responses to implied between-object actions. Especially, the patient with deficit in selective attention and the healthy aging controls did not show either the advantage for the active object or the inhibition on passive objects, while the patient with deficit in response inhibition showed a facilitative effect on responses aligned with the passive objects where the young adult participants showed an inhibitory effect (Chapter 2-5). These results suggested that both response inhibition and selective attention play crucial roles in affordance selection. The following sections will discuss the implications of these findings.

6.4.1 Aging affects the extraction of implied between-object interaction

Before discussing the effect of cortical lesions, we would like to discuss the finding that healthy aging alters responses to paired objects. The performance of the healthy older adult participants did not replicate either of the effects observed in the young adult participants. Nevertheless, the performance of the healthy older adult participants suggests that they still differentiate between the active and passive objects. Their responses aligned with the active objects were quicker than those aligned with the passive objects. However, such differentiation is not affected by the co-location between objects, i.e. the implied action between objects. This finding contrasts with findings in Chapter 2 where this differentiation depended on the correct co-location. There are at least two explanations for this difference.

First, the healthy older adult participants' responses may be affected by the perceptual features of the objects, e.g. size or general shape, to a larger extent than the affordance of the objects. Note that Chapter 2 ruled out the processing of perceptual features as an influential factor for young participants because the difference between responses aligned with active and passive objects were modulated by co-location. It has been proposed that the activation of action-related representation associated with specific objects can be switched on or off depending on available cognitive resources (Rumiati, Papeo, & Corradi-Dell'Acqua, 2010). The healthy older adult participants might be subjected to aging-induced decline in cognitive resources (Kirasic, Allen, Dobson, & Binder, 1996). Consequently, given that the object pairs were task-irrelevant in the present experiment, the processing priority might be moved away from the affordance of the objects and the between-object action relations, to focus on perceptual processing. However, the frontal-lesion patient GA exhibited signs of being influenced by co-location between objects (a facilitative effect of co-location on responses aligned with the passive object). GA is age-matched with the healthy older adult participants, and should be subjected to comparable aging-induced cognitive alternation. It is unlikely that GA is immune from similar decrease of resources caused by aging. Therefore, it is unlikely that the older adult participants are completely immune to influence from implied between-object actions. Nevertheless, it is possible that their processing priority shifts from affordance processing to the selection of perceptual features, and this shift might be the cause of quicker responses aligned with the active objects across co-location conditions in older healthy participants.

A second possibility here is that the healthy older adult participants still extract action relations between objects and the affordance of object pairs. However, due to the aging-induced change in executive functions, they did not effectively select the responses congruent with the affordance of the active objects over those congruent with the passive objects. The age-related change in executive functions has been well established (Kirasic et al, 1996; Verhaeghen & Cerella, 2002; Fabiani, 2012). On the whole, it is agreed that capabilities decrease with aging in response selection and inhibition of distracting information, due to age-related alternation of the frontal-parietal network, in particular the prefrontal cortex (Fabiani, 2012; Li, Lindenberger, & Sikström, 2001; Milham et al., 2001; Mishra, Anguera, Ziegler, & Gazzaley 2013; Solbakk et al., 2008; Verhaeghen & Cerella, 2002). Following this line of reasoning, we speculate that the healthy older adult participants did extract affordances of both objects but cannot effectively select between them in an adaptive way, which resulted in the absence of affordance-based effects.

6.4.2 The role of selective attention

The patient with lesion in the superior parietal cortex, PF, did not exhibit either typical effect of implied between-object actions, neither did the healthy older adult participants. Though, as mentioned earlier in section 6.3, it is possible that with longer SOA or more sufficient exposure to the stimuli PF can process affordance-related information, the noticeable weakening of any effects of paired-object affordance in PF and older adult participants suggested already changes in the processing of paired-object affordances.

In addition, PF showed an orientation effect when the active objects were presented in the right visual field. Recall her problem is in attending to object in the left visual field, and the right visual field is her "good" side. When the active objects were presented in her "good" side, PF's responses were generally quicker when an active object was presented in canonical orientation (thus in the correct co-location with the passive object), than when the active objects were in manipulated, un-functional orientation (the incorrect co-location condition). Importantly, this orientation effect of PF was not modulated by responses compatibility, i.e. the effect does not differ between responses aligned with the active and passive objects. This is different from the performance of young adult participants, for whom only responses aligned with the passive objects, but not those aligned with active objects or the averaged response time across hands, were robustly affected by the co-location. In addition, instead of being facilitated, young adult participants' responses aligned with the passive objects were slower in the correct than the incorrect co-location conditions.

One possibility is that PF's performance may be the result of a deficit in affordance extraction as her lesion includes bilateral anterior intraparietal sulcus (aIPS). Several studies indicate that aIPS is involved in affordance extraction (Binkofski et al., 1998; Culham et al., 2003; Frey et al., 2005; Rice, Tunik, et al., 2006; Rice et al., 2007; Tunik et al., 2005). Also in Chapter 4 TMS to aIPS disrupted the processing of paired objects affordance. However, here affordance extraction might not be the crucial factor, since PF does not have any syndrome associated with motor control or recognition. Instead, her deficit takes the form of extinction and simultanagnosia, which is well accepted to be a deficit in selective attention (Dalrymple, Barton & Kingstone, 2013; Chechlacz et al., 2012).

Another possibility is that the driving factor of PF's distinct response pattern is her deficit in selective attention rather than affordance selection. Note that a difference between responses of PF and healthy older participants is that PF exhibited an orientation effect across hands when the active objects were presented on her "good" (right) side. In other words, this orientation effect is independent of which type of objects the responses were aligned with and whether they are compatible with the affordance of the active objects. This suggested that this effect does not come from affordance-based processing. As the effect of co-location solely depended on object layout and only existed when the active objects were on PF's "good" side, it is conceivable that PF's deficit in attention might have biased her attention towards a "good-side-only" strategy, i.e. preferably processing the stimuli presented in her "good" side. The influence of object orientation might be associated with higher familiarity to objects in their canonical orientations, compared to objects in non-canonical orientations (as the active objects in the correct compared to the incorrect co-location conditions). This higher familiarity might be better perceived when the active objects (the objects whose orientation changes across conditions) were presented in PF's "good" side than when they are in the "bad" side. This increased familiarity of the visual stimuli, though task irrelevant, might have captures PF's attention to the stimuli in general and produced a general facilitation on responses to the subsequent visual stimuli (the target). Therefore, the orientation effect might be the product of perceptual processing instead of affordance-based processing. Consistent with the supposed “good-side-only” strategy, PF’s right-hand responses were consistently quicker that the left-hand ones. This can be a handedness effect. However, the lack of such effect in healthy participants suggested that it can also be the result of a lopsided visual representation of PF in which spatial codes of objects on the right side are always stronger than those from the left side. In addition, different from the healthy older adult participants, PF did not show general quickening effect when the responses were aligned with the active objects compared to those aligned with the passive objects across co-location conditions. This might also be the result of the “good-side-only” strategy, which acted on active and passive objects unselectively when they are on her “good” side, and thus evened out the advantage for active over passive objects.

6.4.3 Response inhibition is critical for the selection of the active objects over passive objects

The response pattern of the patient with medial frontal lesion, GA, is quite distinct from the response patterns of any population we examined so far. Especially, the responses aligned with the passive objects result in facilitation rather than inhibition from implied between-object actions. This dramatic change in response pattern compared with healthy older adult participants suggests that response inhibition plays a critical role in responding to paired objects. We consider GA’s distinct response pattern as a result of GA’s failure in inhibiting responses to attentional orienting evoked by active objects. As noted by Roberts and Humphreys (2011b), the orientation of the active objects may have an attentional orienting effect similar to that of an arrow often used in attentional cueing experiments. This similarity led them to suggest that the active object may act as a cue to direct visuospatial attention towards the passive objects, i.e. the direction of the active objects’ functional use. This directional cue might have produced reflexive motor responses sharing the same spatial codes, which are aligned with the passive objects. Since GA’s ability to inhibit responses is diminished, responses aligned with passive objects are facilitated rather than inhibited as in younger healthy adults.

In addition, GA's responses aligned with the active objects were quicker than those aligned with passive objects in the incorrect co-location condition. The advantage for active objects in the incorrect co-location condition might be a residual of the general advantage for active objects observed in healthy older adult participants. For GA, the advantage for the active objects might be diminished by the attentional orienting towards the passive object and away from the active object in the correct co-location condition. Further, when the co-location was incorrect, responses aligned with the passive objects no longer benefited from such orienting, thus become slower, even slower than those aligned with active objects, probably also due to the distraction presented by an active object presented in non-canonical orientation. Taken together, we speculate that relying on response inhibition, young healthy participants can inhibit the impulsive responses following the attention orienting cued by the active objects towards the passive objects. In the case of healthy older adult participants, due to the age related declining in executive functions, they could not inhibit the responses aligned with the passive objects following the attention orienting as effectively, but still maintained certain extent of cognitive control, hence the lack of difference between co-locations. For GA, with lesion in the response inhibition network, his deficit is more severe, hence such attention orienting caused by active objects produced the most profound influence on his responses compared to other samples.

Worth noticing, GA also suffers from lesion in temporal lobe. Is it possible that his distinct response pattern is the result of the ventral stream deficit instead of response inhibition? We consider this to be unlikely because of two reasons. First, our TMS study (Chapter 4) found that stimulation of the ventral stream does not systematically alter the responses to implied between-object actions, suggesting that the ventral stream processes are not crucial in generating the observed effects in healthy younger adults and possibly in GA. Second, GA's deficit in object recognition mainly affects the recognition of living things, and he does not show problems with object recognition and semantic knowledge of man-made object. The symptom profile of GA suggested that the temporal lesion mainly affected his episodic memory in the form of amnesia. Though we do not rule out the possibility that GA's lesion in temporal lobe contributes to his distinct response pattern, we do not consider it is a major cause.

6.4.4 Roles of executive functions in affordance selection

In the present study we found that selective attention and response inhibition networks both contribute to responses to implied between-object actions. Our results added insights from two aspects to the discussion on affordance selection. First, we found that the performance of GA differed greatly from PF and older healthy participants. This suggests that at least for older population, their response to implied between-object actions relies heavily on response inhibition. Our results with GA suggested that implied between-object actions are automatically perceived, but some motor activation of afforded actions were inhibited in the response inhibition stage, probably in the ACC and other medial frontal areas. Interestingly, these areas in response selection network are not among the central areas previously considered to be involved in affordance selection, which are mainly in the frontal-parietal network (Cisek, 2007; Cisek & Kalaska, 2010; Thill et al., 2013). Admittedly, these brain regions are closely interconnected, and patient lesions are rarely restricted to one area. However, our results with GA still indicate the need to investigate the contribution of response inhibition in affordance selection. Second, our results suggest that affordance selection in multi-object scenarios might be affected via the frontal-parietal network. Previous theories and models of affordance selection (Cisek, 2007; Cisek & Kalaska, 2010; Thill et al., 2013) suggested that the frontal-parietal network actively contribute to the selection of affordance under the influence from decision-making and intention. Extending this list, our results here suggested that implied between-object actions also contribute to affordance selection via executive control. With decline in executive functions, the prioritization of the active objects was less apparent in affordance selection, and selection might rely heavily on input from the semantic or perceptual processes (see previous discussion).

6.4.5 Limitations

There are several caveats in applying these findings to the explanation of affordance selection in general. First, with samples smaller than studies with young participants, the experiments reported in this chapter might suffer from reduced power. The negative results thus should be treated with caution, especially on making cross-study comparison.

Second, the present results indicated the influence from response inhibition. However, it has been proposed that as part of the healthy aging process, older adults shift from proactive decision strategies to reactive decision strategies, resolving competition between activated responses at a later stage (Jimura, & Braver, 2010; Grady, 2012). In contrast, younger adults implement a constant preparatory attentional control and effectively use cue information early on. The age-related decline in selective attention might lead to an over-reliance at the later selective stage, i.e. the response inhibition stage, and lead to a distinct responses pattern in healthy older and the medial frontal lesion patient.

Another caveat concerns the importance of executive functions in general. It is important to note that there is an age-related reduction in occipital activity coupled with increased frontal activity (Davis, Daselaar, Fleck, & Cabeza, 2008; Grady et al., 1994; Solbakk et al, 2008). This posterior-anterior shift in aging is likely to reflect an attempt to compensate for deficits in sensory by control processes (Cabeza et al., 2004; Grady et al. 1994; Grady, McIntosh & Craik, 2005; Madden, Connelly & Pierce, 1994). In other words, younger healthy adults might not rely as heavily on executive functions in extracting and selecting affordance as the older adult participants.

Similarly, though our findings in this chapter suggested a heavy influence from controlled processes, e.g. top-down attentional control and response inhibition, it is important to bear in mind that the younger adults might rely on controlled processes at a lesser degree than older adults (Davis et al., 2008; Heuninckx, Wenderoth, Debaere, Peeters, & Swinnen, 2005; Park & Reuter-Lorenz, 2008). Recall that affordance selection (Cisek, 2007; Cisek & Kalaska, 2010; Thill et al, 2013) and extraction can be carried out in a highly implicit and automatic manner (e.g. Goslin et al., 2012; Handy et al., 2003; Tucker & Ellis, 1998, however see Cho & Proctor, 2011 and Pellicano et al., 2010 for examples of task-sensitivity of affordance-based effects and see Rumiati, et al, 2010 for a theoretical explanation). Consequently, it is possible that the young healthy adults might rely on automatic, affordance-based processes, in contrast to controlled and perceptual-based processes, to a larger extent than older adults, and future work is needed to examine whether and how executive functions contribute to affordance selection in multi-object scenarios in young adults.

Chapter 7 General discussion

How will implied between-object actions affect responses? This has been the general research question behind the studies presented in this thesis. In this chapter, I would like to summarize the main findings across chapters and present some conclusions and speculations based on these results. Finally, I will briefly mention the limitations of the present thesis and will identify some research questions for further investigations.

In a paradigm adopted from single-object affordance compatibility paradigm, Chapter 2 identified two behavioral effects from implied between-object actions on manual response, i.e. the advantage for the active objects in the correct co-location condition and the inhibitory effect from implied between-object actions on the passive objects. Here these two effects refer to contrasts between two different pairs of conditions and address two distinct but strongly related effects on affordance selection. The advantage of the active objects was based on the contrast between responses aligned with the active and the passive objects in correct co-location condition, and illustrates the relative advantage of the active over passive objects when both were presented in co-location implying between-object interaction. On the other hand, the inhibitory effect on the passive objects was indicated by the comparison between responses compatible with the passive objects in correct and incorrect co-location conditions, and it reflects how the presence and absence of a co-location implying between-object interaction affect affordances of the passive objects in affordance selection. Nevertheless, though addressing distinct aspects of affordance selection, both effects suggested an automatic prioritization of the affordances associated with the active objects in action-related object pairs.

Chapter 3, together with Chapter 2, confirmed that these effects are based on action-related processing instead of object recognition and identification, and further suggested that the effect of implied actions can be driven by the presence of an action-related structural cue of affordance. Also, these two chapters suggested that these effects are based on the activation of broadly defined action codes instead of specific motor programs for the implied actions. Chapter 4, using TMS technique, revealed the importance of the dorsal visual stream in generating the effects of implied actions and supported the assumption that the affordance of the active objects plays a dominant role in the observed effects. Chapter 5 examined the acquisition of new between-object actions from the perspective of tool use learning, and found a dissociation between establishing declarative knowledge and procedural knowledge of action relations between objects. Chapter 6 examined the performance of patients with selective brain lesions and healthy older adults, and revealed that executive functions, in particular response inhibition and selective attention, play critical roles in affordance selection. Taken together, these findings outlined the main effects of task-irrelevant implied between-object actions on affordance selection, suggested crucial neural correlates and cognitive processes associated with this influence, and underlined affordance selection between action-related objects.

The main findings and their theoretical implications have been discussed in detail in corresponding chapters. Still there are some points raised by more than one chapter. I would like to highlight such points here.

7.1 The effects of implied between-object actions

7.1.1 The dominance of the active objects

The dominance of active objects in affordance selection received converging support across chapters. The two effects reported in Chapter 2, i.e. the advantage for the active objects and the inhibition on the passive objects, pointed to an automatic prioritization of the affordance of the active objects in paired-object scenarios. Chapter 3 pinned down the source of the advantage for the active objects to the stronger affordance they bear, compared to the passive objects. Chapter 3 also identified action-related structures as one of the possible source of such dominance. However, reanalysis of Experiment 1 in Chapter 2 and Experiment 1 in Chapter 3 suggested that implied actions between active and passive objects still evoke selection of active over passive objects when the active objects do not have handles, but elongated axes. This finding brought forth two possibilities. First, object handle is not the only structure producing such dominance. Second, certain distinct aspect in the representation of the active objects (e.g. semantic or procedural knowledge about its function and functional use) can also contribute to the dominance in question. These two possibilities are not mutually exclusive. A class of action-related structural features and distinct aspect of object representation may both be sources of the dominance of active objects in implied between-object actions. Chapter 4 further demonstrated that TMS stimulation only alters responses to implied between-object actions when the dorsal processing of active objects was impaired, suggesting that even if it is distinct representation of the active objects that biased the affordance selection to active objects, such representation is based on the dorsal instead of the ventral visual stream, thus more likely to be related to the action-based processing, in contrast to any semantic process.

These results collectively suggest that the dominance of the active objects comes from the processing of action-related features they (or the animal-environment system they belong to) bear, e.g. affordance. This notion is consistent with previous explanations of the effect of implied between-object actions in object identification tasks. For instance, based on the results of their temporal judgment study, Roberts and Humphreys (2011a) suggested that there might be two separate components of the effects of action relations, which weighted differently on the perception of active and passive objects. In one stage, the action relations between objects affect the visuomotor responses to the objects, i.e. priming the afforded action between objects in visuomotor (left premotor and parietal) regions of the cortex. Therefore this stage produces a bias towards the affordance of active objects. The second stage groups the two objects and affects the active and the passive object to comparable extents. Similarly, for patients suffering from extinction, the effects of orienting active objects to the patient's dominant hand raised only when the objects were shown from the participant's (egocentric) reference frame (as if the participant is using the objects), suggesting the influence of perceived action implication of the objects, hence an effect based on motor-related processes (Humphreys, Wulff, et al., 2010).

7.1.2 The inhibitory effect on the passive object

The present thesis for the first time reported direct evidence about affordance competition and selection (Cisek, 2007; Thill, et al., 2013) in action-related object pairs, and revealed an inhibitory effect on affordance of the passive object (Chapter 2). The present thesis extended previous literature in affordance selection by illustrating influence from implied actions in multi-object visual scenes. The neural correlates of the observed inhibitory effect were explored in Chapter 4 with TMS technology and in Chapter 6 with neuropsychological methodology. Worth noticing, this inhibitory effect was replicated cross chapters (Chapter 2, 3, 4 and 5) at least for familiar pairs of action-related objects in young healthy adult samples. Chapter 6 suggested that this inhibitory effect might also involve response inhibition based on the cingulo-opercular network and selective attention linked with the fronto-parietal network (Barch, 2013; Braver et al., 2001; Corbetta & Shulman, 2002; Dosenbach et al., 2008; Petersen & Posner, 2012; Tian et al, 2014). However, as detailed in Chapter 6, this conclusion requires caution in transferring to general population.

7.2 Speculative mechanism

Then, what is the mechanism behind the effects of paired-object affordance? The chapters of this thesis collectively informed the answer to this question. Regarding the driving stimuli of the effects in question, Chapter 2, 3, and 4 collectively suggested that the paired objects affect responses by the perceived affordance of the active objects. Further, the results suggested that affordance is not only extracted from single objects, but also across objects: this stronger affordance has to be perceived within an action-related configuration (Chapter 2), and at the same time at the sub-object level the action-related structures of the objects, e.g. a handle, provide crucial information (Chapter 3). Regarding the procedure, the activation might depend on visuomotor representation acquired after slow consolidation (Chapter 5) instead of semantic information and familiarity of visual scene (Chapter 3 and 4), or the declarative knowledge of between-object actions per se, which can be acquired rapidly in learning (Chapter 5). Once an object pair is perceived, a direct result is the activation of broadly defined action codes. These codes are predominantly associated with the active objects, and those associated with the passive objects were inhibited (Chapter 2). The inhibition of the passive-object affordance is contingent to the pick-up of active-object affordance (Chapter 4), and more than one component of executive functions might be involved in this inhibition, i.e. response inhibition based on the cingulo-opercular network as well as attention selection based on the frontal-parietal attention network (Chapter 6). Based on these finding, two speculations can be made.

7.2.1 A sketchy representation of interact-ability

A seeming ambiguity of the findings of this thesis is how much responses to paired objects rely on functional and structure-based affordances, respectively. Recall the theoretical proposals reviewed in Chapter 1, which suggested parallel representations of the structure-based/volumetric/variable affordance and the function-based/stable affordance (e.g. for a review, see Binkofski & Buxbaum, 2013; Buxbaum & Kalénine, 2010; see also Glover, 2004; Johnson-Frey, 2004; Pisella, Binkofski, Lasek, Toni, & Rossetti, 2006; Rizzolatti & Matelli, 2003; Vingerhoets, 2014 for similar dissociation). The former relies on the physical feature of the objects and directs the prehensile action towards the objects, while the later relies on experience and learned stimuli-action association (Buxbaum & Kalénine, 2010; Thill et al., 2013; for the definition of the stable/variable affordance, see Borghi & Riggio, 2009).

Chapter 3 highlighted the importance of the structure-based information, and Chapter 4 and 5 reinforced the crucial role of affordance-based processes in the effects in question. However, Chapter 2 and 3 also revealed that the effects require the processing of action relations between objects, such as the co-location between objects. This implies analysis of the functional aspect of the visual scene, at least at some preliminary level, since the action relation ties closely to the functional use of the active objects. How will these two lines of evidence reconcile? The results from single object presentation might help to illustrate a mechanism behind it. Recall that Experiment 3, Chapter 2 did not find statistical evidence for any inhibitory effect on the empty space. Even though in this case the empty space might still have been perceived as hidden or implicit objects, the different pattern of the results suggested that the affordance of the active object as the only presented object cannot replicate the inhibitory effect in paired-object scenario. The only two changes in terms of affordance between single- and paired-object scenarios are the weakening of interaction implication between objects and the explicit affordances of a passive object. However, the affordances of the passive objects along are not manipulated across co-location conditions in paired-object scenarios, thus cannot explain the inhibitory effect on passive objects. Therefore an obvious conjecture here is that in the paired-object scenarios, what is automatically extracted is a sketchy representation of “interact-ability” between objects, alongside the affordances of both active and passive objects. This feature led to the distinct effects observed in paired-object, but not in single-object scenarios. Here, I use the term “interact-ability” referring to the possibility of interaction between objects (e.g. the possibility of a scooping action between a pair of properly positioned spoon and bowl). Analogous to affordance, this “interact-ability” is dictated by the appropriate co-location and action-related structures of the objects, instead of semantic and functional association between objects. “Interact-ability” might be decided by the affordances suggested by structural features, e.g. the handle of a spoon and the elongated axis of a bottle, as well as by the relative values among them, e.g. co-location and orientation. “Interact-ability” can present between objects which are not commonly used together but are positioned suitable for an action by one object towards the other (Chapter 3, Experiment 1 and 2). For instance, a spoon and a ping pong ball bear “interact-ability” when the ping pong ball is held at appropriate height to be hit or scooped by the spoon, but not when they are in opposite corners of a room. In contrast, “interact-ability” is weak even for commonly interacting objects if their co-location does not permit any valid interaction, as in the incorrect co-location condition in the paradigm used in the present thesis.

This notion of the extraction of interact-abilities can be considered as an extension of the concept of affordance, and fits well with Gibson’s (1979) conception that affordance is integral in the continuous visual input from the entire visual environment. Note such interaction-ability is not really a functional affordance in the traditional sense, as it does not specify the exact action involved and the exact outcome to be expected (Experiment 1 and 2 in Chapter 3). At the same time, it is only loosely analogous to structure-based affordances, though probably being informed by them (Experiment 2, Chapter 3), because again it does not specify any specific prehensile actions (as suggested by Chapter 2 and 3). Though being distinct in these aspects, the current thesis is not arguing that "interact-ability" is a separate class of affordances like functional and structural affordances. It is possible that it simply reflects how affordances in a visual scene are “grouped” together, thus, being secondary to single-object affordances. Similar secondary features might be, for instance, density or variety of affordances in a visual scene. Future work is needed to examine how such "interact-ability" is independent or dissociable from single object affordance.

7.2.2 Maps of action possibilities and interact-abilities

In addition to the idea of extracting interact-ability, it is also possible that the spontaneous processing of a visual scene containing action-related objects generates a map of crudely defined interact-abilities and single-object affordances across this scene. The mapping would be relatively free from semantic knowledge of objects. Especially, the relative values deciding interact-abilities (co-location, implication of interaction etc) might even be the primary information picked up from a multi-object scenario, in contrast to specific, object-based affordance extracted in a local, analytic manner.

From the affordance map, it can be supposed that the stronger affordance was selected, which triggers inhibitory effects on competing affordances on the same map. This speculated process of affordance selection differs from existing theoretical suggestions (e.g. Cisek, 2007; Thill et al, 2013) in that it suggests the integration between affordance and relative spatial information, and makes proposal regarding the scale in which affordance is picked up.

Admittedly, these speculations are far from fully scrutinized, and should not be accepted without thorough examination. Future work is needed to test the proposed extraction of interaction-ability and the 'holistic' mapping of affordances in multi-object scenarios, their nature and their neural correlates, and, especially, whether the relative location of the action-related structural features are sufficient to activate such a "between-object" affordance.

7.3 Affordance selection in a visual scene

Widening the focus and extending it to a more general field, the present thesis linked affordance selection to visual scene perception. This topic repeatedly appeared in the discussion of each chapter.

As we have mentioned, Chapter 2 suggested that affordance of paired objects were evaluated on the scale of configuration of object pairs. Though this effect is dominated by the affordance of the active objects (Chapter 3 and 4), the dominated affordance initiates inhibition on other objects in the scene (Chapter 4). This echoes previous findings that positioning objects correctly for interaction groups the objects into a perceptual unit (e.g. Riddoch et al., 2003), as well as the results suggesting the importance of visual context in perceiving object pairs (Humphreys, Wulff, et al., 2010; Riddoch et al., 2011; Yoon, et al., 2010). Riddoch and colleagues (Riddoch et al., 2011) directly manipulated the configuration of paired objects, and found such manipulation alters the effect of paired objects on reducing visual extinction.

The present thesis also confirmed the qualitative difference between the affordance-based effects of paired objects and that of single objects (Chapter 2 and 5). The effect of a visual context implying between-object actions might be a source of such differences. In this sense, the present thesis indicates that contextual information affects affordance extraction not only via task requirement and intention set (Bub & Masson, 2010; Loach, et al., 2008; Masson et al., 2011; Pavese & Buxbaum, 2002; Pellicano, et al., 2010; Symes, et al., 2005; Tipper et al., 2006; Yoon, et al. 2010), but also via the presence of a potential goal of the active object. Admittedly, the presence of a recipient object might cast its impact by emphasizing the potential action between objects and bias the intention set of the observers. Whether or not the impact is produced via alternating action intention, results of the present thesis suggested that such contextual information can be registered without support from experience and semantic association. To examine whether meditation from intention exists, future work is needed to compare the difference between the influences of a passive objects (thus the formation of a scene) with other kinds of contextual information indicating functionality of the objects, i.e. a verbal prime about the function of objects.

7.4 Limitations and outlooks

Finally, I would like to point out some limitations of the thesis, and I suggest future work to provide further insight. The first limitation is that the present thesis exploits a highly simplified laboratory setting. In the present thesis, line drawings of objects instead of real objects were used as stimuli, and most experiments measured key-pressing task which only share the left-right dimension of the affordances of presented objects. The nature of the setting and the artificial format of the task might have limited the degree of specification in affordance extraction and selection, and future work is needed to test whether interact-abilities between objects influences responses in a more naturalistic experiment setting. A second limitation is that the present study did not manipulate action intention towards the objects, but held it at a minimum level. It is highly possible that action intention might bring crucial qualitative differences to affordance selection, and a comprehensive understanding, probably of higher ecological validity, might be achieved only after affordance selection was investigated with action intention at medium or high level.

In addition, the present study focused on two-object scenarios. Just as using line drawings of objects, this setting greatly simplified the visual input and increased the relative salience of the implied action between objects (by removing all other stimuli). Will the effects of implied between-object actions remain in more complex visual scenes consisting of more objects? Can we extract multiple interact-abilities from a same visual scene? Can we hold them simultaneously? Will they compete? How do we choose? How do they affect our conscious perception and motor responses to the whole scene? These questions are all worth exploring, and answering them will bring further insight into scene perception.

Importantly, the questions point towards a potential characteristic of visual scene, which is rarely investigated before: similar to the affordances of a single object, the meaning of a visual scene might not only reside in its semantic meaning and perceptual features, but also in the actions it affords to the animal and the actions between various parts of this scene. Earlier in this chapter I suggested that "interact-ability" can be a feature one picks up from visual scenes in a manner analogous to the extraction of affordance. This leads to a question that whether there is other affordance-like feature of the multi-object visual scene which can be automatically extracted in similar manner, e.g. the density and variation of affordances provided by a visual scene? Can they be counted as separate classes of affordance? Future work is needed to answer this question properly.

7.5 Summary

The present chapter briefly reviewed findings from previous chapters and discussed their implication on the research question of the present thesis, i.e. how will the implied between-objects actions affect responses? Collectively, the findings of the present thesis suggested an automatic prioritization of the active over the passive objects based on the processing of action-related information of the objects, which is relatively independent from the identities of the objects and the object pairs. These findings extended previous literature in affordance selection by illustrating affordance selection between action-related objects and the influence from such implied action relation. Further, this chapter suggested that the results in previous chapters may reflect the extraction of "interact-ability", together with single-object affordances, from multi-object scenarios, and that these action-related features can be included into certain map for the visual scene (see discussion in section 7.2). This chapter further underlined the need for thorough investigation on whether and how action-related information is extracted in realistic and complex visual scenes and how such extraction is analogous or different from the extraction of single-object affordances.

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Appendix

Appendix for Chapter 2

Appendix 2-A: Stimuli used in Experiment 1 and 4

	Active Objects	Passive Objects
1	Screwdriver	Screw
2	Jug	Glass
3	Bottle	Glass
4	Jug	Cup
5	Kettle	Cup
6	Bottle	Cup
7	Jug	Bowl
8	Kettle	Bowl
9	Bottle	Bowl
10	Watering can	Plant
11	Saw	Wood
12	Axe	Wood
13	Hammer	Nail
14	Pliers	Nail
15	Spoon	Bowl
16	Baseball bat	Baseball
17	Table tennis bat	Ping pong ball
18	Tennis racket	Tennis ball
19	Badminton racket	Birdie
20	Knife	Tomato
21	Knife	Carrot
22	Knife	Pepper
23	Wrench	Nut

Appendix 2-B: Stimuli used in Experiment 2

	Active objects	Passive objects
1	Screwdriver	Screw
2	Jug	Glass
3	Bottle	Glass
4	Jug	Cup
5	Whisk	Bowl
6	Bottle	Cup
7	Jug	Bowl
8	Brush	Dustpan
9	Bottle	Bowl
10	Spatula	Frying pan
11	Hammer	Nail
12	Opener	Bottle
13	Corkscrew	Bottle
14	Pliers	Nail
15	Spoon	Bowl
16	Ladle	Saucepan

Appendix 2-C: Stimuli used in Experiment 3

	Active Objects
1	Screwdriver
2	Jug
3	Bottle
4	Jug
5	Kettle
6	Bottle
7	Jug
8	Kettle
9	Bottle
10	Watering Can
11	Saw
12	Axe
13	Hammer
14	Pliers
15	Spoon
16	Baseball Bat
17	Table Tennis Bat
18	Tennis Racket
19	Badminton Racket
20	Knife
21	Knife
22	Knife
23	Wrench

Appendix 2-D: Material evaluation

Methods

Participants

Two separate groups of volunteers (12 (four males) each, mean age 22 years and 20 years respectively) from the University of Birmingham research participation scheme participated in the material evaluation. The first group participated in Part 1 of material evaluation, in which they evaluated the stimuli used in Experiment 1, 2 and 4, on (a) the familiarity of action relation within each object pair, (b) the effectiveness of manipulation of implied actions by changing co-location and (c) affordance of each object (whether an object afford a left or a right hand action). The second group participated in Part 2 of material evaluation, in which they evaluated the distinction between active and passive objects in each object pair. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received monetary compensation for their time.

Materials and Procedure

In Part 1 of material evaluation, greyscale clip-art style images of 29 pairs of objects, including the ten pairs of objects shared by all three experiments, thirteen pairs used only in Experiment 1 and 4 and another six pairs of objects included only in Experiment 2. The evaluation of the 23 object pairs used in Experiment 1 and 4 and the 16 pairs used in Experiment 2 were analysed and reported separately.

Part 1 of the material evaluation task consisted of four blocks. In each block, each object pair was presented in six variations, and each variation was evaluated in one trial, resulting in 174 trials per block. The variations were generated by manipulating orthogonally the object layout (active-left and active-right) and the co-location (correct, incorrect with the active objects manipulated and incorrect with passive objects manipulated). In this way, the material evaluation replicated all the possible displays of the given pair. In each trial, the object pair was presented at exactly the same location and of the same size as they were in Experiment 1, 2 and 4, and the questions were presented below the images. The participants were required to answer the questions on a five-point scale. The object pair, the question and the choices remained on the screen until a response was made.

In each block, the participants evaluated all object pairs and their variations according to the same question. The sequence of the questions was constant, but the sequence of object pairs within each block varied across blocks and participants.

The four questions served three main purposes:

a. **Familiarity of the action relation** Regarding whether the objects in each pair are typically involved in certain action relation, and whether the action relations between objects were recognized in the incorrect co-location condition :

Are these objects typically used together?

This question was for block 1.

b. **Effectiveness of the manipulation of implied action** Regarding whether their co-location is appropriate for an implied action in the correct co-location condition but not in the incorrect co-location condition:

Are these objects appeared to be being currently used together? Or, are they positioned properly or likely to be used together?

This question was for block 2.

c. **Object affordance** Regarding whether the assumption is valid that objects presented on the left side afford left-hand responses while objects presented on the right side afford right-hand responses:

When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?

When the pair of objects are located in the way they are located on the screen, and you are going to use them together, which hand are you going to use if you are going to handle the object on the left side of the screen?

These two questions were for block 3 and 4 respectively.

Each question was verbally explained to the participants and the evaluation only started after the participants gave explicit indication that they understand each question clearly. Especially, for Question b, it was explained to the participants that the question asked whether they perceive the co-location between objects were conducive to interaction or not, and the “Or,” in Question b leads an alternative expression rather than a different question.

In Part 2 of material evaluation, the participants evaluated the stimuli regarding the distinction between active and passive objects in each object pair, to validate our assignment of active and passive objects. The objects were presented always in the correct co-location (as if being used together to fulfilling certain action). Consequently, each object pair was presented only twice, once with the active object on the left and once on the right side of the screen. The question serves the following question:

d. **Distinction between active and passive objects** regarding which object in each pair was active.

The question was presented as:

When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right one, and press 2 if the right object is going to be used upon the left one.

Results

The response for materials used in Experiment 1 and 4 and Experiment 2 were analysed and reported separately.

The materials of Experiment 1 and 4

Familiarity of the action relation. Objects in each pair were evaluated as typically involved in interaction, and this perception persisted when the two objects were presented in an incorrect co-location. In response to the question "*Are these objects typically used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 4.48, $SD = 0.26$; for object pairs in an incorrect co-location, the mean response was 4.45, $SD = 0.26$. One sample *t*-tests suggest that both ratings significantly diverted from the mid-point, *p*s < .001. A paired sample t-test revealed that the difference between the rating for these two conditions does not differ significantly from each other, $p = .408$.

Effectiveness of the manipulation of implied actions. The manipulation of the implied actions between the stimuli, by changing the co-location, was effective. In response to the question "*Are these objects appeared to be being currently used together? Or, are they positioned properly or likely to be used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 4.78, $SD = 0.14$; for object pairs in an incorrect co-location, the mean response was 2.23, $SD = 0.82$. One sample *t*-tests suggests that both ratings significantly diverted from the mid-point, *p*s < .001. The correct co-located object pairs were judged significantly above mid-point, towards the "yes" direction, $p < .001$, while the responses to the incorrectly co-located object pairs significantly diverted to the "no" direction, $p < .001$. Paired sample *t*-test revealed that the ratings for these two conditions differed significantly from each other, $p < .001$.

Object affordance. The association between object location and its affordance was evident. The objects presented on the left side afford left-hand responses while objects presented on the right side afford right-hand responses. In response to the question "*When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?*" on a five-point scale ranging from "*1: definitely left" to "5: definitely right"*, the mean response to the correctly presented objects on the right side was 3.32, $SD = 0.53$, the ones on the left 2.88, $SD = 0.72$; for object pairs presented in the incorrect co-location, the mean response to the objects on the right side was 3.28, $SD = 0.52$, for the ones on the left side 2.93, $SD = 0.62$. Though the mean values suggested that participants tend to handle right objects with right hand and left objects left hand, one sample *t*-tests suggested that none of the ratings significantly differed from the mid-point, *p*s> .05. However, paired sample *t*-tests revealed significant difference between the rating for left and right objects in both the correct co-location condition ($p = .049$) and the incorrect co-location condition ($p = .034$). Paired sample *t*-tests showed that co-location did not significantly affect the inclination of handling objects with the hand corresponding to its location on the screen (*p*s > .05).

Active-passive distinction. The active-passive distinction between objects was evident. When the active objects were presented on the left side, the participants tended to report that the left objects were active, while in the other object layout condition the participants tended to report that the right objects were active objects. In response to the question "*When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right, and press 2 if the right object is going to be used upon the left one.* ", the mean response when the active objects were on the left side was 1.07, *SD* = 0.05, when the active objects were on the right side 1.98, *SD* = 0.04. One sample *t*-tests suggested that both ratings significantly differed from the mid-point, *p*s<.01. In addition, paired sample *t*-tests revealed that the difference between ratings for object pairs of different layouts was significant ($t(11) = -46.30$, MD = 0.91, $p<.001$).

The materials of Experiment 2

Familiarity of action relation. Objects in each pair were evaluated as typically involved in interaction, and the perception persisted when the orientation of the passive objects were changed. In response to the question "*Are these objects typically used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 4.27, *SD* = 0.24; for object pairs presented in an incorrect co-location, the mean response was 4.21, *SD* = 0.26. One sample *t*-tests suggested that both ratings significantly diverted from the mid-point, *p*s < .001. Paired sample *t*-tests revealed that the ratings for this two conditions did not differ significantly from each other, $p = .169$.

Effectiveness of the manipulation of implied actions. The manipulation of implied actions by changing the co-location was effective. The appropriateness for immediate interaction existed in the correct co-location condition but not in the incorrect co-location condition. In response to the question "*Are these objects appeared to be being currently used together? Or, are they positioned properly or likely to be used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 4.67, *SD* = 0.16; for object pairs incorrectly co-located, the mean response was 1.49, *SD* = 0.88. One sample *t*-test suggested that both ratings significantly diverted from the mid-point, *p*s < .001. The correct co-located object pairs were judged significantly above mid-point towards the "yes" direction, $p < .001$, while the responses to the incorrectly co-located object pairs significantly diverted to the "no" direction, $p < .001$. Paired sample *t*-tests revealed that the differences between the ratings for these two conditions differed significantly from each other, $p < .001$.

Object affordance. The association between object location and its affordance was evident. The objects presented on the left side afforded left-hand responses while objects presented on the right side afforded right-hand responses. In response to the question "*When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?*" on a five-point scale ranging from "*1: definitely left" to "5: definitely right"*, the mean response to the correctly co-located objects on the right side of the pairs was 3.43, *SD* = 0.49, the ones on the left side 2.87, *SD* = 0.75; for object pairs incorrectly co-located, the mean response to the objects on the right side was 3.39, *SD* = 0.47, for the ones on the left side the mean response was 2.89, *SD* = 0.75. Though the mean values suggested that participants tended to handle the right objects with their right hands while the left objects the left hands, one-sample *t*-tests indicated that none of the ratings significantly diverted from the mid-point, *p*s> .05. However, paired sample t-tests revealed significant difference between the ratings for left and right objects in both correctly co-located (*p* = .021) and incorrectly co-located (*p* = .047) object pairs. Paired sample *t*-tests suggested that changing the co-location did not significantly affect the inclination of handling objects with the hand corresponding to its location on the screen (*p*s > .05).

Active-passive distinction. The active-passive distinction between objects was evident. When the assigned active objects were presented on the left side, the participants tended to report that the left objects were active, while for pairs with the other layout the participants tended to report that the right objects were the active ones. In response to the question "*When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right, and press 2 if the right object is going to be used upon the left one.* ", the mean response when the active objects were on the left side was 1.09, *SD* = 0.07, when the active objects on the right side 1.90, *SD* = 0.08. One sample *t*-tests suggested that both ratings significantly differed from the mid-point, *p*s<.01. In addition, paired sample *t*-tests revealed that the difference between ratings for object pairs of different layouts was significant, $t(11) = -20.96$, MD = 0.81, $p<.001$.

Appendix for Chapter 3

Appendix 3-A: Stimuli used in Experiment 1

	Active objects	Passive objects
1	screwdriver	cup
2	jug	Ping pong ball
3	bottle	tomato
4	jug	Tennis ball
5	Bottle	carrot
6	Jug	nut
7	Bottle	wood
8	Hammer	birdie
9	Pliers	baseball
10	Spoon	wood
11	Kettle	screw
12	Kettle	pepper
13	Watercan	nail
14	Saw	bowl
15	Axe	bowl
16	Baseball Bat	plant
17	Ping-Pong Bat	glass
18	Tennis racket	cup
19	Badminton Bat	bowl
20	Knife	nut
21	Knife	glass
22	Knife	nail
23	wrench	cup

Appendix 3-B: Stimuli used in Experiment 2

	Active objects	Passive objects
1	glass	screw
2	glass	nail
3	glass	Ping pong ball
4	cup	screw
5	cup	nail
6	cup	Ping pong ball
7	frying pan	screw
8	Frying pan	nail
9	frying pan	Ping pong ball
10	pot	screw
11	pot	nail
12	pot	Ping pong ball
13	bowl	screw
14	bowl	nail
15	bowl	Ping pong ball
16	glass	nut
17	cup	nut
18	Frying pan	nut
19	pot	nut
20	bowl	nut
21	glass	birdie
22	cup	birdie
23	Frying pan	birdie
24	pot	birdie
25	bowl	birdie

Appendix 3-C: Material evaluation

C.1 Methods

C.1.1 Participants

A groups of volunteers (12 (four males), mean age 20 years respectively) from the University of Birmingham research participation scheme participated in the material evaluation. The first group evaluated the stimuli used in Experiment 1 and 2, on a) the familiarity of each object pair, b) the effectiveness of manipulation of implied between-object action by changing co-location and c) affordance of each object, and d) the distinction between active and passive objects. All participants were right-handed and had normal or corrected-to-normal vision. Participants gave informed consent and received monetary compensation for their time.

C.1.2 Materials and Procedure

The participants evaluated 23 pairs used in Experiment 1 and 25 pairs used in Experiment 2 regarding the above mentioned aspects.

The material evaluation session contains 5 blocks. In each of the first four blocks each object pair was presented in four variations, and each variation was evaluated in one trial. The variations were generated by manipulating orthogonally the way of presentation (active-left and active-right) and the co-location (correct, incorrect with the active objects manipulated and incorrect with passive objects manipulated). In this way the material evaluation replicated all the possible displays of the given pair in Experiment 1 and 2. In each trial, the object pair was presented at exactly the same location and of the same size as they were in Experiment 1 and 2, and the questions were presented below the images. The participants were required to answer the questions on a five-point scale. The object pair, the question and the choices remained on the screen until a response was made. In the fifth block, the object pairs used in Experiment 1 and 2 were evaluated according to a fourth aspect, i.e. the distinction between active and passive objects in each object pair, to validity our assignment of active and passive objects. The objects were presented always in the correct co-location (as if being used together to fulfilling certain action) in the fifth block. Consequently in the active-passive judgement block each object pair was presented only twice, once with the active object on the left and once on the right side of the screen.

In each block the participants evaluated all object pairs and their variations according to the same question. The sequence of the questions was constant, but the sequence of object pairs within each block varied across blocks and participants.

The five questions served four main purposes:

a. **Familiarity of the action relation** Regarding whether the objects in each pair are typically involved in certain action relation, and whether the action relations between objects were recognized in the incorrect co-location condition :

Are these objects typically used together?

This question was for block 1.

b. **Effectiveness of the manipulation of implied action** Regarding whether their co-location is appropriate for an implied action in the correct co-location condition but not in the incorrect co-location condition:

Do these objects appear to be currently used together? Or, are they positioned properly or likely to be used together?

This question was for block 2.

c. **Object affordance** Regarding whether the assumption is valid that objects presented on the left side affords left-hand responses while objects presented on the right side affords right-hand responses:

When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?

When the pair of objects are located in the way they are located on the screen, and you are going to use them together, which hand are you going to use if you are going to handle the object on the left side of the screen?

These two questions were for block 3 and 4 respectively.

d. **Distinction between active and passive objects** regarding which object in each pair was active. The question was presented as:

When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right one, and press 2 if the right object is going to be used upon the left one.

Each question was verbally explained to the participants and the evaluation only started after the participants gave explicit indication that they understand each question clearly. Especially, for Question b, it was explained to the participants that the question asked whether they perceive the co-location between objects were conducive to interaction or not, and the “Or,” in Question b leads an alternative expression rather than a different question.

C.2 Results

The response for materials used in Experiment 1 and 2 were analysed and reported separately.

The materials of Experiment 1 (active-passive object pairs which do not typically interact with each other)

Familiarity of action relation Objects in each pair were not evaluated as typically involved in the same action. The absence of action relation persisted in the incorrect co-location condition. In response to the question "*Are these objects typically used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 1.44, *SD* = 0.28; for object pairs incorrectly co-located, the mean response was 1.41, *SD* = 0.31. One sample *t*-tests suggested that both ratings were significantly below the mid-point, *p*s < .001. Paired sample t-test revealed that the ratings for these two conditions did not differ significantly from each other, $p > .05$.

Effectiveness of manipulation of co-location The manipulation of implied action by changing the co-location of objects was efficient. Object pairs positioned suitable to be used together still gave a higher impression of being used together compared to the pairs in which the orientation of active objects were manipulated. In response to the question "*Are these objects appeared to be being currently used together? Or, are they positioned properly or likely to be used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 3.46, *SD* = 1.02; for object pairs incorrectly co-located, the mean response was 1.54, *SD* = 0.40. One sample *t*-tests suggested that in the correct co-location condition the judgement did not significantly differ from the midpoint ($p > .05$), while in the incorrect co-location condition the ratings significantly diverted from the mid-point (t (11) = -12.623, $p < .001$), towards the 'no' direction. Paired sample *t*-test revealed that the difference between the ratings for these two conditions differed significantly from each other (t (11) = 7.76, $p < .001$, MD = 1.92), with responses in the correct co-location condition biased more to the 'yes' direction compared to the incorrect co-location condition.

Object affordance The association between object location and its affordance was evident. The objects presented on the left side afforded left-hand responses while objects presented on the right side afforded right-hand responses. In response to the question "*When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?*" on a five-point scale ranging from "*1: definitely left" to "5: definitely right"*, the mean response to the correctly co-located objects on the right side was 3.73, *SD* = 0.64, the ones on the left side 2.86, *SD* = 0.98; for object pairs incorrectly co-located, the mean response to the objects on the right side was 3.53, *SD* = 0.53, for the ones on the left side the mean was 3.00, *SD* = 0.89. Though the mean values suggested that participants tended to handle right objects with right hand and left objects left hand, one sample *t*-tests suggested that only the ratings for the right objects significantly differed from the mid-point, in both the correct co-location condition (t(11) = 3.90, $p = .002$) and the incorrect co-location condition (t(11) = 3.47, $p = .005$), while responses for the objects on the left side did not differ from the midpoint in both the correct and the incorrect co-location conditions, *p*s> .05. This might reflect the general preference of right hand over left hand among our right-handed participants. However, paired sample *t*-tests revealed significant difference between the rating for left and right objects in the correct co-location condition ($t(11) = 2.46$, $p = .032$, MD = 0.86) and marginally significant difference in the incorrect co-location condition ($t(11) = 2.03$, $p = .068$, *MD = 0.52*). Paired sample *t*-tests showed that the manipulation of action relation does not significantly affect the inclination of handling objects with the hand corresponding to its location on the screen (*p*s > .05).

Active-passive distinction The active-passive distinction between objects was evident. When the designed active objects were presented on the left side the participants tended to report that the left objects were active, while for passive-active object pairs the participants tended to report that the right objects were active. In response to the question "*When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right, and press 2 if the right object is going to be used upon the left one.* ", the mean response to the active-passive object pairs was 1.06, *SD* = 0.06, the passive-active objects 1.96, *SD* = 0.04. In addition, one sample *t*-tests suggested that both ratings significantly differed from the mid-point, *p*s<.001. Also, paired sample *t*-tests revealed that the difference between ratings for active-passive and passive-active pairs was significant ($t(11) = -39.64$, MD = 0.90, $p<.001$).

The materials of Experiment 2 (pairs of passive objects)

Familiarity of action relation Objects in each pair were not evaluated as typically involved in the same action regardless of their co-location. In response to the question "*Are these objects typically used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 1.17, *SD* = 0.35; for object pairs incorrectly co-located, the mean response was 1.18, *SD* = 0.33. One sample *t*-tests suggested that both ratings significantly diverted from the mid-point, *p*s < .001, towards the 'No' end. Paired sample *t*-tests revealed that the ratings for these two conditions did not differ significantly from each other, $p > .05$.

As stated in the main part of the manuscript, we divided the object pairs according to whether the assigned active objects have a handle, and subjected the rating into ANOVA with handle-ness and co-location as within-subject factors. The results showed that the absence of action relation existed in both the handled and non-handle materials; neither the main effect of handleness nor the interaction with co-location was significant (*p*s > 0.1). In addition, one sample *t*-tests suggested that all ratings significantly diverted from the mid-point (*p*s < .001), towards the 'No' end.

Effectiveness of manipulation of co-location The appropriateness of the co-location for serving the common action remained low regardless of the orientation of the active objects. In response to the question "*Are these objects appeared to be being currently used together? Or, are they positioned properly or likely to be used together?*" on a five-point scale ranging from "*1: definitely No*" to "*5: definitely Yes*", the mean response to the correctly co-located object pairs was 2.20, *SD* = 0.66; for object pairs incorrectly co-located, the mean response was 1.97, *SD* = 0.51. One sample *t*-test suggested that the ratings in both the correct ($t(11) = -4.23$, $p = .001$) and the incorrect co-location conditions ($t(11) = -6.98$, $p < .001$) significantly diverted from the mid-point, with the objects were judged not being currently interacting. Paired sample *t*-tests revealed that the differences between the ratings for these two conditions did not differ significantly from each other, $p > .05$.

To examine whether the same pattern existed for pairs with both ‘handled active objects’ and ‘non-handle active objects’, we divided the rating of the two kinds of object pairs and subjected the ratings into ANOVA with handleness and co-location as within subjects factors. The results showed that handleness of the assigned active objects has a significant main effect ($F(1, 11) = 32.08$, $p < .001$, $\eta^2 = .75$, MD = 0.54), with the object pairs perceived more likely to be interacting than those with a non-handle ‘active’ object did. The interaction between handleness and co-location was not significant ($p > .4$). Nevertheless, one sample *t*-test still suggested that the ratings in all conditions significantly diverted from the mid-point ($p < .02$), with the objects judged not being currently interacting. Paired sample *t*-tests revealed that the differences between the ratings for these two conditions did not differ significantly from each other ($p > .05$).

Object affordance The association between object location and its affordance was evident. The objects presented on the left side afforded left-hand responses while objects presented on the right side right-hand responses. In response to the question “*When the pair of objects are located in the way they are currently located on the screen, and you are going to use them together, which hand are you going to use to handle the object on the right side of the screen?*” on a five-point scale ranging from “*1: definitely left” to “5: definitely right”*, the mean response to the correctly co-located objects on the right was 3.47, $SD = 0.66$, the ones on the left side 2.73, $SD = 0.77$; for object pairs incorrectly co-located, the mean response to the objects on the right side was 3.32, $SD = 0.53$, for the ones on the left side 2.70, $SD = 0.74$. Though the mean values suggested that participants tended to handle the right objects with their right hands while the left objects the left hands, one sample *t*-tests indicated that only the rating for the objects on the right side in the correct co-location condition significantly differed from midpoint ($t(11) = 2.44$, $p = .033$) and the difference between the midpoint and the ratings for the objects on the right side in the incorrect co-location condition reached marginal significance ($t(11) = 2.11$, $p = .058$), while the ratings for objects on the left side did not significantly divert from the mid-point ($ps > .05$). This might reflect the general preference of right hand over left hand among our right-handed participants. However, paired sample t-tests revealed significant difference between the ratings for left and right objects in both the correct co-location condition ($t(11) = 2.83$, $p = .016$, MD = 0.74) and the incorrect co-location condition ($t(11) = 2.75$, $p = .019$, MD = 0.62). Paired sample *t*-tests suggested that the rotating of the assigned active objects (major objects) did not significantly affect the inclination of handling objects with the hand corresponding to its location on the screen ($ps > .05$).

To examine whether the same pattern existed for pairs with both ‘handled active objects’ and ‘non-handle active objects’, we divided the rating of the two kinds of object pairs and subjected the ratings into ANOVA with handle-ness, co-location, object (‘assigned active’/major vs. passive) and object location (left vs. right) as within subjects factors. The results revealed no significant main effect of handleness (p > .2). However, there are significant interactions between object (F (1, 11) = 5.73, p = .036, η^2 = .34) and handleness, and between object, object location and handleness (F (1, 11) = 5.48, p = .039, η^2 = .33). Analysis of simple effects revealed that when the assigned active/major objects were presented on the right side, they were rated more suitable to be manipulated by right hand when they had handle, than not (F (1,11) = 17.84, p = .001, η^2 = .62). None of other conditions was affected by handleness. Other significant simple effects includes: passive objects were always rated more suitable for left-hand responses than assigned active/major objects, regardless of handleness (ps < .02); the assigned active/major objects were rated more suitable to be manipulated by right hands, regardless of handleness (ps < .025).

Active-passive distinction The participants could not distinguish the 'assigned active'/major objects from passive objects. In response to the question "When the pair of objects are located in the way they are located on the screen, and you are going to use them together, how will these two objects interact? Please press 1 if the object on the left hand side is going to be used upon the right, and press 2 if the right object is going to be used upon the left one. ", the mean response to the active-passive object pairs was 1.48, SD = 0.30, the passive-active objects 1.48, SD = 0.32. In addition, one sample t-tests suggest that neither of the ratings significantly differed from the mid-point, ps>.05. Also, paired sample t-tests revealed that the difference between ratings for active-passive and passive-active pairs was not significant (p > .05).

However, further analysis divided object pairs in the term of whether the 'assigned' active object in the pair has a handle, in the same way as in the analysis of Experiment 7. A repeated-measure two-way ANOVA was carried out, with each participant's average rating for each category as DV and handle-ness (with handle vs. without handle) and the location of the assigned active/major object (left to the passive object vs. right to the passive object) as IVs. The results suggested that even though the main effects of both factors were not significant (ps < .05), their interaction was significant (F(1, 11) = 5.59, p = .038, η^2 = .34). Analysis of the simple effects revealed that the interaction was mainly driven by the trend that no matter the assigned active/major objects were on the left or right to the passive objects, when the assigned active/major objects had handle, the participants tended to consider them really 'active' in the given pairs, thus made more 'left' responses when the assigned active/major objects were on the left side and more 'right' responses when they were on the right, compared to the no-handle pairs. This trend was marginally significant in both the active-left (F (1, 11) = 3.27, p = .098, η^2 = .23, MD = 0.12) and active-right condition (F (1, 11) = 3.97, p = .072, η^2 = .27, MD = 0.13).

Appendix 3-D: Re-analysis of Experiment 1 Chapter 2 excluding the "handled" active objects

RT data were initially entered into an ANOVA with SOA (240 ms and 400 ms), co-location (correct vs. incorrect), the layout of paired objects (active-left vs. passive-left) and response compatibility (active vs. passive-object) as within-subjects factors. In addition, we examined the contrast of interests for the two effects of implied actions: passive vs. active objects in the correct co-location condition, and the correct vs. the incorrect co-location condition for responses aligned with the passive objects.

There was a main effect of SOA, F (1, 29) = 90.17, p < .001, η^2 = 0.76, with RTs in the 240 SOA ms condition longer than in the 400 ms SOA condition (MD = 18 ms). The main effect of the response compatibility was significant, F (1, 29) = 25.09, p < .001, η^2 = 0.46, with responses congruent with the active objects quicker than those congruent with the passive objects (MD = 8 ms). None of the interactions was significant. However, planned pairwise contrast suggested that responses aligned with the active objects were quicker than those aligned with the passive objects in their pairs, F (1, 29) = 20.38, p < .001, η^2 = 0.41, MD = 9 ms, and responses aligned with the passive objects were slower in the correct than in the incorrect co-location condition, F(1,29) = 6.49, p = .016, η^2 = 0.18, MD = 4 ms. The results replicated the previous effects of implied between-object actions.

Appendix 3-E: Re-analysis of Experiment 1 Chapter 3 excluding the "handled" active objects

RT data were initially entered into an ANOVA with SOA (240 ms and 400 ms), co-location (correct vs. incorrect), the layout of paired objects (active-left vs. passive-left) and response compatibility (active vs. passive object) as within-subjects factors.

There was a main effect of SOA, F (1, 21) = 110.48, p < .001, η^2 = 0.84, with RTs in the 240 SOA ms condition longer than in the 400 ms SOA condition (MD = 24 ms). The main effect of response compatibility was significant, F (1, 21) = 6.84, p = .016, η^2 = 0.25, with responses congruent with the active objects quicker than those congruent with the passive objects (MD = 4ms). The interactions between response compatibility and co-location was significant, F (1, 21) = 29.06, p < .001, η^2 = 0.58. Analysis of simple effects indicate that responses aligned with the active objects were quicker than those aligned with the passive objects in their pairs, F (1, 21) = 28.37, p < .001, η^2 = 0.58, MD = 12 ms, but not in the incorrect co-location condition (p = .117); responses aligned with the passive objects were slower in the correct than in the incorrect co-location condition, F(1,21) = 8.33, p = .009, η^2 = 0.28, MD = 8 ms, while responses aligned with active objects were quicker in the correct than the incorrect co-location condition, F(1,21) = 10.79, p = .004, η^2 = 0.34, MD = 8 ms. The results replicated the previous effects of implied between-object actions.

Appendix 3-F: Contrasting the effects of implied between-object actions on active and passive objects in reaching task

In the analysis reported in Experiment 3, Chapter 3, all the conditions were included. Note that in this analysis, the same as all the previous analysis, when comparing the correct co-location condition with either incorrect co-location condition, the co-location effect for the active and for the passive objects were not comparable, because only one of them (depends on which incorrect co-location condition was involved) maintained orientation across co-locations. For this objects, the difference between co-location conditions includes not only the effect of implied between-object actions, but also influence from its own orientation. For the objects remained in the same orientation, however, the co-location effects consists solely of the effect of co-location. To focus on the effect of co-location without considering the influence from the orientation change of the object, a second set excluded conditions in which the responses were compatible with objects whose orientation varied in the incorrect co-location condition (see Figure A3-1 for an illustration of the design the second set of analyses).

Here we excluded responses aligned with the manipulated objects, i.e. those aligned with the active objects in the incorrect co-location condition with a manipulated active object, and those aligned with the passive objects when the co-location was incorrect because the passive object was manipulated (see Figure A3-1 for an illustration of the conditions included in the analysis). An ANOVA was conducted with co-location (correct vs. incorrect with the other object rotated), object layout (active-left vs. active-right) and response compatibility (active-object vs. passive-object) as within-subjects factors. The dependent variable was the initiation time. The movement time data were not analysed because the first set of analyses indicated that the only driving factor in movement time was handedness.

There was a main effect of SOA, F (1, 19) = 65.76, p < .001, η^2 = .78, with RTs in the 240 ms SOA condition longer than in the 400 ms SOA condition (MD = 15 ms). The main effect of co-location was significant, F (1, 19) = 6.26, p = .022, η^2 = .25, with responses in the correct co-location condition slower than in the incorrect co-location condition (MD = 3 ms). The main effect of response compatibility was significant, F (1, 19) = 26.69, p < .001, η^2 = .58, with responses congruent with active objects quicker than those congruent with passive objects (MD = 8 ms). The interaction between co-location and response compatibility was not significant, F (1, 19) = 3.12, p = .093, η^2 = .14, however the pairwise comparison revealed that the responses congruent with the passive objects were significantly slower in the correct, compared with the incorrect, co-location condition, F (1, 19) = 5.76, p = .027, η^2 = .25, MD = 6 ms, while the same difference was not significant for response congruent with the active objects, F < 1.

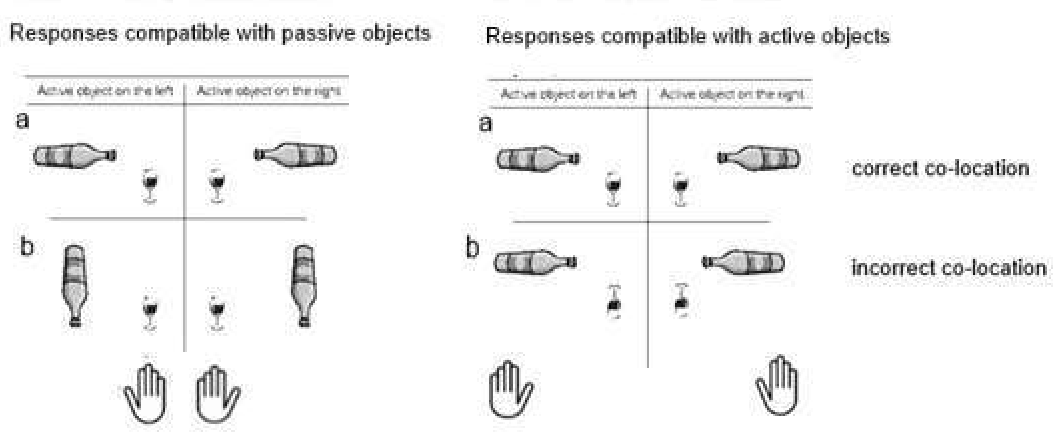


Figure A-1. Conditions included in the second ANOVA. The effect of correct co-location between objects on responses compatible with passive objects were examined by contrasting the correct co-location condition with the incorrect co-location condition with the active objects rotated, while the effect on active objects was examined by contrasting the correct co-location condition with the incorrect co-location condition with the passive objects rotated.

Appendix for Chapter 4

Appendix 4-A: complete list of stimuli

	Active Objects	Passive Objects
1	Screwdriver	Screw
2	Jug	Glass
3	Bottle	Glass
4	Jug	Cup
5	Kettle	Cup
6	Bottle	Cup
7	Jug	Bowl
8	Kettle	Bowl
9	Bottle	Bowl
10	Watering Can	Plant
11	Saw	Wood
12	Axe	Wood
13	Hammer	Nail
14	Pliers	Nail
15	Spoon	Bowl
16	Baseball Bat	Baseball
17	Table Tennis Bat	Ping Pong Ball
18	Tennis Racket	Tennis Ball
19	Badminton Racket	Birdie
20	Knife	Tomato
21	Knife	Carrot
22	Knife	Pepper
23	Wrench	Nut

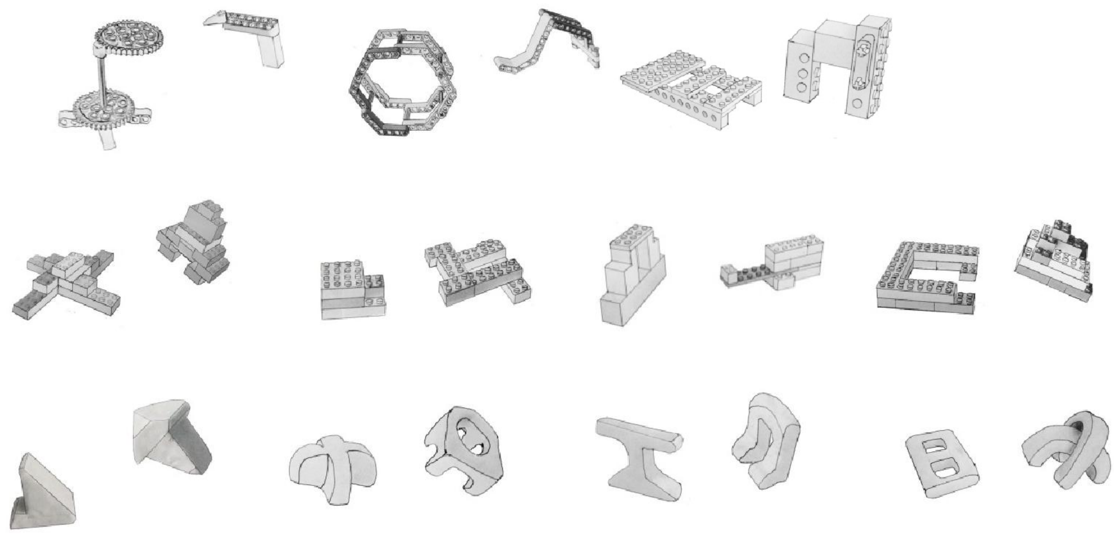
Appendix for Chapter 5

Appendix 5-A: Stimuli used as familiar pairs of objects

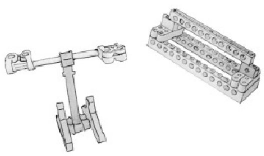
	Active Objects	Passive Objects
1	Bottle	Glass
2	Jug	Cup
3	Whisk	Bowl
4	Broom	Dustpan
5	Spatula	Frying pan
6	Hammer	Nail
7	Corkscrew	Bottle
8	Ladle	Saucepan
9	Kettle	Cup
10	Watering Can	Plant
11	Axe	Wood
12	Knife	Tomato

Appendix 5-B: Stimuli used as novel object pairs

Novel object pairs to be used in the learning experiment



Stimuli did not pass stimuli evaluation (the designed active objects were not always considered as active objects.



Appendix 5-C: Material evaluation: itemwise

Because the distinction between active and passive objects were of particular importance in our study, to confirm that we designed appropriate object pairs, i.e. the designed interaction between objects suggest a clear "active" role for one object and a clear "passive" role for the other, before conducting other analysis we conducted itemwise analysis on responses made to novel objects in the block regarding the active-passive distinction, Experiment 1. We used chi-square test to examine the rating for each pairs of novel objects separately. We find that for all expect one pair of objects (as shown in Appendix 5-B, lower panel), the rating to this question predominantly fell to the choice in congruence with our design (i.e. when the active objects were presented on the left side, the responses were predominantly "1", and in the other layout condition "2"). We excluded the problematic pair (chi-square = 1.22, $p = .25$, ps $< .05$ for all other pairs) from all analysis reported and all presentation of following experiments.

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