# OBJECT-RELEVANT KINEMATICS INFLUENCE IMITATIVE COMPATIBILITY

By

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# CHAPTER I

# INTRODUCTION

Over the past two decades, a tidal shift in psychological research on human action and perception has led to a proliferation of papers examining embodied views of cognition. Embodied cognition is a phrase that has had several different implications, but it is often introduced with historical reference to opposing information processing claims (e.g. see Barsalou, 1999; Cisek, 2008; Wilson, 2002). Information processing theory generally holds that the goal of psychological research is to investigate cognitive processes occurring in a black box connected to separate modular mechanisms for perceptual input and motor output. On the other hand, embodied theories of cognition, such as Barsalou's Perceptual Symbol Systems theory (Barsalou, 1999; 2003; 2008; 2009), claim that cognition has developed in conjunction with the perceptual and motor capabilities of the human body and is shaped directly by experience using our perceptual and motor systems. In the eagerness with which researchers have pursued findings on embodied cognition, important questions have inevitably been overlooked or have escaped rigorous evaluation. In the following dissertation, I examine the intersection between two phenomena that have previously remained isolated from one another, but have been united under the banner of embodied cognition: imitative compatibility and object-linked motor content.

The first embodied phenomenon central to this dissertation is imitative compatibility (or "automatic imitation"). Numerous studies (e.g. Bertenthal, Longo, & Kosobud, 2006; Catmur & Heyes, 2010; Longo, Kosobud, & Bertenthal, 2008; Longo & Bertenthal, 2009; Press, Bird, Walsh, & Heyes, 2008; Press, Gillmeister, & Heyes, 2006) suggest that the human motor system is predisposed to produce observed actions and, because of this, it is easier to produce actions that are similar to those observed than to produce actions that are different. The specific claims made about imitative compatibility effects with regard to embodiment are as follows. First, experience with contingencies between one's own motor behavior and with the sensory consequences of that behavior (e.g. proprioception, visual, tactile) lead to enduring associations (see Cook, Press, Dickson, & Heyes, 2010; Elsner & Hommel, 2004). Subsequently, these associations are used in comprehending others' actions (i.e. observed actions generate motor activity that can be used for action prediction). Embodied cognition theorists accept that action processing does not exclusively involve motor activation – acknowledging, for example, that other non-motor specialized processing of others bodies seems to occur in the superior temporal sulcus and that areas involved in motor-related action processing are connected to the STS (for a review on human motion processing see Blake & Shiffrar, 2007). However, these theorists do hold that motor experience and motor activations are directly relevant for action comprehension (see Paulus, 2011 for a novel perspective on the relationship between motor activation and action comprehension).

The second embodied phenomenon examined in this dissertation is what I will call object-linked motor content (OLMC). As heirs to centuries of sophisticated manufacturing, the typical actions of present day human beings involve one or more of a number of objects and a range of environmental effects. Despite the diversity of possible objects and effects available, our daily experience often involves objects that we have used for tens, hundreds, or thousands of hours. Moreover, given we tend to use many of these objects for a limited set of stereotyped actions and across many repetitions of these actions we tend to reproduce similar motor patterns to produce repeated environmental effects. Thus, present day human beings have numerous stored, automated action patterns associated with particular objects.

As several studies have shown, this repeated experience with object use can lead to motor content becoming an integrated part of object representations such that even when one is not attempting to produce a stereotyped action for an object, associated motor content is still activated by an image or even the name of the object (e.g. Creem-Regehr, Dilda, Vicchrilli, Federer, & Lee, 2007; Valyear, Cavina-Pratesi, Stiglic, & Culham, 2007). In this way, motor content becomes *linked* to a particular object or object category. Numerous authors have claimed that OLMC is an important mechanism supporting tool use in human and non-human primates (see Johnson-Frey, 2004; Lewis, 2006) and it has been discussed by Barsalou as important evidence for embodied cognition (Barsalou, 2009). However, thus far, the relevant work has been primarily concerned with testing *whether* we incorporate *any* motor experience into object concepts. This claim has generally been supported, but we must now begin the difficult tasks of (1) specifying the detailed content of these motor representations and (2) determining how variations in task conditions and stimulus features influence represented content.

Though there have been numerous investigations of imitative compatibility and OLMC phenomena, these investigations have generally remained isolated from one another. In the case of imitative compatibility, investigations have largely ignored the role of objects and the environment in action processing. Most studies of imitative compatibility have employed EMG or motion tracking hardware to measure *objectless* hand motions (e.g. Bertenthal et al., 2006; Catmur & Heyes, 2010; Longo et al., 2008; Longo & Bertenthal, 2009; Press et al., 2008; Press et al., 2006). In the case of OLMC, authors have frequently claimed that they are exploring a mechanism that might explain ideomotor apraxia and support advanced tool use (e.g. see

Johnson-Frey, 2004; Lewis, 2006), but have ignored the question of how the mechanisms of OLMC may be integrated with other broader perspectives on action perception and production. Investigations of OLMC have focused primarily on whether any kind of motor activation is observed when viewing an object and not on how this activation may be integrated into action representation and performance. To approach this intersection in the literature and to further our understanding of each embodied phenomenon, the present investigations employ a well-known imitative compatibility paradigm similar to that used by Brass, Bekkering, & Prinz (2001), but in which participants made key press or key release responses to a familiar numeric keypad.

### *Imitative Compatibility and the Human Mirror Neuron System (MNS)*

One of the most influential areas of research in the past 20 years has been the investigation of mirror neurons. Research with monkeys (e.g. di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Rizzolatti & Craighero, 2004) and human subjects (e.g. Chong, Cunnington, Williams, Kanwisher, & Mattingley, 2008; Fadiga, 1995; Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010) suggests that certain neuronal populations that are active when producing actions are activated by observing conspecifics perform matching actions. The presence of these "mirror neurons" has been taken by many to support certain claims of embodied cognition suggesting we rely on our own motor programs in action perception[1]. In line with these findings, several authors have claimed that imitative compatibility is the behavioral consequence of processing matching versus conflicting observed and perceived motions within the neural populations of the MNS (e.g. Capa, Marshall, Shipley, Salesse, & Bouquet, 2011;

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[1] Notably, however, certain authors have challenged the legitimacy of this claim (e.g. Hickok, 2009) and even challenged claims about the presence of mirror neurons in humans (Lingnau, Gesierich, & Caramazza, 2009).

Kilner, Paulignan, & Blakemore, 2003; Longo et al., 2008; Press, Bird, Flach, & Heyes, 2005; Wohlschläger & Bekkering, 2002). This somewhat controversial claim is attractive because it relates the function of certain basic neural units supporting embodied cognition (mirror neurons) to behavioral-scale matching effects (see Brass & Heyes, 2005; Heyes, 2011; Iacaboni, 2005).

Given that links between imitative compatibility and mirror neuron function might bridge an important divide between neural and behavioral levels of understanding human action processing, certain studies have attempted to verify that the behavioral results of imitative compatibility studies conform to the empirical patterns to be expected based on observed properties of mirror neurons. One finding in studies of the human MNS that has received a good deal of attention in the imitative compatibility literature is that the human MNS seems to respond to both object-directed and objectless actions (Fadiga et al., 1995; Maeda, Kleiner-Fisman, & Pascual-Leone, 2002; Lui et al., 2008), whereas monkey mirror neurons generally respond only to object-directed actions (Rizzolatti & Luppino, 2001). This has led to the suggestion that humans have mirror neurons that respond to the details of motion kinematics. Action kinematics are patterns of change in joint angles of human limbs and digits. Such a possible kinematic sensitivity in the human MNS could be specifically important for human imitation skill, supporting the ability to mimic the detailed form of an action by mapping the observed kinematics onto one's own motor system (Rizzolatti & Craighero, 2004).

Following the finding of kinematic sensitivity in the human MNS, certain studies have attempted to identify kinematic imitative compatibility effects (e.g. Press et al., 2008). However, obtaining a kinematic compatibility effect in behavioral data has proven somewhat difficult. The first difficulty for identifying any kind of imitative compatibility is to dissociate these effects from dynamic spatial compatibility effects. Dynamic spatial compatibility involves more efficient responding when there is a correspondence between the spatial directions of observed and produced movements and/or a correspondence in relative final position of observed and produced motions (see Bosbach, Prinz, & Kerzel, 2004; Bosbach, Prinz, & Kerzel, 2005a; Bosbach, Prinz, & Kerzel, 2005b). One method that has shown a clear dissociation between dynamic spatial and imitative compatibility was introduced by Brass et al. (2001). Brass et al. (2001), demonstrated that participants are faster to produce either finger taps (flexions) or lifts (extensions) when observing the same type of motion from an onscreen model's finger (e.g. watching a tap while making a tap response) as compared to when observing the other type of motion. Brass et al. dissociated imitative from spatial compatibility by presenting a block of trials with the onscreen motions upright and a block with the motions inverted. Thus, in the upright block, the spatial direction of observed taps and lifts was the same as for the participants' responses (and thus spatial and imitative compatibility were confounded). But, in the inverted case, onscreen taps were upward and the onscreen lifts were downward (and thus spatial and imitative compatibility were opposed). Through this dissociation and analyzing the contributions of imitative and spatial compatibility independently, Brass and colleagues were able to identify an imitative compatibility effect that could not be explained by spatial compatibility alone. Notably, however, the Brass et al. results do not provide enough information to call their imitative compatibility effect a kinematic compatibility effect.

One reason that the Brass et al. results cannot be definitively labeled a *kinematic* compatibility effect is that the relationships between the model and participant actions to the environment were the same. Specifically, both model and participants made table *taps* or finger *lifts* away from the table surface. Thus, it may be that actions were being coded relative to the environment and that kinematics were largely ignored. Kinematics were isolated in the present research by introducing an asymmetry between the objects involved in participant responses and those onscreen. Specifically, in the following experiments, participants produced familiar meaningful object-directed finger flexions (curling motion of finger toward palm) to press a key or finger extensions (straightening motion away from palm) to release the same key. However, the onscreen finger flexions and extensions involved no object contact.

The asymmetry between observed (objectless) and produced (object-directed) motions allows for a rigorous test of kinematic compatibility effects. A simpler method of testing for kinematic compatibility effect would be to ensure that no objects were included either in participant or in model motions. This would certainly suggest that kinematics alone could generate a compatibility effect. However, if there are truly two separate kinds of action processing carried out by MNS, one for kinematic action similarity and another for object-directed action similarity, the purely objectless experiment would not inform us about how these two types of processing interact. By introducing an object asymmetry in the experiments below kinematic compatibility can be isolated because there will ostensibly be no overlap in the object-directed processing (as observed objectless and produced key press motions do not overlap in this domain) and kinematic overlap will be manipulated according to the match in motion type (flexion or extension). Thus, using the Brass et al. paradigm with an asymmetric object arrangement allows this research to contribute to recent attempts to connect MNS processing to imitative compatibility phenomena.

## *Object-Linked Motor Content: Definitions and Evidence*

A second advantage of the proposed imitative compatibility paradigm is that it allows me to investigate how objects, and potentially object-linked motor content, influence imitative compatibility. Object-linked motor content is a term that describes motor information relevant for using an object that can be elicited by online perception of an object type (e.g. elicited by an object name, an object image, an object sound, or an object texture) or by offline object representations. Importantly, this motor content is elicited independently from actually planning to produce that motor content (or planning to use the object in a manner that would require the relevant motor commands). I further define OLMC as based on experience with specific object types. This experiential aspect of OLMC excludes other object-based motor activations such as that generated by canonical neurons[2], which ostensibly reflect the translation of object geometry into muscle patterns for grasping (see Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Murata, Gallese, Luppino, Kaseda, & Sakata, 2000; Rizzolatti & Luppino, 2001). Though several experimental phenomena have been observed that can be explained by OLMC, no adequate label has yet been provided to describe the range of motor representations elicited by object concepts and percepts.

Numerous brain imaging studies directed at understanding human tool use support the claim that images, names of objects, and even typical object use sounds activate motor cortex (see Johnson-Frey, 2004; Lewis, 2006 for reviews). Further evidence for OLMC has come from behavioral studies in which participants are presented with a useful object and asked to respond to a task-relevant cue (e.g. the tint of the object) or an object property (e.g. object category or

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[2] *Canonical neurons* in monkey F5 fire when an animal grasps an object and when the animal observes the object without grasping it (Jeannerod, Arbib, Rizzolatti, & Sakata, 1995; Murata, Gallese, Luppino, Kaseda, & Sakata, 2000; Rizzolatti & Luppino, 2001). Furthermore, inactivation of AIP and area F5 to which it connects, leads to an inability for monkeys to correctly scale their grip prior to reaching an object (Rizzolatti & Luppino, 2001). Importantly, when encountering an object, there are often numerous separate parts that could be grasped in different ways. One proposal for how specific grasps are generated is that AIP represents all possible grasps and then, based attention and goals, sends information for a single grasp to area F5 where a motor prototype is selected (Rizzolatti & Lupino, 2001).

material composition) with a manual action. Importantly, the manual response alternatives are involve either typical or atypical motions for a given object on a trial (e.g. making either a typical flat handed response for a stapler versus making an atypical pointing gesture for a stapler based on the color in which the stapler appears). These studies show that object-typical actions are faster and more accurate (e.g. Bub & Masson, 2006; Bub, Masson, & Cree, 2008; Glover, Rosenbaum, Graham, & Dixon, 2004; Masson, Bub, & Breuer, 2011; Tucker & Ellis, 2004).

Most of the imaging research on OLMC has shown increases in motor activity for tools over activity observed for animals, buildings, or artifacts without associated uses (Johnson-Frey, 2004; Lewis, 2006). This body of work suggests that some form of motor content is linked specifically to useful objects, but does not give us the detailed composition of that content. One exception to this ambiguity in imaging studies of OLMC comes from Creem-Regehr and colleagues (2007), who have shown that fMRI activations observed while participants view useful objects is likely to reflect both associated grasp- and other use-related motor activity. The authors trained participants with half of a set of novel objects as “tools” (trained for specific movement sequences) and half as “graspables” (grasped and manipulated for an equal amount of time without associating movements). [For a related study, see Valyear et al. (2007).] Subsequently in an fMRI scanner, participants viewed, imagined grasping, or imagined using objects based on images presented from the training set. Most importantly, both when participants *imagined using* and when they merely *viewed* objects, there were differences in motor-cortical activation between tools and graspables. This suggests that non-grasp-related action content (ostensibly related to object use) is activated when both imagining use of and when passively viewing an object with a known use. So, it would appear that more than just the initial grasping phase of an action can be represented in OLMC. Additionally, the authors found no differences between tools and graspables when participants imagined grasping the objects. This indicates that, at least for recently learned action associations, imagined action performance (grasping) that conflicts with prior learned actions may suppress the use-related motor content.

The novel research presented here is particularly concerned with how object-linked action kinematics and directional information may influence links between action perception and production. One study that has looked specifically at directionality in OLMC is by van Elk, van Schie, and Bekkering (2009b)[3]. These authors tested whether useful objects facilitate motor production compatible with the positions/directions of typical body-relative object use. Participants viewed images either of a person holding a "self-directed" object either typically used near one's body (e.g. a microphone) or a "world-directed object" typically used in conjunction with another object in the environment (e.g. pliers) away from one's body. All stimulus images depicted objects held near the body.

In the critical final experiment by van Elk et al. (2009), participants made *toward* movements from a home key to a near key or *away* movements to a far key. Participants were told to press one response button for objects that were made of plastic and the other button for objects that were not (with response mappings counterbalanced). Asking participants to respond to the material composition of the objects made typical use-location task-irrelevant and provided a stronger test of how this particular form of OLMC might influence responding. The authors found an interaction based on response compatibility with object typical movement (i.e. for objects like pliers, away key responses were relatively faster than toward responses and for objects like microphones, toward key responses were relatively faster than away key responses).

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[3] Though work by Taylor, Lev-Ari, & Zwaan (2008) shows interesting contextual activation of directional motor information, those results are not discussed here because they were based on responses to object names embedded within a narrative and may not be directly comparable to other results presented here.

Though one cannot discount the possible role for the visible actor holding the relevant objects in producing the van Elk results, the findings can generally be interpreted as showing that directional information can be linked to object representations.

### *Connecting OLMC and Imitative Compatibility: Action Components and Reference Frames*

Though previous research gives us a helpful starting point for thinking about imitative compatibility and OLMC, numerous questions remain. Before presenting the experiments below that investigate this intersection of two prominent embodied cognition phenomena, I discuss two methodological challenges for this work. The first challenge is isolating kinematic, spatial, and action-effect contributions to both imitative compatibility and OLMC. Taking the relevant example of OLMC with key presses, if participants associate press actions with keys, this might actually involve several distinct associations. First, the kinematic pattern (a finger flexion) might be associated with the object. Second, a spatial direction (downward) might be associated with the object. Finally, an action effect (the clicking sound, the downward motion of the key, and the proprioceptive feedback from the returned pressure from the key on one's finger) might be associated with the object. Whereas only the first type of association might count as object-linked *motor* content, certain embodied theories of perceptual and conceptual representation, such as Perceptual Symbol Systems theory (Barsalou, 1999) might predict that each of these components would become associated with keys and might be differentially reactivated based on the context (see also Dutzi & Hommel, 2009; Hommel, 2009).

To clarify the above issue, I provide two examples of OLMC – one involving grasp-related OLMC and the other involving OLMC for object-directed motion. In typical OLMC experiments, objects are presented and participants make responses that either match or mismatch object-associated actions. A response advantage for matching actions is then taken to suggest that the object itself activates a representation of OLMC that interferes with or facilitates actions based on similarity. If we take an example of grasp-related OLMC, interference/facilitation in a paradigm like that mentioned could mean that a particular visual spatial configuration (shape) of the hand is stored in association with the object (and this spatial representation then facilitates the motor commands that produce that particular shape). Alternatively, efferent motor commands needed to achieve a particular joint configuration might be stored in association with an object. Finally, one might associate anticipated afferent proprioceptive or tactile feedback with an object. In the example case of OLMC related to object-directed motions, one might associate with an object: kinematics, spatial directions, and the perceptual effects obtained from acting on the object in a particular way. These overlapping possible associations also present a difficulty for imitative compatibility paradigms. In this case, it can be unclear which overlapping features of observed and produced actions are responsible for generating compatibility effects. In the following experiments, I isolate the action components relevant for OLMC and for imitative compatibility.

A second challenge for understanding imitative compatibility and OLMC lies specifically in that spatial representations are formed relative to several frames of reference. Reference frames can be thought of as axes for determining location or orientation relative to the components of the body or the environment. Reference frame axes do not necessarily divide space into discrete units as a Cartesian axis does, but do provide points (e.g. the location of one's hand) from which other spatial information can be established. People tend to encode their actions simultaneously within multiple egocentric (body-based) and allocentric (environment-based) frames and coordinating these various frames poses an important challenge to coordinating action and perception and this will be important in the following experiments.

The specific reference frame issue that will be central to the following experiments involves coordinating and selecting among allocentric reference frames[4]. Allocentric reference frames provide several coordinate systems that are often hierarchically nested. Moreover, several of these coordinate systems can simultaneously influence action planning and judgment. One paradigm that demonstrates multiple coding of spatial information is the "Simon" task (Simon & Ruddel, 1967; Simon, 1990). In a classic Simon task, participants respond to an object that appears in one of two or more locations. Participants respond to object properties (e.g. color or shape) using spatially distinct responses (e.g. keys on a keyboard). For example, imagine that brown or green circles may appear in isolation on the left or right side of the screen on a trial. Participants are asked to respond to green stimuli with the 's' key on the left or respond to brown stimuli with the ';' key on the right. With this key mapping, the simple version of the task will show that participants are faster to respond to green circles (requiring an 's' response) when the circles are on left than on the right and are faster to respond to brown circles (requiring a ';' response) when the circles are on the right. An explanation of this result is: the green ('s') and red (';') key locations within the keyboard's reference frame lead to faster responses to objects on the corresponding sides of space within the screen-based reference frame (see Hommel, 1993; however, see Figliozzi, Silvetti, Rubichi, & Doricchi, 2010).

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[4] A relevant difficulty, but one which is not addressed by the studies in this concerns coordinating egocentric frames of reference in order to produce an action. For more information on this topic, see Buneo & Anderson (2006); Colby (1998); and Crawford, Henrique, & Medendorp, (2011).

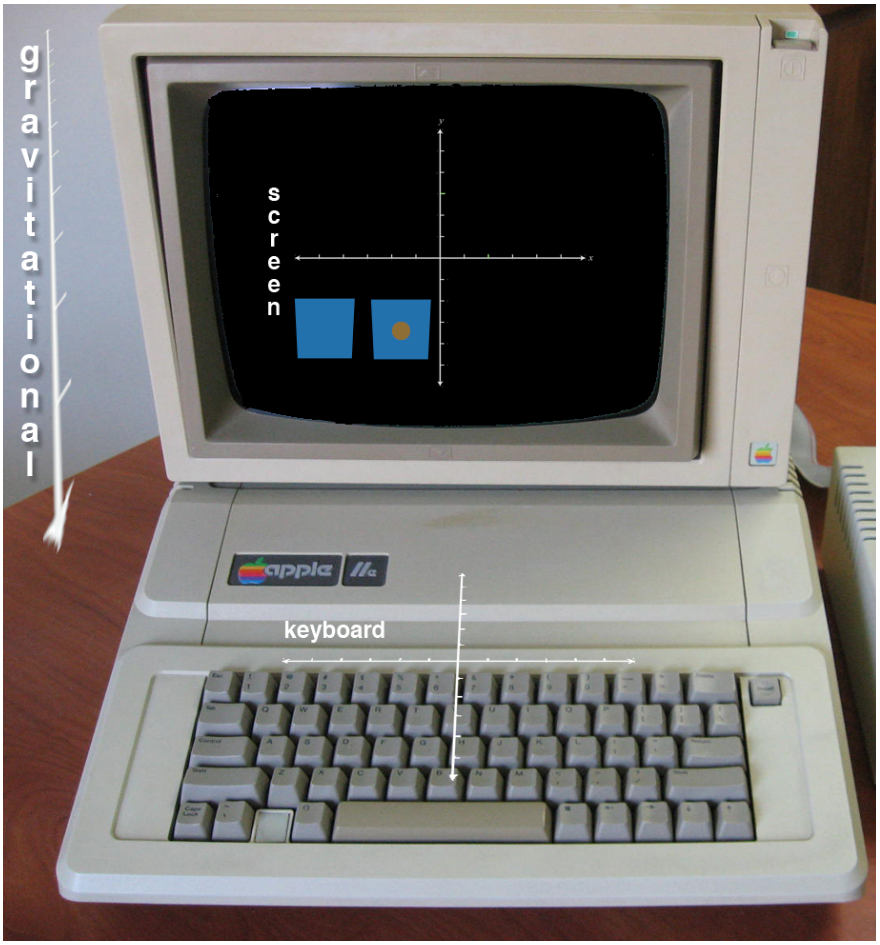


Figure 1: Depiction of Multiple Coding of Spatial Reference Frames. These are the final frames from the upward and downward finger motion stimuli presented to participants in the present study. The same finger motion images were superimposed on one background depending on condition.

When the situation becomes more complex (as in Figure 1), the results of a Simon task can reveal that multiple spatial reference frames additively affect responses (see Roswarski & Proctor, 1996). Taking the figure as an example, with the same color-to-key mappings as in the previous example, one might observe that the brown circle (which would be responded to with the right-side ';' key) would be encoded as being on the left-hand side of the screen-based reference frame, but on the right square in the configuration of squares presented. Thus, right responses would be slowed due to the circle appearing left side of the screen, but would be speeded somewhat by appearing in the right square.

Importantly, however, this multiple spatial coding is not obligatory. One important distinction is between a Simon task and a task-relevant S-R compatibility task (Fitts & Deininger, 1954; Fitts & Seeger, 1953). In a Simon task, participants respond to a *task-relevant* stimulus feature (such as color) and the *task-irrelevant* spatial information affects response time and/or accuracy. However, in a spatial S-R task, participants explicitly indicate the position of an object with respect to a given reference frame (e.g. left or right side of a screen). In this case, the multiple additional spatial frames in which an object might be coded do not show an influence. Thus, actively making spatial judgments within a frame may suppress the influence of other frames. Moreover, several papers suggest people access reference frames in a task- and context-specific manner (Battaglia-Mayer, Caminiti, Lacquaniti, & Zago, 2003; Klatzky & Wu, 2008). When we think of various familiar object-directed motions (e.g. pressing a key, throwing a Frisbee, or twisting a bottle cap) spatial components of these motions might be judged relative to several frames of reference. Thus, to better understand directionality in OLMC, the following studies will take account of reference frames.

## *Experimental Research: Examining Imitative Compatibility with Keyboards*

The present experiments introduce a new paradigm to examine an intersection between two embodied phenomena: imitative compatibility and object-linked motor content (OLMC). To examine this intersection, these experiments introduce a mismatch between the goals and action effects of participant and model motions. Participants produced familiar meaningful key press motions or performed key release motions. However, the kinematically-similar onscreen motions (finger flexions and extensions) involved no object contact. The present paradigm allowed us to address two experimental questions.

One question addressed by this paradigm is whether one can obtain a kinematic compatibility effect independent of other types of action compatibility. Though an investigation of imitative compatibility by Press et al. (2008) demonstrated a compatibility effect that the authors claimed was based on kinematics alone, certain objections can be raised to these findings. Certain aspects of the Press et al. were critical to the claim that the findings reflected kinematic compatibility. First, onscreen motions were presented with no background visible so object-relative coding was not possible. Second, participant and model motions were hand opening and closing motions (spreading fingers and thumb or making a fist), so motions were necessarily objectless. Finally, the axis along which participants made opening and closing motions was orthogonal to the axis of observed motions, which argues against an interpretation of the authors' results in terms of dynamic spatial congruency.

Despite the strengths of the Press et al. study, a study by Jansson, Wilson, Williams, & Mon-Williams (2007) suggests that the Press study and others may be explained by an abstract spatial match between observed and produced actions. In one of their experiments, Jansson et al. modified the paradigm of Press, Bird, Flach, & Heyes, 2005, which was essentially the same as that used by Press et al. (2008). Jansson et al. had participants make opening or closing motions of their hand while observing either orthogonal opening/closing hand motions or while observing an orthogonal pair of onscreen dots moving toward or away from one another. Jansson et al. found no differences between the size of the compatibility effects for moving hands and the size of the compatibility effects for moving dots. Though one can raise certain objections to the within-subjects design employed by Jansson et al., the results cast doubt on the claims made by Press et al. (2008) regarding a kinematic compatibility effect.

The present study provides a more rigorous test of kinematic compatibility. First, the present method ensures that imitative compatibility effects can be dissociated from dynamic spatial compatibility effects. Following Brass et al. (2001), these experiments present a block of trials with onscreen motions upright and a block with onscreen motions inverted (see Figure 2). In the upright block, imitative and spatial compatibility are confounded. In the inverted block, imitatively compatibility is always opposed to spatial compatibility. Additionally, the present experiments adapt the Brass et al. paradigm to be a more rigorous test of *kinematic* compatibility by introducing an asymmetry in the object/goal-based compatibility between observed and produced actions. Specifically, observed and produced actions always conflict at the object/goal level (i.e. object-directed participant actions and objectless model action). However, conflict is manipulated at the kinematic level (i.e. whether participant and model kinematics are similar or different). Notably, a negative result here (observing no kinematic compatibility effect) would not rule out that a kinematic matching process occurs, but would show that this matching process is not robust to an object/goal mismatch.

The second question addressed by the object asymmetry present in these experiments is about how the objects participants interact with influence imitative compatibility. Though there may be several manners by which objects influence compatibility effects, one possibility is through OLMC. Specifically, the press actions learned for a keyboard may automatically influence how non-canonical release actions could be produced with the object. Alternatively, when responding with a relevant object, OLMC may influence how observed motions are encoded (such that producing a typical press motion leads to different processing of observed actions than producing an atypical release motion). The present experiment is unlike prior investigations of OLMC first because any OLMC effect would be linked to the response device rather than to images of a series of objects presented unpredictably across trials.

Interestingly, one can make contrasting predictions for the influence of OLMC on imitative compatibility. First, if we assume that keyboards activate downward/flexion motions, it may be that there is greater interference of onscreen downward/flexions on producing upward/extension motions because these observed motions correspond with the object-typical response. A similar increase in the size of compatibility effects for participant extensions motions could be expected if representations of object-typical flexions (OLMC) interfere with a possible facilitation by onscreen extensions. Cases could also be made for how OLMC decreases interference in producing object-typical flexion motions or increases facilitation from observed flexions (though there would be some issues in calling this OLMC because the motions are object typical).

Contrary to the above proposal, one might also expect a greater compatibility effect for downward/flexion motions in the following experiments. If representations of object-typical flexions are actively inhibited in order to produce object-atypical extensions, this may lead to a reduced influence of flexion motions on extension motion production. Finally, it is important to note that, other features of object-typical action (such as the allocation of attention during object-typical versus object-atypical responses) could play an important role in influencing how participant actions are planned and how model actions are processed in the presence of a familiar object. OLMC is merely an interesting possible influence that motivated the design of the following experiments.

### *Overview of the Experiments*

The first four experiments presented below investigate imitative compatibility with an object asymmetry between observed and produced motions. Participants produced motions toward or away from an object while observing objectless onscreen motions. The first experiment shows an imitative compatibility effect for flexion key press responses, but not for extension key releases. The following experiments analyze several aspects of this response specificity. Experiments 2 and 3 investigate whether the specificity is linked to directions of motion, kinematics, or action goals and find that kinematics are the most likely component. Experiment 4 tests the same kinematics with a new object (a light switch) and finds the same specificity effect. Experiment 5 involves objectless responses from participants to ensure that the prior findings were not due to stimulus confounds. This experiment shows effects more comparable to those obtained by Brass et al. Altogether, the experiments suggest a pattern of flexion specificity when responding with objects. The relationships to OLMC and other possible explanations for the results are presented following the experiments.

# CHAPTER II

## EXPERIMENT 1

In this experiment, participants observed objectless index finger extensions and flexions produced by an onscreen model hand. The model movement onset served as a go signal for participants to make key press (flexion) or key release (extension) movements, depending upon the instructed response for that block. Following Brass et al. (2001), to dissociate imitative from spatial compatibility, one block of trials was presented with the onscreen model's hand upright and one block was presented with the model's hand inverted. In the upright block, the spatial direction of observed motions is the same as for the participants' responses. In the inverted case, spatial directions are dissociated from movement types.

A final component of the present experiment was the manipulation of whether a background scene context was visible (as in Brass et al.) or absent. Though previous results have found compatibility effects even in the absence of a background scene (Press et al., 2008), investigating the role of the background scene in the Brass et al. paradigm is especially important because the prior results hinge on the claim that any observed imitative compatibility effect with an inverted scene cannot be attributed to a spatial match (because spatial and imitative compatibility were opposed in the inverted condition). However, given the entire scene was inverted (not merely the hand within the scene), the relationship between scene-relative spatial directions and movement types in the inverted trials were still consistent with the relationship in the upright trials (e.g. a flexion "tap" motion in the Brass study was always "downward" in the scene toward the table). Thus, it remains possible that participants were merely coding the spatial direction of observed motions relative to a scene-based reference frame in the original Brass study. The present background manipulation tests that possibility.

## *Method*

### *Participants*

Forty-five undergraduate and graduate students from Vanderbilt University participated in this study for class credit. Three participants were excluded for failing to follow instructions, and 2 were excluded for exceeding the 10% error criterion. This left 40 participants' data for analysis (age range: 18-25, mean age: 19.4, 5 males).

### *Apparatus*

All stimuli were presented using Matlab R2007b with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) on an eMac computer (monitor vertical refresh: 89 Hz; monitor dimensions: 32 cm x 24 cm, 36.9˚ x 28˚ of visual angle) running Mac OS 10.4. Participants were seated approximately 48 cm from the display. Responses were made to the central '2' key on a Targus USB keypad (model PAUK10U). The surrounding keys were removed from the keypad and a foam square was taped to the key to raise it slightly. The keypad was attached to another keypad directly above it using screws and wooden struts (see Figure 7). The pictured upper keypad was used in the second experiment. To ensure the bottom keypad did not move during the experiment, it was affixed to the surface of the table at which participants were seated.

### *Materials*

For each of the experiments in this report, the stimuli were frames from video sequences in which the first author’s (henceforth model) index finger moved upward or downward (following Brass et al., 2001). The same frame was used as the starting position for each apparent motion sequence for the model, with 3 successive downward or upward frames afterward for each sequence. These sequences were recorded from an angle slightly above the hand to ensure that the features of the hand were visible on the starting frame. To ensure that the motions appeared natural, the author attempted to move a similar distance for upward and downward finger motions, but did not attempt to align motions to a particular stopping point. Given this, the distance covered from the first to last frame of the downward motions was slightly smaller (approximately 3.2˚) than for upward motions (approximately 4.4˚). The frames used for each sequence were selected so that the finger images were taken from the same time points of each video sequence. Before presenting the moving finger images onscreen, the backgrounds of the recorded images were removed in Adobe Photoshop CS. During the experiment, the hand image sequences were either drawn on a tabletop and wall background or superimposed on the uniform gray background that filled the screen (see Figure 2). With the background present, stimulus images subtended 29.9˚ by 18.9˚ of visual angle.

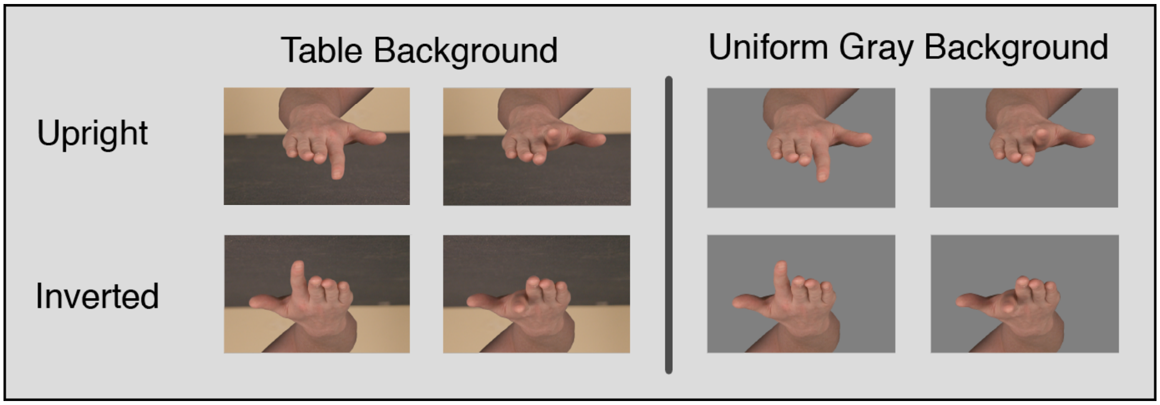


Figure 2: Onscreen Motion Types Observed by Participants. These are the final frames from the upward and downward finger motion stimuli presented to participants in the present study. The same finger motion images were superimposed on one background depending on condition.

*Procedure*

Before beginning the critical trials, participants were introduced to using the response apparatus during a familiarization phase. In this phase, participants made five downward key press responses and five upward key releases when prompted by text onscreen. After a successful press or release, the screen flashed 4 times. The flash effect was produced by alternating between white and a black frames each presented for 20ms.

Following familiarization motions, participants completed 240 experimental trials (see Figure 3) split into two equal counterbalanced response blocks. In each block, participants made either exclusively press or exclusively release responses with their right index finger. Participants were asked to make the instructed motions as soon as the model's finger began to move in either direction. Half of the participants saw model movements with a table background present and the other saw movements with a uniform gray background. Trials began with a 1200ms ITI frame with a uniform gray screen. The model movement sequence then began with the starting position frame presented for 800, 1600, or 2400ms. The next two movement frames were presented for 34ms. The third and final frame remained onscreen for 1500ms or until participants responded.

Within each response block, there were two counterbalanced sub-blocks. One sub-block showed the model's hand upright and the other sub-block showed the model's hand inverted. Thus, in the upright sub-block, model flexions were always spatially downward and model extensions were always upward, but in the inverted sub-block, flexions were upward and extensions were downward (see Figure 2). The direction of model motions was selected randomly on each trial.

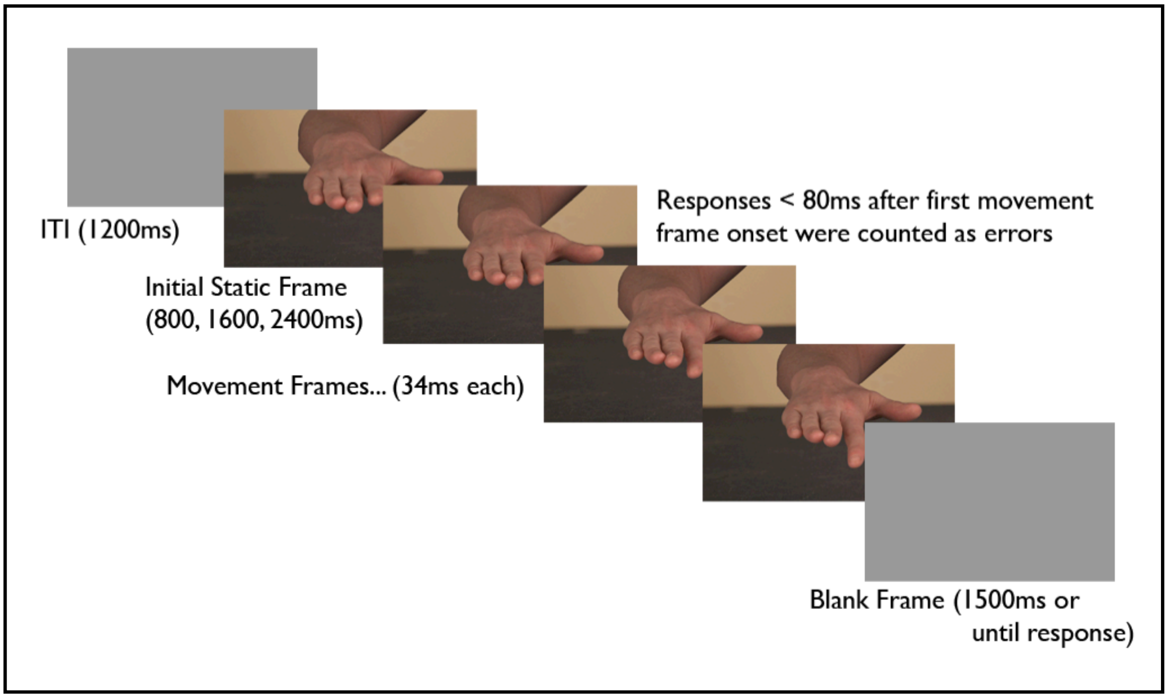


Figure 3: Time Series Diagram of Events in Each Experimental Trial.

### *Analysis*

*Errors.* Errors included participants moving in the wrong direction, anticipations, and failing to respond within the response interval. Errors involving the wrong direction occurred in less than 0.3% of trials on average, failures to respond occurred in less than 0.9% of trials on average, and anticipation errors occurred on less than 1% of trials on average. Participants who exceeded 10% total errors were removed from the analysis. Because the only meaningful errors for an analysis would be incorrect directions, an analysis of errors was not conducted.

*Reaction times.* All reaction times below 80ms (anticipation errors) or above 800ms were excluded from the analysis.

*Distribution Analyses*. In addition to analyses of mean reaction times, several authors have employed RT distribution analyses with data in imitative compatibility paradigms. Such analyses have been used in justifying claims about the nature of differences between spatial and imitative compatibility. Brass et al. proposed that differences between the spatial and imitative compatibility distributions suggest that imitative effects emerge as participants have more time to process the observed motions (i.e. at the longer RTs present in the later quintiles). Differences in the time course of distributions for compatibility components has also been used as the basis of certain recent attempts to model imitative and spatial compatibility effects in different paradigms (see Boyer, Longo, & Bertenthal, 2012; Catmur & Heyes, 2011; Cooper, Catmur, & Heyes, 2012).

To perform the quintile analyses, Brass and colleagues (2001) performed a quintile analysis (Ratcliff, 1979) in which average Vincentized reaction time distributions were formed for each participant for each compatibility condition (ordering that participants' reaction times into quintiles from shortest to longest using a linear interpolation technique described by Ratcliff, 1979). Distributions were formed for each participant for the imitatively compatible, imitatively incompatible, spatially compatible, and spatially incompatible reaction times for that participant. We have conducted the quintile analysis using difference scores for the size of the spatial and imitative compatibility effects (see Catmur & Heyes, 2011 for a similar procedure).

## *Results*

### *Aggregate Analysis*

An initial repeated-measures ANOVA that included both response types (presses and releases), showed interactions between compatibility effects and response type. For these reasons, we looked at each response type in separate ANOVAs.

The ANOVA for (upward) extension release responses included SOA (800, 1600, or 2400ms), imitative compatibility (compatible or incompatible), and spatial compatibility (compatible or incompatible) as within-subjects factors. Background condition (table or no background) was included as a between-subjects factor. The analysis showed only a main effect of SOA, $F(2, 68) = 104.23$, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M = 362$ms, $SD = 57$ms; 1600ms SOA: $M = 318$ms, $SD = 61$ms; 2400ms SOA: $M = 310$ms, $SD = 66$ms). Importantly, there were no significant effects of spatial compatibility, $F(1, 38) = 1.07$, $p = .31$, or of imitative compatibility, $F(1, 38) = .01$, $p = .91$, for the upward/release extension responses.

The ANOVA for (downward) flexion press responses included the same factors as above. The analysis showed a main effect of imitative compatibility, $F(1, 38) = 32.76$, $p < .0001$, with faster responses on anatomically compatible ($M = 357$ms, $SD = 62$ms) than incompatible trials ($M = 372$ms, $SD = 64$ms). There was also a main effect of spatial compatibility, $F(1, 38) =$

12.37, *p* < .005, with faster responses on compatible (*M* = 359ms, *SD* = 62ms) than incompatible trials (*M* = 369ms, *SD* = 63ms). Finally, there was a main effect of SOA, *F*(2, 76) = 112.48, *p* < .0001, with responses being faster for longer SOAs (800ms SOA: *M* = 394ms, *SD* = 60ms; 1600ms SOA: *M* = 355ms, *SD* = 61ms; 2400ms SOA: *M* = 346ms, *SD* = 68ms). Compatibility effects for both responses are pictured in Figure 4.

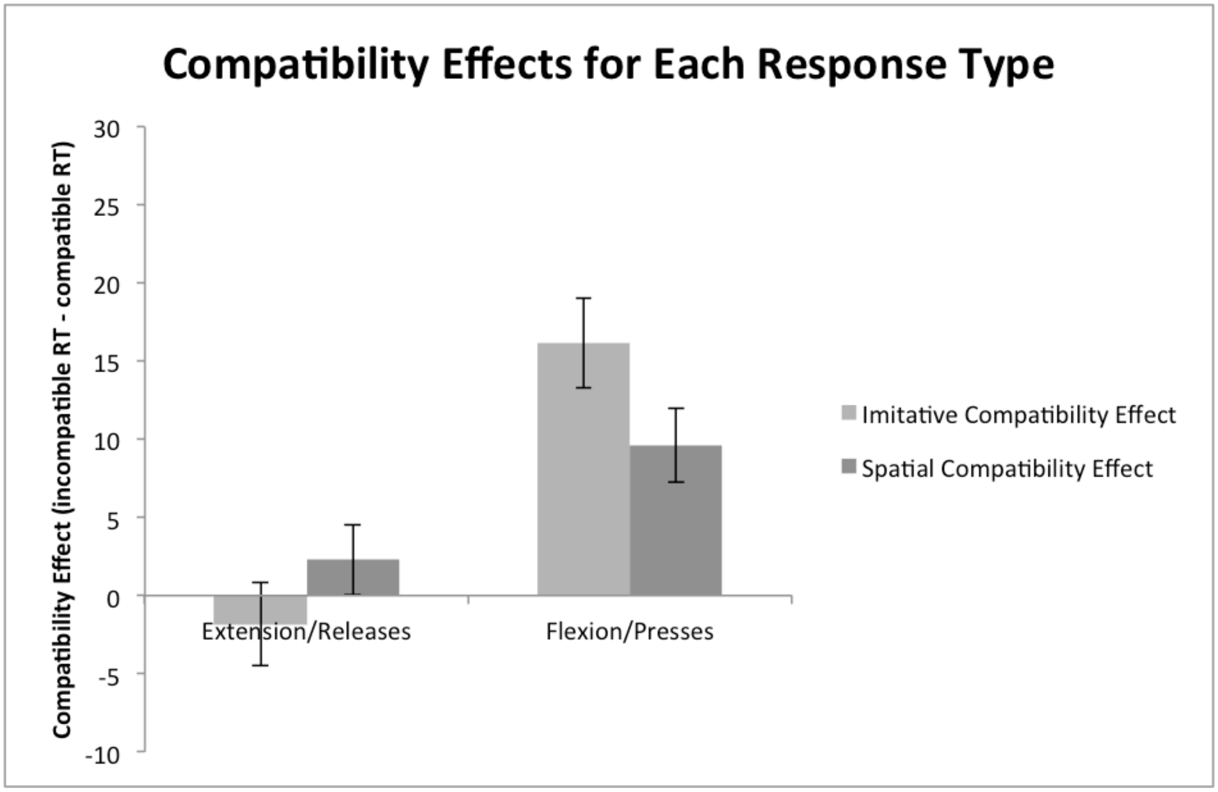


Figure 4: Compatibility Effects for Experiment 1. Error bars indicate standard error of compatibility effect.

### *First Response Analysis*

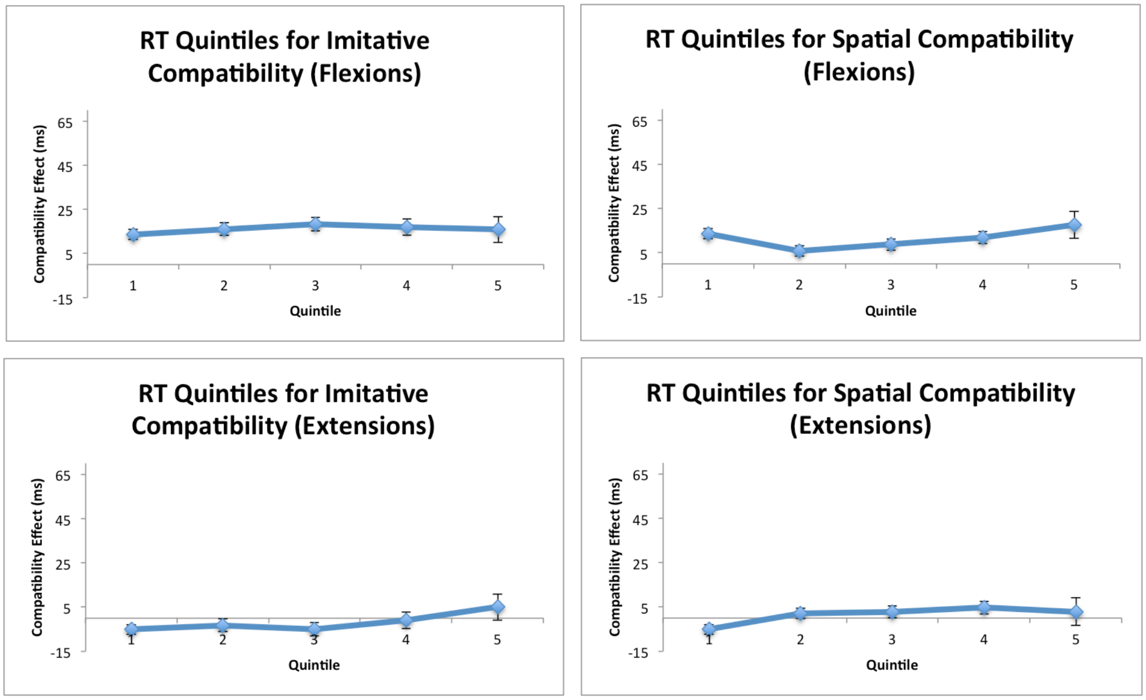
To ensure that the above effects emerged in participants' first response block, we conducted a between-subjects analysis. Separate analyses for press and release responses included SOA, anatomical compatibility, and spatial compatibility as within-subjects factors. Background condition was included as a between subjects factor. The effects in the first response ANOVAs generally replicated the findings above. For extension releases there was only a significant main effect of SOA, $F(2,38) = 43.82$, $p < .0001$. For flexion presses, there were main effects of SOA, $F(2,34) = 70.35$, $p < .0001$, anatomical compatibility, $F(1,17) = 15.22$, $p < .005$, and spatial compatibility, $F(1,17) = 9.48$, $p < .01$.

### *Distribution Analysis*

Following Catmur & Heyes (2011), data were collapsed into difference scores for each compatibility component. Response type (presses and releases), quintile (1-5), and compatibility component (type compatibility vs. spatial compatibility) were included within-subjects factors. Because violations of sphericity were consistently observed for these data, all statistics reported on RT distributions across experiments are from multivariate tests using Wilks' Lambda.

Because the initial ANOVA showed a 3-way interaction involving response type, each response type was analyzed separately. The ANOVA for (upward) extension release responses included the same factors as above. The analysis showed no significant effects.

The ANOVA for (downward) flexion press responses included compatibility component (spatial or imitative compatibility) and quintile (1-5). This ANOVA showed an interaction between compatibility component and quintile, $F(1, 36) = 3.51$, $p < .05$. Separate ANOVAs for each component showed that the effect of quintile was not significant for either component, but was larger for the spatial compatibility component, *F*(4, 36) = 2.34, *p* = .07, than for the imitative compatibility component, *F*(4, 36) = 1.04, *p* = .40. Quintile plots of the response time distribution are provided in Figure 5.



RT Quintiles for Imitative Compatibility (Flexions)

RT Quintiles for Spatial Compatibility (Flexions)

RT Quintiles for Imitative Compatibility (Extensions)

RT Quintiles for Spatial Compatibility (Extensions)

Figure 5: Reaction Time Distributions for Experiment 1.

*Discussion*

The above results showed additive imitative and spatial compatibility effects for participants’ key press, flexion responses. First, flexion responses were faster when initiated in response to observed flexion motions than when initiated in response to extensions. Additionally, downward (flexion) responses were faster when participants observed downward motions than when they observed upward motions. Similar effects were absent for key release, extension motions. Finally, the results were not influenced by manipulation of the background image present during onscreen motions.

One important question for the above results is what they indicate about the possibility of obtaining a kinematic compatibility effect. As mentioned, this task introduces a goal-object asymmetry between participant (keypad-directed) and model (objectless) motions. Given this asymmetry, the above paradigm provided a powerful test of whether kinematic matches/mismatches produce compatibility effects even when goals are asymmetric. Obtaining a purely kinematic compatibility effect has interesting implications for questions about the connections between imitative compatibility and the human mirror neuron system, which I will return to in the general discussion. Though compatibility effects were limited to downward/flexions in the above experiment, this does suggest that at least for that response type, a match between the goal of an observed action (flexion or extensions) and a produced action (key press or release) are not necessary to generate imitative compatibility effects. Thus, the possibility of a kinematic compatibility effect is supported, though the effect was not robust for both response types.

Perhaps most interesting among the findings in this experiment, I observe what I will call a “response specificity effect”. There was an asymmetry in compatibility effects with keypad responses: Both spatial and imitative compatibility were limited to familiar downward press responses. Release responses did not show either effect. Notably, this is unlike the findings Brass and colleagues, who observed compatibility effects for both taps and lifts.

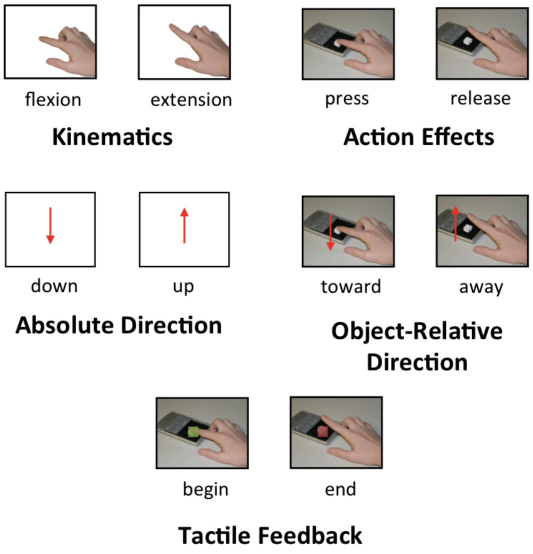


Figure 6: Confounded Components of Response Specificity Effect.

Importantly, if the downward/flexion/press responses above were selectively sensitive to compatibility, this could result from a number of confounded components of the motion (see Figure 6). Some possibilities include the kinematics (flexions), tactile feedback (contacting a key), absolute spatial directions (gravitationally downward key presses), relative spatial directions (moving a finger toward a key), and action effects (depressing a button). Certain of these components may uniquely contribute or the components may additively contribute to whether compatibility effects are observed. In the following experiments, we attempt to isolate the critical components.

A finding that will not be discussed further in the following experiments is that the presence or absence of a background accompanying model movements did not seem to substantially alter compatibility effects. This suggests that kinematic compatibility is possible without environment-relative coding (as the Press et al., 2008 results suggest) and, furthermore, that the compatibility effects in our paradigm were not even influenced by the surrounding environment.

One unifying view of embodied cognition phenomena that has important connections to the findings involving a background scene is Barsalou's Perceptual Symbol Systems theory. Barsalou's theory of representation involves *simulators* that are built up from repeatedly attending to multi-modal feature conjunctions (Barsalou, 1999; Barsalou, 2009). Simulators are then available (as "concepts") that can produce situation-specific *simulations,* which are partial re-enactments of previous sensory-motor content (Barsalou, 2009). Critically, Barsalou maintains that OLMC is one example of such partial re-enactment. I will return to certain other details of Barsalou's theory in the general discussion.

Regarding background scenes, a particularly relevant claim by Symbol Systems theory is that simulations are *situated*[5] in the background experiences and actions with which they have been commonly paired (Barsalou, 2003; Barsalou, 2008; Barsalou, 2009). That is, concepts activate relevant situational information and, conversely, situations activate associated concepts (Barsalou, 2008). Rather than recalling the entire breadth of possible conceptual information, concepts are said to generate "situated conceptualizations" in which the information relevant to the current context is recalled along with a concept (Barsalou, 1999; Barsalou, 2003a; Barsalou,

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[5] One objection that has been raised to the claim that cognition is situated is that this is a tautology: encountering an object is always within a particular physical context and with a particular task. Others have claimed the same tautological status for offline "situated cognition" (Greeno & Moore, 1993). However, Wilson (2002) has pointed out that we can think about objects in contexts in which they might never possibly be found (e.g. thinking about an elephant while spelunking). Moreover, we can construct counterfactuals and representations of situations that we have never experienced (Wilson, 2002). Though she is certainly right about the human capacity for offline cognition, it might be said that Wilson misses the point. Barsalou's version of the situatedness claim is generally *about offline cognition*. Though it may be tautological, Baraslou's suggests that our offline access to concepts is mediated by the particular purposes for which and by the contexts in which this access occurs.

2008). One major implication of situated conceptualizations for OLMC is that elicited motor activity should vary based on meaningful variations in context.

Barsalou's Symbol Systems theory could be interpreted to suggest that when the context for an action is more concrete, the simulation of the action may be stronger and, thus, a background should lead to a stronger compatibility effect. Moreover, the orientation of a background image provides an additional vertical frame of reference for judging the spatial direction of finger movements and therefore, one might have expected some influence of this manipulation. However, one might argue that merely presenting an objectless background image may not substantially alter the meaning of an action in such a way that compatibility effects would be influenced. Furthermore, the background image presented did not include identifiable landmarks to establish a vertical axis and that may be necessary to obtain any substantial impact of scene-relative coding. Though we do not further discuss the null effect for our sparse background conditions, the role of the onscreen environment in imitative compatibility effects remains an open and interesting question that may have important consequences for further development of theories such as Perceptual Symbol Systems.

The final finding in Experiment 1 comes from the response time distribution analysis. In the original study by Brass and colleagues, the authors found that both spatial and imitative compatibility effects increased in size across quintiles, but imitative effects increased by a greater amount in the last two quintiles of the distribution (see Appendix A for a version of the original Brass et al. effects in terms of difference scores). The authors took this to suggest that imitative effects may become more prominent when participants have more time to process the observed motions (i.e. at the longer RTs present in the later quintiles). Similar procedures have been used in other experiments as well (see Catmur & Heyes, 2011). Importantly, however this pattern has not been observed in all available research that has investigated imitative compatibility (see Jansson et al., 2007).

As can be seen from comparing the distribution plots for the current experiment to those obtained by Brass et al., the present experiment did not show a pattern like that observed by those authors. However, it is worth mentioning that quintile effects were only observed for downward/flexion responses, which is consistent with the mean reaction time analyses. Further analyses including the Brass et al. data would be needed to confirm that these were statistically different, but a visual comparison seems mostly adequate (though standard error information is lacking for the Brass plots).

# CHAPTER III

## EXPERIMENT 2

In the previous experiment, we found that only object-directed downward key presses (flexions), but not upward key releases (extensions), generated compatibility effects when observing onscreen extension and flexion finger motions. In Experiment 2, we used an inverted keypad such that participants generated *downward/flexion* key *releases* and *upward/extension* key *presses*. This allowed us to dissociate the effects of participant actions (presses and releases) from the action kinematics (flexion and extension). In this experiment, downward release responses had object-typical kinematics (flexions) and spatial directions (downward), but atypical action effects (releases), atypical tactile feedback (ceasing contact), and atypical object-relative motions (away). Upward press responses had object-typical action effects (presses), but atypical kinematics (extensions), and atypical spatial directions (upward). It is unclear whether tactile feedback (ceasing vs. initiating contact) and object-relative direction (toward vs. away) should be considered typical or atypical for the upward presses given the orientation of the hand relative to the apparatus, but we will assume that these are atypical as the relationship between the areas of the hand (upper fingernail) experiencing tactile feedback are not the same as in the object-typical motions (pad of the finger).

## *Method*

### *Participants*

Forty-one undergraduate students from Vanderbilt University participated in this study for class credit. Five participants were excluded for failing to follow instructions, and 3 were excluded because for exceeding the 10% error criterion. This left 33 participants' data for analysis (age range: 18-28, mean age: 19.9, 15 males).

### *Apparatus*

The apparatus was the same as used in Experiment 1.

### *Materials*

The materials were the same as in Experiment 1.

### *Procedure*

The procedure was similar to that in Experiment 1, but the central key on the upper pad of the response apparatus was used (see Figure 7). Participants made either an upward finger extension *press* response with their index finger or downward flexion *release* response. Additionally, to ensure that participants were familiar with only one of their possible responses at a time, practice was divided into two phases. The first practice phase was presented before the first response type block and the second practice phase was presented before the second response type block.

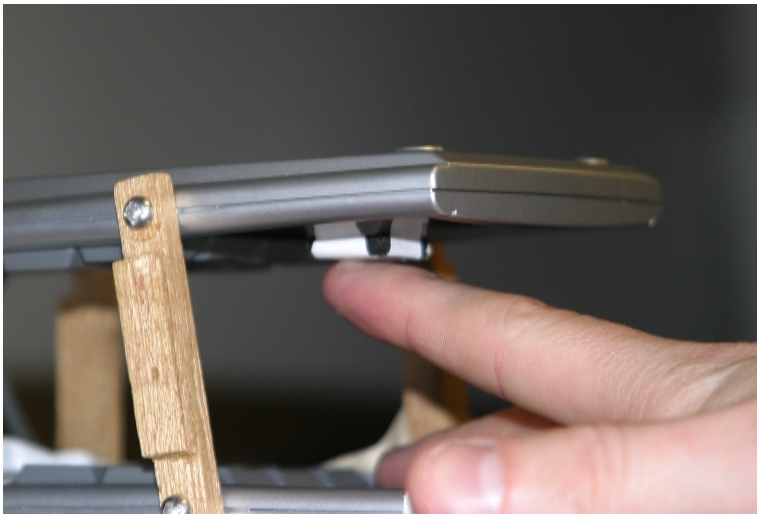


Figure 7: Response Apparatus for Experiments 1 and 2. Here the device is configured for Experiment 2, with the response key on the top keypad.

*Analysis*

*Errors.* Errors involving the wrong direction did not occur during this experiment, failures to respond occurred in less than 0.2% of trials on average, and anticipation errors occurred on 2.2% of trials on average. Participants who exceeded 10% total errors were removed from the analysis. Because the only meaningful errors for an analysis would be incorrect directions, an analysis of errors was not conducted.

*Reaction times.* All reaction times below 80ms (anticipation errors) or above 800ms were excluded from the analysis.

## *Results*

### *Aggregate Analysis*

An initial repeated-measures ANOVA that included both response types (presses and releases), interactions between compatibility effects and response type. Thus, as before, we looked at each response type in separate ANOVAs.

The ANOVA for (upward) extension press responses included SOA (800, 1600, or 2400ms), anatomical compatibility (compatible or incompatible), and spatial compatibility (compatible or incompatible) as within-subjects factors. Background condition (table or no background) was included as a between-subjects factor. The analysis showed only a main effect of SOA, $F(2, 62) = 134.00$, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M = 432$ms, $SD = 80$ms; 1600ms SOA: $M = 393$ms, $SD = 78$ms; 2400ms SOA: $M = 379$ms, $SD = 77$ms). The main effect of imitative compatibility was not significant, $F(1,31) = .02$, $p = .89$, and neither was the effect of spatial compatibility, $F(1,31) = 1.50$, $p = .23$. No other effects achieved significance.

The ANOVA for (downward) flexion release responses included the same factors as above. The analysis showed a main effect of imitative compatibility, $F(1, 31) = 14.43$, $p < .001$, with faster responses on compatible ($M = 340$ms, $SD = 64$ms) than on incompatible trials ($M = 355$ms, $SD = 71$ms). Additionally, there was a main effect of spatial compatibility, $F(1, 31) = 20.29$, $p < .0001$, with faster responses on compatible ($M = 339$ms, $SD = 65$ms) than on incompatible trials ($M = 356$ms, $SD = 70$ms). Compatibility effects for both responses are pictured in Figure 8. There was also a main effect of SOA, $F(2, 62) = 196.38$, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M = 388$ms, $SD = 72$ms; 1600ms SOA: $M = 335$ms, $SD = 69$ms; 2400ms SOA: $M = 321$ms, $SD = 63$ms). Finally, there was a significant interaction between imitative compatibility and SOA, $F(2, 62) = 3.29$, $p < .05$. Simple main effects comparisons at each level of SOA showed that the type compatibility effect was only significant for the 800ms, $F(1, 31) = 12.97$, $p < .005$, and 1600ms, $F(1, 31) = 9.54$, $p < .005$, SOAs, but not for the 2400ms SOA, $F(1, 31) = 1.03$, $p = .32$.

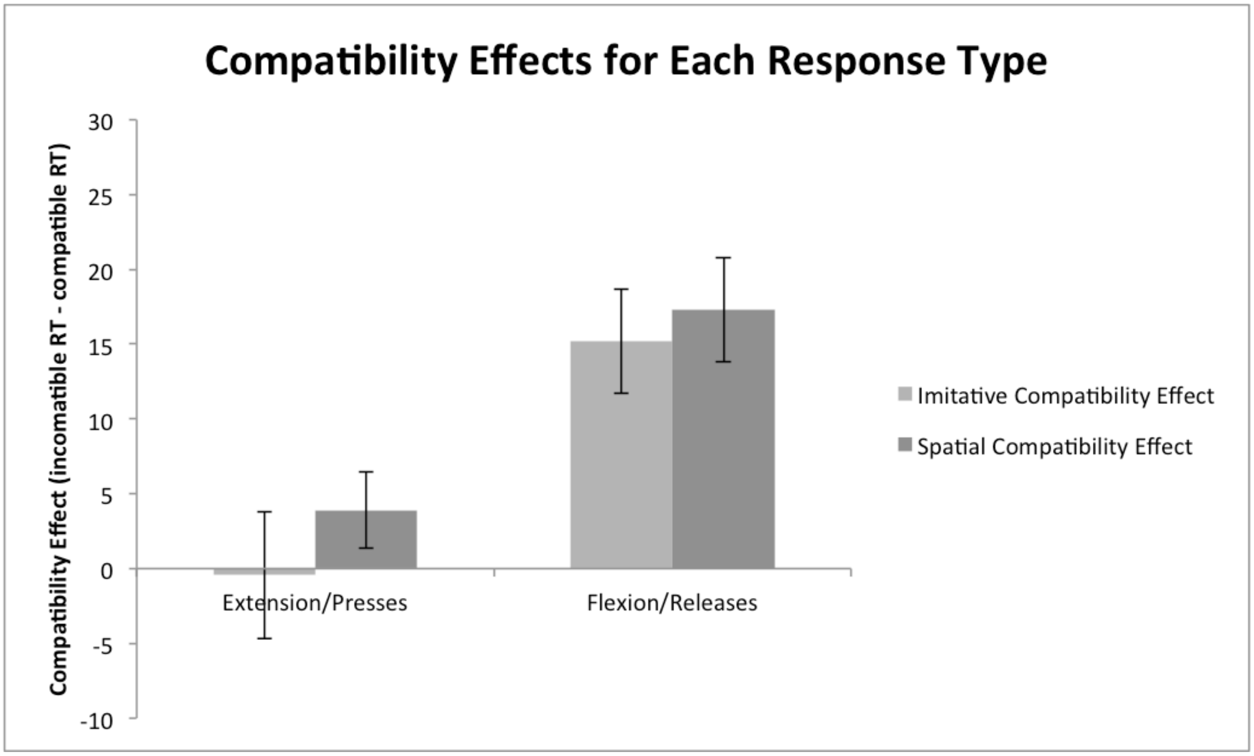


Figure 8: Compatibility Effects for Experiment 2. Error bars indicate standard error of compatibility effect.

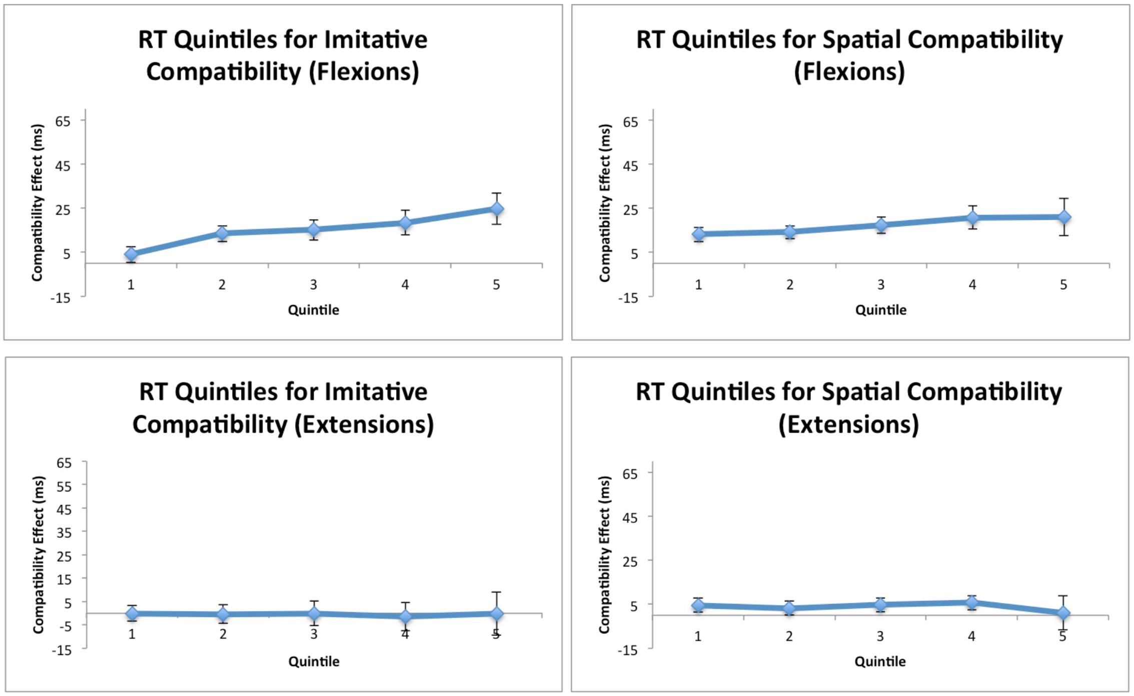
*First Response Analysis*

The effects in the first response ANOVAs generally replicated the findings above. For extension presses there was a main effect of SOA, $F(2, 30) = 65.29$, $p < .0001$. The main effects of type compatibility, $F(1, 15) = .26$, $p = .62$ and spatial compatibility, $F(1, 15) = .67$, $p = .43$, were not significant. However, there was a significant interaction between spatial compatibility and SOA, $F(2, 30) = 3.45$, $p < .05$. Simple effects analyses showed that at the 1600ms SOA participants extension responses were faster, $F(1, 15) = 6.51$, $p < .05$ on spatially compatible ($M$ = 364ms, $SD$ = 65ms) than incompatible ($M$ = 379ms, $SD$ = 79ms) trials, but this was not true at the 800ms SOA, $F(1, 15) = .22$, $p = .64$, or the 2400ms SOA, $F(1, 15) = .24$, $p = .63$.

For flexion releases, there were main effects of SOA, $\mathrm{F}(2, 28) = 90.41$, $p < .0001$, imitative compatibility, $F(1, 14) = 13.62$, $p < .005$, and spatial compatibility, $F(1, 14) = 6.76$, $p < .05$, mirroring those in the within-subjects analysis. The interaction between imitative compatibility and SOA observed in the within-subjects analysis failed to achieve significance, $F(2, 28) = 1.63$, $p = .21$.

### *Distribution Analysis*

An initial ANOVA included response type (presses and releases), quintile (1-5), and compatibility component (type compatibility vs. spatial compatibility) were included as within-subjects factors This analysis showed only a significant main effect of response type, $F(1, 32) = 14.99$, $p = .001$, echoing the similar finding in the analyses above. Because differences had been observed between response types previously, each response was also analyzed in a separate ANOVA including compatibility component (spatial or imitative compatibility) and quintile (1-5). The ANOVA for (upward) extension press responses showed no significant effects. The ANOVA for (downward) flexion release responses showed a main effect of quintile, $F(1, 32) = 2.74$, $p < .05$, such that compatibility effects increased across quintiles. As can be seen from Figure 9, compatibility effects generally increased across quintiles for both spatial and imitative components.


RT Quintiles for Imitative Compatibility (Flexions)

RT Quintiles for Spatial Compatibility (Flexions)

RT Quintiles for Imitative Compatibility (Extensions)

RT Quintiles for Spatial Compatibility (Extensions)

Figure 9: Reaction Time Distributions for Experiment 2.

## *Discussion*

The results of Experiment 2 showed that when producing downward flexion key *release* motions, which had object-typical kinematics and spatial directions but atypical action effects, compatibility effects were observed. For upward extension key presses, with typical object-directed action effects (presses), there were no main effects of compatibility.

Generally, these findings replicate those in Experiment 1, however, interactions between SOA and imitative compatibility for downward flexions and between SOA and spatial compatibility for upward extensions (in the between-subjects analysis) suggests that the inverted spatial frame of reference provided by the relative orientation of the keypad may have altered compatibility effects. However, given that the main effect of compatibility remained, and interactions with SOA were not reliable across the within- and between-subjects analyses, the dominant finding from this study is that the previous results of a specificity effect for downward/flexions with a keypad are replicated even when the spatial relationship between the finger and the pad are reversed and the goal state (pressing a key) is not associated with the downward/flexion response.

This experiment shows that compatibility effects are still specific to downward/flexion responses even when these responses did not produce a typical action effect (depressing a button). However, it is noteworthy that goals and action effects still make a potentially important contribution to the foregoing results. Specifically, it is worth emphasizing that both downward/flexions and upward/extensions are common motions during typing (as typing involves both pressing an releasing a key), but only flexions have shown a compatibility effect in the above experiments. During typing, downward flexions typically produce the action effects such as characters appearing on a computer screen. Thus, rather than these experiments reflecting a specificity of compatibility effects for responses that are typical for the keypad, they reflect a specificity for responses that typically produce action effects. We will return to this point in the general discussion. Importantly, the above experiments do not allow us to dissociate the contributions of spatial and kinematic features of motion to the response specificity effect. This issue is addressed in the following experiment by using an orthogonally oriented keypad.

# CHAPTER IV

# EXPERIMENT 3

The previous experiments suggest that object-directed downward flexion responses may be uniquely susceptible to interference from other motions. However, the prior experiments confound the kinematic flexion pattern with the gravitationally downward direction for these motions. In this experiment, we isolated the kinematic components model motions from spatial components. The keypad was oriented on its side and attached to a weighted box. Participants made leftward/flexion/press responses and rightward/extension/release responses.

If the results of previous experiments reflected *kinematic* specificity, we would expect to find compatibility effects only for (leftward) flexion key presses in this experiment. However, if spatial directions are solely responsible, then we would expect to find compatibility effects for neither (or perhaps both) of the responses in this experiment because the spatially downward direction of motions and the spatially opposing response (upward) are no longer present. Finally, an intermediate pattern of results may emerge if both typical kinematics and typical spatial directions play a role in the previously observed specificity effects.

## *Method*

### *Participants*

Twenty-three Vanderbilt University students and members of the Nashville community participated in this experiment (age range: 18-31, mean age: 20.38, 6 males).

*Apparatus*

All stimuli were presented using Matlab R2010a with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) on a Mac Mini computer (monitor vertical refresh: 89 Hz; monitor dimensions: 32 cm x 24 cm, 36.9˚ x 28˚ of visual angle) running Mac OS 10.6. The response device was the same type of keypad used in Experiment 1, but the side-oriented pad was attached to a weighted cardboard box with Velcro strips. The box was also affixed to the table with Velcro strips and positioned to the right of the monitor approximately where the pad had been located in the prior experiments. A small cloth wrist pad was provided to allow participants to comfortably adopt a side-oriented hand posture.

*Materials*

The materials were the same as in Experiment 1 and 2, but all motions were presented with a table background present. We avoided manipulating background condition as this manipulation was not critical to the question motivating this experiment and because there were no critical differences between background conditions in the previous experiments.

*Procedure*

The procedure matched that of Experiment 1, except that the keypad was orthogonally oriented and participants adopted an appropriate side-oriented hand posture throughout the experiment, with their forearms resting on the cloth rest.

### *Analysis*

*Errors.* Errors involving the wrong key press occurred on less than 0.2% of trials, failures to respond occurred in less than 0.3% of trials on average, and anticipation errors occurred on less than 0.2% of trials on average. Because the only meaningful errors for an analysis would be incorrect key responses and errors were rare, an analysis of errors was not conducted. No participants were excluded for exceeding the 10% error criterion in this experiment.

*Reaction times.* All reaction times below 80ms (anticipation errors) or above 800ms were excluded from the analysis.

## *Results*

### *Aggregate Analysis*

An initial repeated-measures ANOVA that included both response types (presses and releases), showed interactions between compatibility effects and response type. Thus, as before, we looked at each response type in separate ANOVAs.

The ANOVA for (rightward) extension release responses included the same factors as above. The analysis showed only a main effect of SOA, $F(2, 44) = 90.32$, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M = 316$ms, $SD = 39$ms; 1600ms SOA: $M = 280$ms, $SD = 42$ms; 2400ms SOA: $M = 269$ms, $SD = 44$ms). As can be seen in Figure 10, the main effect of imitative compatibility was not significant for extension responses, $F(1, 22) = .05$, $p = .82$.

The ANOVA for (leftward) flexion press responses included SOA (800, 1600, or 2400ms), anatomical compatibility (compatible or incompatible), and onscreen hand orientation (upright or inverted) as within-subjects factors. Onscreen hand orientation was included because spatial compatibility could not be analyzed in this experiment due to the orthogonal spatial relationship between participant and model hand axes. The analysis showed a main effect of imitative compatibility, $F(1, 2) = 5.63$, $p < .05$, with faster responses on compatible ($M$ = 318ms, $SD$ = 47ms) than on incompatible trials ($M$ = 327ms, $SD$ = 56ms). Additionally, there was a main effect of SOA, $F(2, 44) = 57.07$, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M$ = 353ms, $SD$ = 61ms; 1600ms SOA: $M$ = 311ms, $SD$ = 51ms; 2400ms SOA: $M$ = 303ms, $SD$ = 45ms).

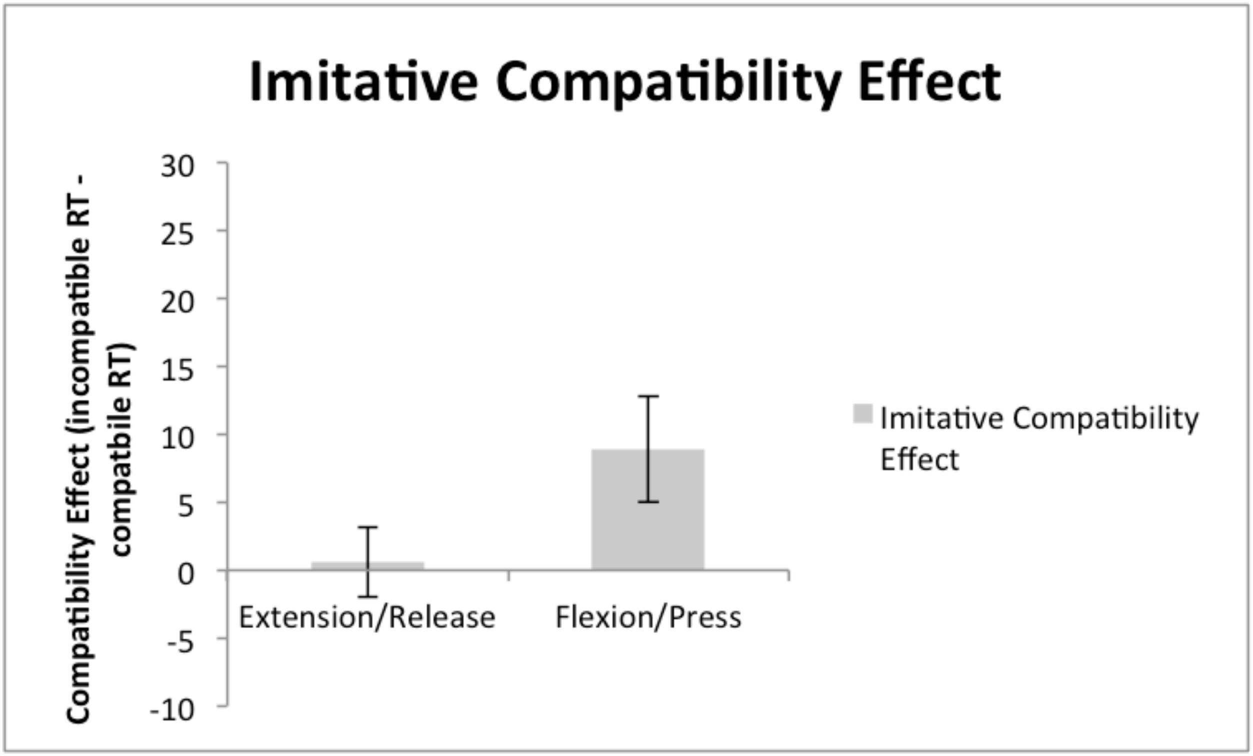


Figure 10: Imitative Compatibility Effects for Experiment 3. Error bars indicate standard error of compatibility effect.

### *First Response Analysis*

The effects in the first response ANOVAs differed slightly from the findings above. For downward extension releases, only the main effect of SOA was significant, $F(2, 20) = 65.41$, $p < .0001$, with faster responses for increasing SOAs as above. For leftward flexion presses only the main effect of SOA was significant, $F(2, 22) = 25.27$, $p < .0001$, with faster responses with increasing SOA as above. The effect of imitative compatibility did not reach significance, $F(1, 11) = 2.96$, $p = .11$, but responses were numerically faster for imitatively compatible ($M$ = 332ms, $SD$ = 52ms) than imitatively incompatible ($M$ = 341ms, $SD$ = 62ms) trials.

### *Distribution Analysis*

An initial ANOVA included response type (presses and releases) and quintile (1-5) as within-subjects factors. Compatibility component (type compatibility vs. spatial compatibility) was not included in this analysis because spatial compatibility was not being considered in this experiment. This analysis showed no significant effects.

Because differences had been observed between response types previously, each response was also analyzed in a separate ANOVA including quintile (1-5) as a within-subjects factor. The ANOVA for (leftward) flexion presses showed a main effect of quintile, $F(4,19) = 2.99$, $p < .05$. It should be noted that though there was a significant interaction, the change in the distribution occurred primarily between the first and second quintiles, thus this does not reflect a pattern similar to that observed by Brass et al. (2001). The ANOVA for (rightward) extension releases did not show a significant effect of quintile, $F(4,19) = .52$, $p = .73$ (see Figure 11).

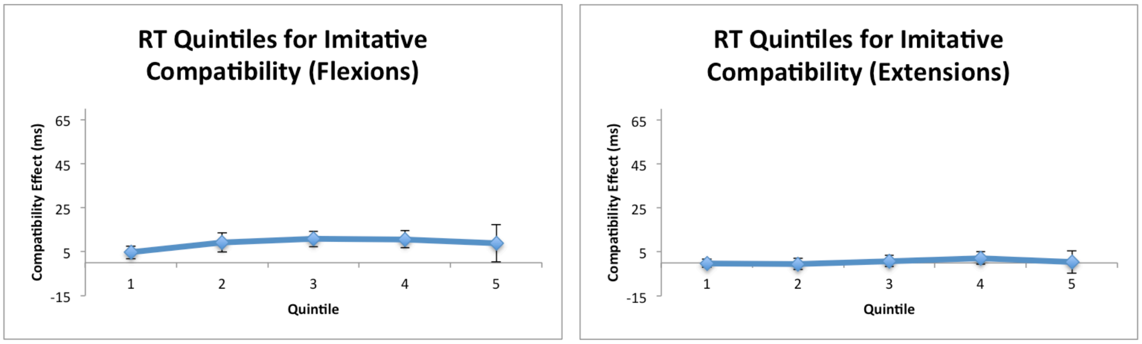


Figure 11: Reaction Time Distributions for Experiment 3.

### *Discussion*

This experiment presented participants with a side-oriented keypad so that the spatial direction of press/release motion was no longer typical with respect to gravity. This also made participant responses orthogonal to model motions so that no there was no direct spatial compatibility between observed and produced motions. The within-subjects results showed a significant compatibility effect for flexion press responses but not for extension release responses. Notably, showing this flexion specificity with the orthogonal key orientation suggests and that the response specificity is can be obtained based on action kinematics alone independent of spatial compatibility. However it is important to note, that the above findings do not *exactly* replicate the prior findings given the compatibility effect was numerically smaller in the within-subjects analysis and was not significant in the first response analysis. This could be taken to suggest that by moving the keypad away from the canonical horizontal orientation (and thus eliminating the association between downward directions and flexion kinematics), as was present in all the prior experiments, the response-specificity effect is weakened. However, the present experiment generally supports the idea that kinematics can drive response-specificity effects.

# CHAPTER V

## EXPERIMENT 4

The prior experiments generally suggest that reaction times to produce finger flexion motions are influenced by compatibility with observed motions, but RTs for extension motions are not. Thus, the above experiments make significant progress in identifying how kinematic, spatial, and action effect components contribute to response specificity for imitative compatibility effects with key devices.

The present experiment is designed to address certain broader questions regarding response specificity in imitative compatibility. First, this experiment makes an initial attempt to determine whether the observed flexion specificity effect is object-general or object specific. An object-specific interpretation would suggest that there is something special about the familiar downward press motions for keypads and may implicate OLMC in producing the specificity effect. However, because the above experiments have only employed a keypad, it remains ambiguous whether an object-specific association between flexion motions and keys is responsible for the specificity effect or whether flexion specificity may instead be a general feature of compatibility effects involving objects. One difficulty with answering this question is that extension motions are very rare in real-world object interactions.

To begin to address the question of whether the response specificity effect is object-general or object-specific, the present experiment employs a novel light switch response device. Though flexions are also likely to be more common motions for a light switch than extensions, interactions with a switch are likely to be considerably more variable than for keyboards.

Anecdotal evidence from colleagues suggests that individuals use their thumbs, middle fingers, and the side of the index finger to interact with a switch. Thus, flexion motions are unlikely to have as clear of an entrenched association with action effects as they do for keyboards.

A second advantage of the present experiment is that it permits a test of a particular theoretical account of response specificity. Under this object-specific explanation, learned object-relevant action sequencing explains the response specificity effect. Within typical keyboard use, downward/flexions (presses) are commonly part of a set of paired action components in which a downward/flexion/press is then followed by an upward/extension/release. So, response specificity may be a general feature of action compatibility for responses that are components of different ordered portions of an object-typical action sequence. In such a case, later parts of a frequently produced action sequence (e.g. extension/releases) would not be susceptible to interference from earlier parts of the same sequence (e.g. flexion/presses), but earlier parts of a sequence would be susceptible to interference from later parts. Motions typically directed toward light switches do not involve salient repeated flexion/extension pairs. Thus, if an action sequence order effect is alone responsible for response specificity observed above, one might expect the light switch to show compatibility effects for both flexion and extension responses.

## *Method*

### *Participants*

Twenty-four Vanderbilt University students participated in this study for class credit or cash compensation (age range: 18-25, mean age: 19.3, 10 males).

### *Apparatus*

All stimuli were presented using the same equipment as in Experiment 3. The response apparatus was a custom-made response box that resembles and operates like a light switch (see Figure 12). Upward or downward presses on the light switch separately triggered the left and right button switches from a USB mouse. The range of motion of the switch was restricted as compared to a typical light switch (as participants were only able to move the switch slightly in either direction to trigger a response).

Figure 12: Response Apparatus for Experiment 4.

### *Materials*

The materials were the same as used in Experiment 3.

### *Procedure*

The procedure matched that of Experiment 3, except that flexion responses involved holding an index finger above the switch and pressing downward and extension responses involved holding an index finger below the switch and pressing upward.

### *Analysis*

*Errors.* Errors involving the wrong direction did not occur during this experiment, failures to respond occurred in less than .08% of trials on average, and anticipation errors occurred on less than .01% of trials on average. Because error rates were low and the only meaningful errors for an analysis would be incorrect directions, an analysis of errors was not conducted.

*Reaction times.* All reaction times below 80ms (anticipation errors) or above 800ms were excluded from the analysis.

## *Results*

### *Aggregate Analysis*

An initial repeated-measures ANOVA that included both response types (presses and releases), showed interactions between compatibility effects and response type. Thus, as before, we looked at each response type in separate ANOVAs.

The ANOVA for upward extension presses included SOA (800, 1600, or 2400ms), imitative compatibility (compatible or incompatible), and spatial compatibility (compatible or incompatible) as within-subjects factors. The analysis showed a main effect of SOA, *F*(2, 46) =

43.59, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M = 546$ms, $SD = 71$ms; 1600ms SOA: $M = 511$ms, $SD = 69$ms; 2400ms SOA: $M = 510$ms, $SD = 73$ms). Neither the effect of imitative compatibility, $F(1, 23) = .19$, $p = .67$, nor the effect of spatial compatibility, $F(1, 23) = .26$, $p = .62$, achieved significance.

The ANOVA for downward flexion presses included the same factors as above. The analysis showed a main effect of imitative compatibility, $F(1, 23) = 12.27$, $p < .005$, with faster responses on compatible ($M = 424$ms, $SD = 78$ms) than on incompatible trials ($M = 434$ms, $SD = 79$ms). Additionally, there was a main effect of SOA, $F(2, 46) = 48.30$, $p < .0001$, with responses being faster for longer SOAs (800ms SOA: $M = 457$ms, $SD = 88$ms; 1600ms SOA: $M = 419$ms, $SD = 73$ms; 2400ms SOA: $M = 411$ms, $SD = 77$ms). The main effect of spatial compatibility failed to reach significance, $F(1, 23) = 2.63$, $p = .12$. See Figure 13 a graph of the compatibility effects in Experiment 4.

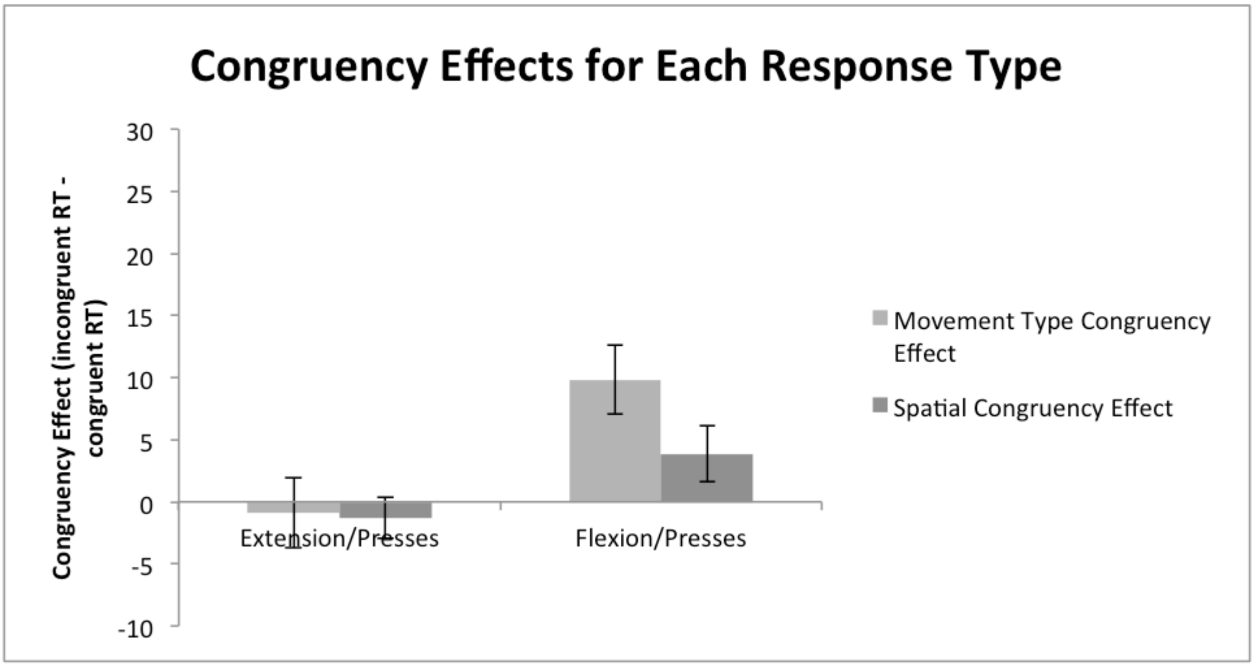


Figure 13: Compatibility Effects for Experiment 4. Error bars indicate standard error of compatibility effect.

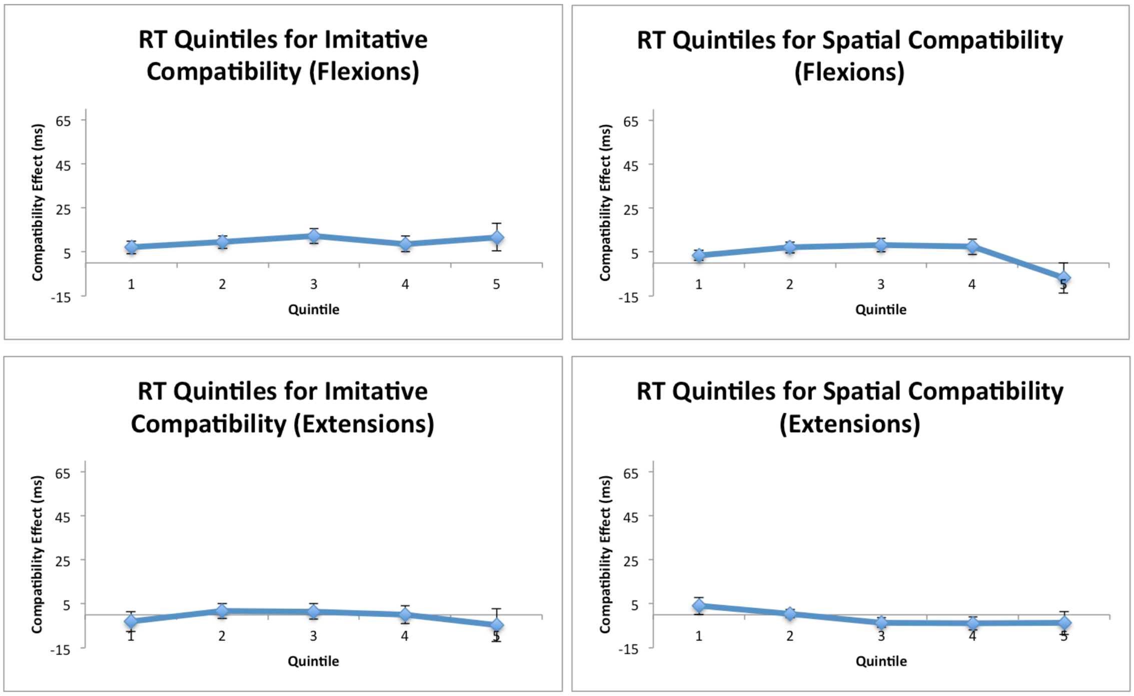
*First Response Analysis*

The effects in the first response ANOVAs generally replicated the findings above. For upward extension presses there was a main effect of SOA, *F*(2, 24) = 12.92, p < .001, but no other effects were significant. For downward flexion presses, there were significant main effects of SOA, *F*(2, 20) = 17.98, p < .0001, and imitative compatibility, *F*(1, 10) = 7.32, p < .05.

*Distribution Analysis*

An initial ANOVA included response type (presses and releases), quintile (1-5), and compatibility component (type compatibility vs. spatial compatibility) were included within-subjects factors This analysis showed only a significant main effect of response type, *F*(1, 23) = 12.06, *p* = .005, echoing the similar finding in the analyses above. Because differences had been observed between response types previously, each response was also analyzed in a separate

ANOVA including compatibility component (spatial or imitative compatibility) and quintile (1-5). Neither ANOVA showed any significant effects. See Figure 14 for graphs of the RT distributions for Experiment 4.



RT Quintiles for Imitative Compatibility (Flexions)

RT Quintiles for Spatial Compatibility (Flexions)

RT Quintiles for Imitative Compatibility (Extensions)

RT Quintiles for Spatial Compatibility (Extensions)

Figure 14: Reaction Time Distributions for Experiment 4.

## *Discussion*

The results of this experiment suggest that for a light switch device, flexions were still the only response to reliably elicit compatibility effects. This makes an object-general account of response specificity effects plausible. Specifically, this would mean an interpretation of the foregoing findings that when one is interacting with *any* device, flexion motions are uniquely susceptible to compatibility effects. It could be argued that an object-general mechanism is involved because flexion motions are a critical component of initiating all grasping motions and are necessary to pick up and hold an object securely. Extensions are more typically associated with ending contact with an object and may be encoded in a fundamentally different way than flexions as these correspond to the cessation of an action.

Another interpretation of the observed downward/flexion specificity is that the effect is not an inherent property of object-directed action, but that flexions are merely more typical motions for both keys and light switches and this learned association is responsible for our effects. Though upward and downward motions of a light switch are typical for the *switch*, the kinematic extensions we asked participants to use to produce upward motions are quite atypical. When reading the instruction to place their index fingers below the switch (and make an upward motion), many participants initially turned their hand upside down to make the response as a flexion using the pad of their finger. This further suggests that extensions are atypical for switches. Intuitions among colleagues suggest that people often adopt an inverted cupping hand configuration and make a flexion or a wrist motion. For downward switch motions, all participants immediately understood how to produce the response. Given these observations, our lack of a compatibility effect with upward extensions may be expected in the above experiment because the switch, like a keyboard, has only flexions associated with action effects. In fact, flexions are overwhelmingly more typical of the motions we use to approach an object for use.

Another important implication of these findings is that the action sequencing interpretation of the prior experiments' results is unsupported. The flexion and extension motions involved in pressing a light switch are not part of action sequences that also involve immediately releasing the switch (as with typical key presses). Thus, it seems that an action sequencing explanation for the response-specificity effect observed with keys is unlikely.

One final note is that the absence of a spatial compatibility effect for the light switch and the absence of a quintile effect for either response type may suggest certain differences between switch and key responses. However, the light switch was oriented at an approximately 35˚ angle to the screen such that participant responses could be comfortably made while the switch was still visible. Thus, this difference in the match between participant and model hand angle might also have influenced these effects.

# CHAPTER VI

# EXPERIMENT 5

The previous experiments suggest that object-directed flexion responses may be uniquely susceptible to interference from other motions. However, given that our stimuli differ from those originally used by Brass and colleagues, it is not possible to rule out an explanation for our results based on our stimuli alone. In other words, it is possible that the specificity of our effects for flexion motions may be an artifact of our stimuli rather than a being a feature of the object-directed motions that have been explored. This is especially important given that Brass and colleagues (2001) observed a stronger effect for tapping responses than for lifting responses in their first experiment suggesting that flexions may generally be more susceptible to interference and our stimuli could simply have made this asymmetry more pronounced. To address this, the present experiment involved finger motions that were not object-directed.

## *Method*

### *Participants*

Thirty-three Vanderbilt University students and members of the Nashville community participated in this experiment. 2 participants were removed because the procedure was administered incorrectly and they were run without the glove, making data unreliable. 6 participants were excluded for exceeding the 10% error criterion. 1 additional participant was excluded because the device was not responding properly. This left 24 participants' data for analysis (age range: 18-25, mean age: 19.3, 8 males).

*Apparatus*

All stimuli were presented using the same equipment as in Experiment 3. The response device was as pictured in Figure 15. Two pairs of infrared (IR) transmitters and receivers were placed above and below the resting location for participants' index fingers. Participants' arms rested on the armrest and the 3rd, 4th, and 5th digits were curled slightly and placed abutting the diagonal board at the head of the device. Participants' index fingers extended into the free space to the left of the armrest. Flexion and extension motions interrupted infrared beams that were detected by aligned IR transistors. The attached computer recorded breaks in the beams using IR transistors in conjunction with NPN switching transistors to trigger click signals for two buttons of a USB mouse. To reduce possible inaccuracy due to reflections of infrared beams off of participants' skin or fingernails, all participants wore a knit black mitten on their right hand.

Figure 15: Response Apparatus for Experiment 5.

### *Materials*

The materials were the same as used in Experiment 3.

### *Procedure*

The procedure matched that of Experiment 3, but the device was as described above. Also, because no button was present to press or release, participants were instructed to make either "tap" or "lift" responses in line with the original instructions used by Brass et al. (2001).

### *Analysis*

*Errors.* Errors involving the wrong direction occurred in less than 0.9% of trials on average, failures to respond occurred in 1.5% of trials on average, and anticipation errors occurred on less than 0.7% of trials on average. Because the only meaningful errors for an analysis would be incorrect directions and these error rates were low, an analysis of errors was not conducted. Errors involving failure to respond may have been somewhat larger in this experiment due to the fact that certain responses may have failed to fully interrupt the IR beam.

*Reaction times.* All reaction times below 80ms (anticipation errors) or above 800ms were excluded from the analysis.

## *Results*

### *Aggregate Analysis*

An ANOVA was conducted that included response type (flexion or extension), SOA (800, 1600, or 2400ms), imitative compatibility (compatible or incompatible), and spatial compatibility (compatible or incompatible) as within-subjects factors. The analysis showed a main effect of SOA, *F*(2, 46) = 68.04, *p* < .0001, with responses being faster for longer SOAs (800ms SOA: *M* = 388ms, *SD* = 61ms; 1600ms SOA: *M* = 343ms, *SD* = 58ms; 2400ms SOA: *M* = 335ms, *SD* = 47ms). Both the main effects of imitative compatibility, *F*(1, 22) = 22.67, *p* < .0001, and spatial compatibility, *F*(1, 22) = 9.37, *p* < .01, were significant. Participants were faster on movement-type-compatible (*M* = 351ms, *SD* = 55ms) than movement-type-incompatible (*M* = 360ms, *SD* = 54ms) trials and were faster on spatially-compatible (*M* = 348ms, *SD* = 50ms) than spatially-incompatible trials (*M* = 362ms, *SD* = 59ms). Importantly, no interactions involving compatibility effects were significant. The final significant result was a significant main effect of response type, *F*(1,22) = 13.87, *p* <.005, with participants making faster upward (*M* = 335ms, *SD* = 57ms) than downward responses (*M* = 377ms, *SD* = 64ms).

Given the unique absence of interactions with compatibility effects in this experiment, simple main effects analyses were conducted to evaluate compatibility effects for each response type. Simple effects analyses of imitative compatibility showed a significant effect for both flexion, *F*(1, 22) = 12.70, *p* < .005, and extension, *F*(1, 22) = 6.28 *p* < .05, responses. Analyses of spatial compatibility showed a significant effect for flexion responses, *F*(1, 22) = 7.22, *p* < .05, and a marginal effect for extension responses, *F*(1, 22) = 4.08, *p* = .056. See Figure 16 for graphs of the compatibility effects.

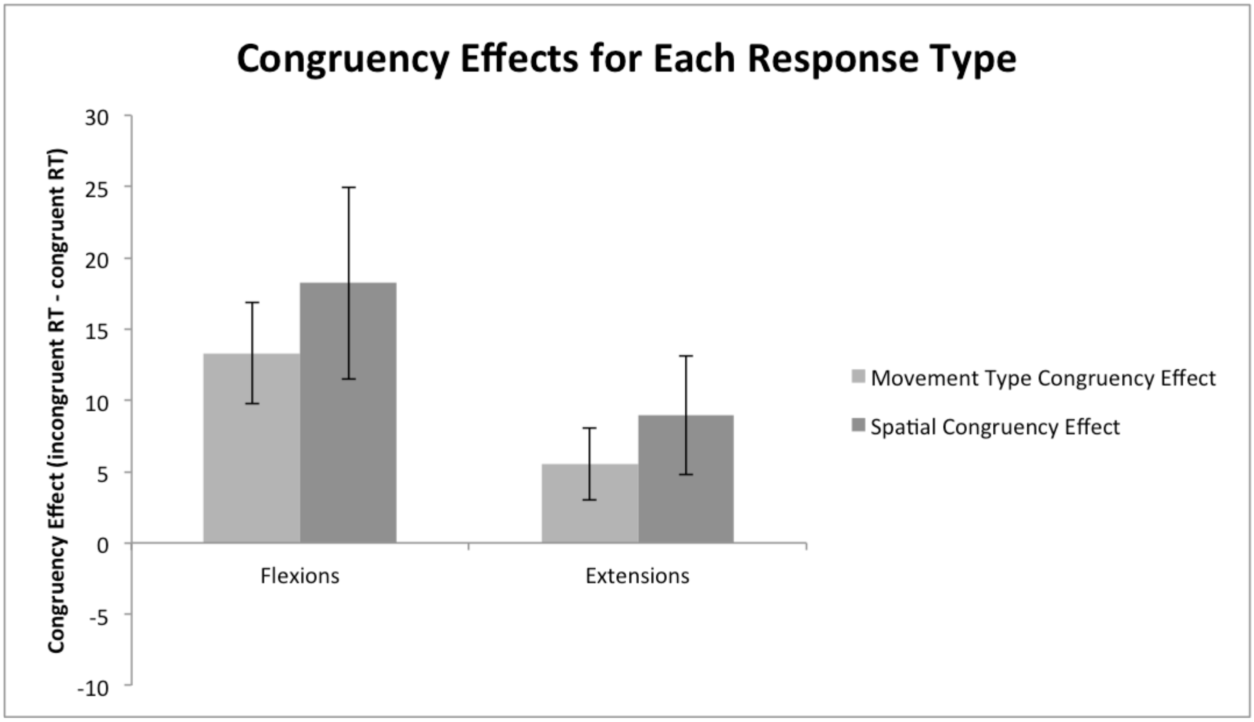


Figure 16: Compatibility Effects for Experiment 5. Error bars indicate standard error of compatibility effect.

### *First Response Analysis*

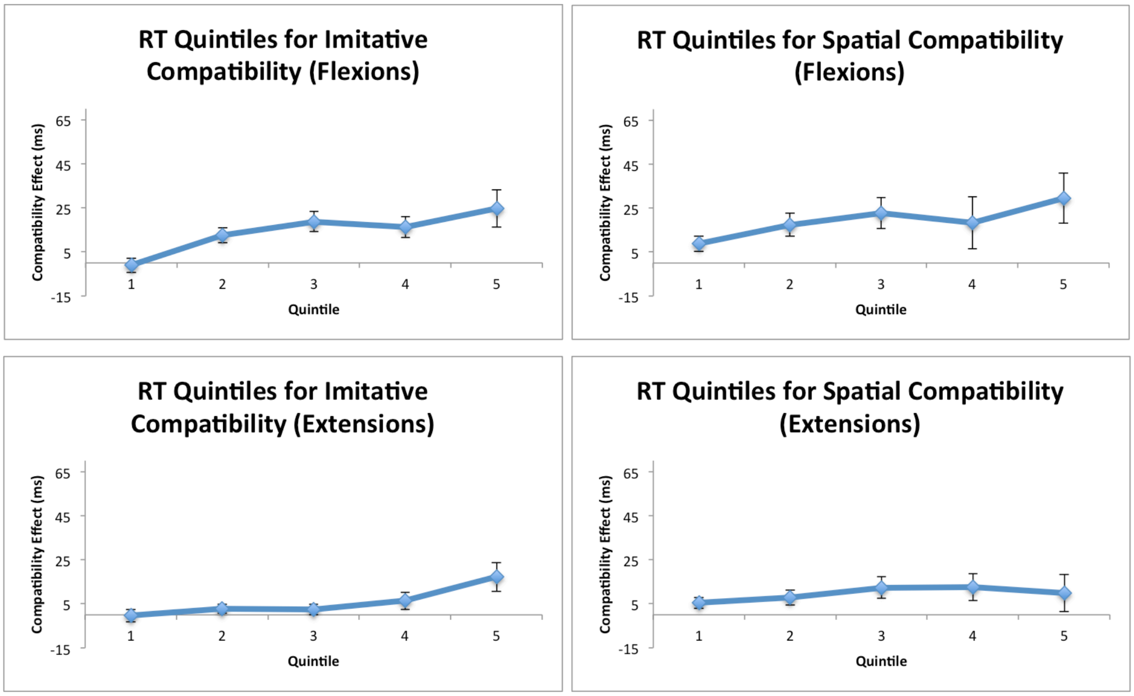
The effects in the first response ANOVA did not exactly replicate the findings from the aggregate analysis. First, given the above results showed no interaction with response type, an ANOVA was conducted with both responses types. This analysis showed significant main effects of SOA, $F(2, 42) = 34.14$, $p < .0001$,with faster responses for longer SOAs (800ms SOA: $M = 396$ms, $SD = 81$ms; 1600ms SOA: $M = 355$ms, $SD = 80$ms; 2400ms SOA: $M = 346$ms, $SD = 63$ms) and of imitative compatibility, $F(1, 21) = 5.24$, $p < .05$, with faster responses for movement-type-compatible ($M = 362$ms, $SD = 71$ms) than movement-type-incompatible ($M = 369$ms, $SD = 75$ms) trials. However, the main effect of spatial compatibility was not significant. Importantly, the interaction between response type and imitative compatibility was also non-significant, $F(1, 21) = 1.91$, $p = .18$.

Despite the above non-significant interaction, simple effects analyses of imitative and spatial compatibility effects were conducted for each response type. For flexion responses, there was a significant main effect of imitative compatibility, $F(1, 21) = 7.04$, $p < .05$, but no significant effect of spatial compatibility, $F(1, 21) = 2.54$, $p = .13$. For extension responses, imitative compatibility, $F(1, 21) = .39$, $p = .54$, and spatial compatibility, $F(1, 21) = .05$, $p = .83$, effects did not achieve significance.

### *Distribution Analysis*

An initial ANOVA included response type (presses and releases), quintile (1-5), and compatibility component (type compatibility vs. spatial compatibility) were included as within-subjects factors This analysis showed a significant effect of quintile, *F*(4, 20) = 7.32, $p < .001$, indicating that compatibility effects generally increased across quintiles (see Figure 17). There was also a significant main effect of response type, *F*(1, 23) = 4.35, $p = .05$, echoing the similar finding in the analyses above.

Because differences had been observed between response types previously, each response was also analyzed in a separate ANOVA including compatibility component (spatial or imitative compatibility) and quintile (1-5). The ANOVA for (downward) flexion press responses included compatibility component (spatial or imitative compatibility) and quintile (1-5). This ANOVA showed a main effect of quintile, *F*(4, 20) = 5.02, $p < .01$. The ANOVA for (upward) extension release responses included the same factors as above. This ANOVA also showed a main effect of quintile, *F*(4, 20) = 5.25, $p < .005$.


RT Quintiles for Imitative Compatibility (Flexions)

RT Quintiles for Spatial Compatibility (Flexions)

RT Quintiles for Imitative Compatibility (Extensions)

RT Quintiles for Spatial Compatibility (Extensions)

Figure 17: Reaction Time Distributions for Experiment 5.

### *Discussion*

The results of this experiment confirm that our stimuli were capable of generating significant imitative compatibility effects with both flexion and extension responses when these responses were objectless. These results support the interpretation of above findings that the response-specificity of compatibility effects was due to the presence of objects in these experiments rather than a confound introduced by using stimuli that differed from those originally used in the similar paradigm employed by Brass et al. (2001).

It is worth noting, however, that in the first-response analysis, spatial compatibility effects were absent for both responses and simple main effects failed to find significant imitative compatibility effects for extension responses. It is unclear how to interpret these findings relative to those obtained by Brass and colleagues as the authors never analyzed the first response type participants made in their experiments. However, given the lack of an interaction between response type and imitative compatibility in this experiment, and the significant effects for each response type in the within-subjects analysis, it seems clear that extension responses were susceptible to interference in this experiment unlike in the prior experiments. The differences in the first response analysis in the experiment raise an interesting question for the imitative compatibility literature more generally as previous studies have not looked at between-subjects effects of producing a single response.

# CHAPTER VII

# GENERAL DISCUSSION

In the experiments above, a response specificity effect was observed for object-directed motions such that object-directed flexion responses were sensitive to kinematic compatibility with observed objectless motions (flexions and extensions) whereas object-directed extensions were not. However, in Experiment 5, when the same stimuli were presented but participant motions were objectless, both participant flexions and extensions were sensitive to compatibility with observed objectless motions (flexions and extensions). These results suggest that the findings of prior investigations of imitative compatibility do not necessarily apply to object-directed motions. Despite the great deal of related work on the human MNS suggesting important differences in how the brain encodes object-directed and objectless motion, the imitative compatibility literature has largely ignored the complexity of how objects and object knowledge might influence imitative compatibility phenomena.

One important goal of the first three experiments in this dissertation was identifying what components of object-directed action were responsible for the specificity effect with keypads. In the first experiment, compatibility effects were limited to downward/flexion key presses. However, this left several confounded features of the typical action that might be responsible for the specificity effect including kinematics (flexions), gravitational spatial directions (downward), object-relative spatial directions (toward), tactile feedback (initiating contact with the finger pad), and action effects (pressing a key). To address this, Experiment 2 inverted the keypad so that participants made downward/flexion key releases and upward/extensions key presses. This dissociated the action effects and object-relative direction of motions from the gravitational direction and kinematic components of motions and showed response specificity for downward/flexion releases. To dissociate the gravitational direction and kinematic components of motion, a third experiment was conducted in which participants responded to an orthogonally oriented keypad: they made leftward/flexion presses and rightward/extensions releases. This experiment showed only significant imitative effects for flexion responses, which suggests that kinematics are the critical component involved in response specificity. However, there were certain differences between the third and the prior experiments. Notably, the imitative compatibility effect was numerically smaller and was absent in a first-response analysis. This result might suggest that both spatial and kinematic patterns are important for response specificity with keypads (with kinematics dominating).

The last two experiments in this dissertation rule out certain possible interpretations for the response specificity effect, but leave several remaining alternatives. Experiment 4 rules out an interpretation based on action sequences. Because Experiments 1-3 involved a keypad, one plausible explanation for the response specificity effects was that the earlier phases (pressing) of a familiar response sequence (e.g. the key press/release sequence involved in typical typing) are sensitive to interference from observing later (releasing) elements of a sequence whereas later (releasing) elements of a sequence are shielded from interference coming from observing earlier (pressing) portions of the same sequence. However, because the same response specificity effect was observed for flexion responses in Experiment 4 using a light switch (for which there is not a typical associated sequence of flexions and extensions), a sequence-based explanation for the response specificity effect seems unlikely. Finally, Experiment 5 rules out a purely stimulus-based explanation for the above findings and suggests that a difference between object-directed and objectless motions truly is responsible for the above results.

### *Reaction Time Distribution Analyses*

In the original study by Brass and colleagues, the authors found that both spatial and imitative compatibility effects increased in size across quintiles, but imitative effects increased by a greater amount in the last two quintiles of the distribution (see Appendix A for a version of the original Brass et al. effects in terms of difference scores). The authors took this to suggest that imitative effects may become more prominent when participants have more time to process the observed motions (i.e. at the longer RTs present in the later quintiles). Unlike the Brass et al. results, the reaction time distributions obtained in the present experiments did not show this pattern. Despite the fact that the overall patterns observed by Brass et al. were not replicated, there were certain interesting differences in the patterns observed across experiments. First, only Experiment 5 showed a significant quintile effect for both types of response kinematics (flexions and extensions). This pattern is consistent with Experiment 5 being the only experiment to show compatibility effects for both response types as observed by Brass et al. Brass et al. observed the pattern of quintile increase for both compatibility components. Thus, unlike the other experiments, Experiment 5 replicated the general pattern of quintile increase, but failed to replicate the specific difference between components.

Notably, in one of the only other studies to employ the Brass et al. (2001) paradigm, Jansson et al. (2007) also failed to find *any* influence of quintile on compatibility effects (as observed in the present Experiments 2 and 4). It remains unclear what conditions are necessary to observe the quintile effects obtained by Brass et al. This provides an interesting question for future work as the specific conditions under which such effects are obtained may further inform theories of imitative compatibility specifically and ideas about human action processing more generally.

### *Connections between Imitative Compatibility and Properties of the Human MNS*

One important conclusion from the above experiments is that kinematic compatibility can generate imitative compatibility effects in the absence of similar action goals. In Experiments 1-4 the objects of the actions participants produced did not match observed objectless actions. Despite this mismatch, compatibility effects were present when participants made flexion motions. Though compatibility effects were limited to flexion responses, this still demonstrates that it is *possible* to obtain a purely kinematic compatibility effect (in the presence of asymmetric goals). This claim is strengthened by Experiment 5, which shows a compatibility effect when both participant and model motions are objectless. Research on the human MNS suggests that certain mirror neuron populations may process action kinematics independently of the whether of a target object is present. The above kinematic compatibility effects support a commonality between this property of the human MNS and imitative compatibility effects.

Importantly, though the above results have been described as kinematic compatibility effects, there is an alternative framework for interpreting the results that deserves further investigation. Though not mutually exclusive, evidence of kinematic compatibility can also be interpreted as evidence for a unique form of spatial compatibility effect that operates in a hand-centered reference frame. In this case, rather than the full pattern of observed joint motion (kinematics) being represented and affecting response production, observed motions are instead coded in directions relative to the top and bottom of the onscreen hand (i.e. the hand of the model and of the participant both establish hand-centered reference frames that are nested within the other spatial frames available). If this is the case, then imitative effects may occur because participants selectively highlight a hand centered reference frame when preparing their own finger motions and when observing others' finger motions and the interference and facilitations within this shared frame leads to compatibility effects that dominate those in gravitational and other frames. This idea deserves further exploration in both the imitative compatibility and MNS literatures.

### *Object-Specific Accounts of Response Specificity*

Despite progress in identifying relevant features of response specificity, much remains for future work to investigate. First, it remains unknown whether the response specificity effect is object-specific. An object-specific account of the effect could be taken to suggest that learned associations between actions and objects (OLMC) are responsible for the specificity. On this account, only object-typical kinematics would be susceptible to compatibility effects and, because the objects we employed had an overwhelmingly stronger association with flexion motions, only flexions showed compatibility effects. One might argue that index finger flexions are not necessarily typical for a light switch and that the flexion specificity for that device precludes this explanation. However, the prevalence of flexions for interactions with light switches is unknown and anecdotal evidence suggests flexions are at least overwhelmingly more typical than extensions if not quite common for light switches.

An object-specific account of response specificity can also be aligned with a broader perspective provided by Barsalou's Perceptual Symbol Systems theory. Barsalou's theory suggests that OLMC may not be a unique association between *objects* and actions, but is instead be an example of an association-based mechanism whereby *perceptual content* is linked with other *perceptual content* and with *motor content* over repeated encounters with relevant dependencies. As mentioned previously, Perceptual Symbol Systems is an embodied cognition proposal defending the idea that concepts are *grounded* in modality-specific sensory-motor experiences rather than being a set of amodal representations (Barsalou, 1999; Barsalou, 2003; Barsalou, 2008). Barsalou's theory involves *simulators* that are built up from attending to repeated multi-modal feature conjunctions (Barsalou, 1999; Barsalou, 2009). These simulators then produce situation-specific conceptual *simulations* that are partial re-enactments of previous sensory-motor content (Barsalou, 2009). Barsalou suggests that OLMC is an example of this reactivation in encounters with familiar useful objects.

### *Object-General Accounts of Response Specificity*

In contrast with an object-specific account, the response specificity effect may be object-general, such that the flexion-specificity of imitative compatibility is simply a property of all object-directed motions (or serves as a default). The specificity effect held true for the two objects employed in the present study and it may be that flexion specificity originates with the critical role for these motions in typical grasping, which marks the first phase of contact with most objects. Or, perhaps there is some critical developmental influence from the role these motions serve in our earliest manners of controlled interaction with objects in palmar, finger, and pincer grasps. Moreover, perhaps flexions are special because of neural architecture rapidly matching appropriate grasps (involving flexion motions) to the shape of an object using canonical neurons. One difficulty with differentiating between the above hypotheses is that with the exception of flicking an object, very few object-directed actions typically involve extensions.

Future work is planned to look at flicking motions as a possible case in which a compatibility effect for extension motions could be restored.

Another object-general explanation that may be relevant to explaining the response specificity effect is that the above experiments involved an asymmetry between participant and model object-directedness. Thus, it remains possible that flexion specificity is a general feature of any compatibility paradigm in which there is an asymmetry between the objects observed onscreen and the objects toward which participant responses are directed. If this explanation is correct, the specificity effect might occur when participants respond to objects while observing objectless motions (as in the experiments above) or might also occur when participants make objectless motions and observe object-directed motions. This explanation seems least parsimonious, but it cannot be excluded. This would suggest that when the objects of observed and produced actions mismatch, only flexions are sensitive to compatibility. The above accounts are merely speculation about the parameters of situations in which a response might be sensitive to compatibility effects. However, even if one did identify the relevant parameters, this would not clearly delineate what *mechanisms* are responsible for the specificity effect. To address this, several possible mechanisms are discussed in detail below.

### *The Importance of Action Effects and Goals*

Before discussing mechanisms *per se*, it is important to discuss the role of action effects and goals in the foregoing results. One interpretation of the above results suggests a very important role for these components in producing compatibility specificity. On an object-specific interpretation, both flexions and extensions are common motions during typing (as typing involves both pressing an releasing a key), but only flexions show a compatibility effect in the above experiments. Thus, we might infer that because only downward flexions typically produce the action effects such as characters appearing on a computer screen during typing, these experiments show compatibility specificity for responses that typically produce action effects. On an object-general interpretation, both flexions and extensions are used when interacting with objects, but only flexions typically initiate tactile feedback and other action effects.

Though goals and action effects are likely to be important for generating the above specificity, it is also possible that some other property of flexions makes them susceptible to interference. For example, it may simply be that the kinematic form of flexion motions is more practiced and thus, a difference in susceptibility to compatibility effects may reflect a difference in the difficulty of relevant motor programming and an influence of this difficulty on available cognitive resources for processing observed motions. Specific mechanisms are explored in greater detail in the next section.

### *Possible Mechanisms for Response Specificity*

Explanations for the response-specificity effects observed in the experiments above can be divided into mechanisms based on motor programming and mechanisms based on cognitive resources. I present one possible motor mechanism and two possible resource-based mechanisms.

The motor programming mechanism I propose is based on the idea that the particular kinematic patterns that are relevant to achieving action effects (flexions) are automatically activated by perceiving or interacting with the relevant objects. Furthermore, unless these motor commands are inhibited, they bias responding toward producing the effect-relevant kinematics (flexions). Thus, when planning to produce extensions, people may actively inhibit default flexion responses. Under this explanation, preparing an extension action leads to prior inhibition of flexion motor commands and, thus, no further interference is observed from flexion motions onscreen. On the other hand, when planning to produce object-directed flexion kinematics, a person would not inhibit the effect-irrelevant (extension) kinematics, as these are not automatically activated. Thus, when making a flexion object-directed motion, onscreen extension kinematics are free to generate competing motor representations. The above explanation can be cast in either object-specific or object-general terms. In the object-specific (OLMC) case, experience with the action effects for certain objects (e.g. keyboards and light switches) individually leads to automatic associations between those objects and flexion motions. In the object-general case, ubiquitous experience (or perhaps a biological default) leads flexion kinematics to be automatically associated with and activated by all objects.

The first proposed cognitive resources mechanism for response specificity is quite simple. This mechanism suggests that resources are allocated differently when preparing flexion versus extension kinematics because well-practiced flexions are cognitively easier to produce, leaving more resources are available to process observed motions (and subsequently to create interference or facilitation of ongoing motor planning). Given that flexions were the only response to produce compatibility effects for object-directed motions and these responses produced numerically greater compatibility effects than extension motions even when these motions were objectless (in both this study and the original study by Brass et al.), this explanation seems plausible. Specifically, it may be that extensions are generally unfamiliar and thus difficult to program and object-directed extensions, which are even more unfamiliar are quite difficult to program. This explanation suffers some difficulties when related to the above experiments however. First, certain motions we asked participants to perform (e.g. a flexion key release) were certainly unfamiliar in many respects and somewhat difficult to perform, because holding a key depressed with one's fingernail is an awkward position to maintain, but these atypical flexion motions were still sensitive to compatibility effects. Furthermore, if greater time is allowed to program an action, one might assume the influence of difficult motor programming to diminish. Thus, one might expect increases in the size of compatibility effects for extensions across RT quintiles or at longer SOAs (as more action preparation time has elapsed and potentially greater processing of the observed motion has occurred), but this was not observed.

The second resources mechanism for response specificity is firmly rooted in the relationship between actions and their effects and is based on how attention is typically used to guide action. This attention-for-action explanation takes its inspiration from the ideas of "event files" and "intentional weighting" discussed by Bernhard Hommel (see Hommel & Elsner, 2009; Wykowska, Schubö, & Hommel, 2011). Essentially the idea is that actions are planned in terms of the environmental effects they achieve and relative to the objects involved and, to support these actions, visual attention is allocated based on typical environmental effects and objects involved. Thus, attention would be allocated differently for flexion motions than for extensions because of the purpose of each motion during normal action.

In the object-specific case of the attention-for-action explanation, flexion key presses are typically associated with a visual effect onscreen and monitoring this effect is important to determine whether the correct key was pressed or whether the key was pressed successfully (see Logan & Crump, 2009 for some more elaborated ideas of an inner and outer control loops in typing). In object-general case, flexions are overwhelmingly associated with contacting an object for use or grasping and visual attention is often required to plan accurate object contact. In either the object-specific or object-general case, extensions motions do not require visual attention for planning or effect monitoring, as action effects are seldom dependent upon their execution. To recapitulate, when performing a typical flexion, attention is directed toward environmental stimuli for the sake of planning and feedback monitoring. Thus, when performing flexion motions in this experiment, the response specificity effect may be due to the typical relationship between attention and action effects. Because actions are typically guided by feedback and planned relative to environmental information when performing flexions, this information is also monitored in this case, but with a potentially deleterious effect because incompatible motions are free to interfere with action production. Conversely, because information from the environment is not used to guide typical extensions, there is a limited influence of the features of observed motions on produced extensions.

The attention-for-action account is complicated somewhat by the objectless case, however. In this case, compatibility effects are observed for both flexions and extensions. However, given that compatibility effects are not observed for object-directed extensions, one might conclude that the attention-for-action account is simply wrong because it would predict compatibility effects for extension motions with objects as well. This can be explained if that attention is allocated very differently for extensions during object-directed actions: Namely, when actions are planned without objects, the motions are planned in terms of kinematics and when actions are planned with objects, the actions are planned with reference to environmental stimuli. One version of this explanation is that the influence of environmental information on directionality and kinematics is actively inhibited when making extension motions with objects because these parameters are not relevant for those motions. Alternatively, it may be that extensions are typically less sensitive to environmental information (i.e. when performing object directed actions), but when performing an objectless motion, the kinematic form or pattern itself becomes the focus of attention as there is no relationship between an effector and an object toward which attention might be directed. If attention becomes selectively directed to kinematics and directionality, then it would be possible to observe interference or facilitation from other observed motions that overlap with the motor plan to which one is attending.

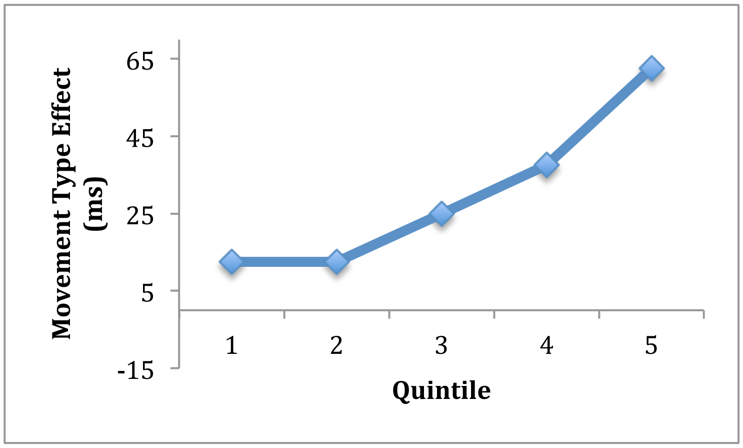
## *Summary and Conclusions*

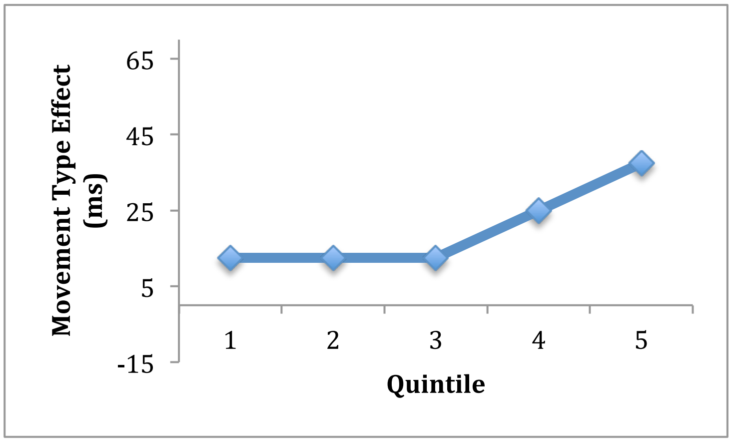
The above experiments suggest that it is possible to obtain a kinematic imitative compatibility effect such that even when there are differences in the objects toward which observed and produced motions are directed, the match in kinematics leads to faster responding on compatible trials. However, this kinematic matching effect was restricted to flexion kinematics in the above experiments. Experiments with a keypad and an experiment with a light switch showed compatibility effects for flexion kinematics, but not for extension kinematics. When participants made non-object directed responses using IR sensors, compatibility effects were observed for both flexion and extensions kinematics.

Within the domain of imitative compatibility research, the kinematic specificity effect is of particular interest and suggests that objects have a critical influence on how perceived and produced actions are matched to one another. For research on object-linked motor content, these results provide a novel direction of examining how OLMC might affect online interactions with a response device. Though it cannot be certain that OLMC is involved in the observed response-specificity effects, the current paradigm pushes the boundaries of current OLMC research into a domain where this phenomenon may have an enduring influence on action production and perception beyond that observed in other paradigms (in which it could be argued that OLMC merely reflects an ephemeral component of object identification). Together, the above results raise interesting questions about the connections between object knowledge, action effects, and action processing. Furthermore, the present research provides an example of how investigations of embodied phenomena can benefit from expanding beyond an isolated focus on object representations or on action processing and expand into an area in which relevant object and action representations are situated within the action-environment interface.

# Appendix A

Quintile plots adapted from Brass et al. (2001)





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