

# An Action Sequence Withheld in Memory Can Delay Execution of Visually Guided Actions: The Generalization of Response Compatibility Interference

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Withholding an action plan in memory for later execution can delay execution of another action, if the actions share a similar (compatible) action feature (i.e., response hand). This phenomenon, termed *compatibility interference* (CI), was found for identity-based actions that do not require visual guidance. The authors examined whether CI can generalize to both identity-based and location-based actions that require visual guidance. Participants withheld a planned action based on the identity of a stimulus and then immediately executed a visually guided action (touch response) to a 2nd stimulus based on its color identity (Experiment 1), its spatial location (Experiment 2), or an intrinsic spatial location within an object (Experiment 3). Results showed CI for both left- and right-hand responses in Experiment 1. However, CI occurred for left- but not right-hand responses in Experiment 2 and 3. This suggests that CI can generalize to visually guided actions under cognitive control but not to actions that invoke automatic visual-control mechanisms where the left hemisphere may play a special role (C. Gonzalez, T. Ganel, & M. Goodale, 2006). The *code occupation* account for CI (G. Stoet & B. Hommel, 2002) is also discussed.

*Keywords:* action planning, memory, visually guided action, ventral–dorsal visual pathways

Everyday actions such as turning on an appliance, starting one's car, and programming a television remote require the production of action plans. An action plan is a set of muscle commands that are structured before a movement sequence begins that allows the entire sequence to be carried out (Keele, Cohen, & Ivry, 1990). According to Jeannerod (1997), action planning requires that the appropriate motor schemas are selected among the available motor schemas, are related to the proper internal and external cues, and are organized into the appropriate sequence. Sometimes people have to momentarily suspend the execution of one action plan in order to execute another action. For example, a person may actively plan a sequence of responses required to change the channel on his or her television with a remote control, but before he or she starts execution of this planned response, her or she may execute another action, such as catching a glass of water a cat has just knocked over. An interesting question to ask is whether one's ability to carry out an immediate action, such as retrieving the water glass, is affected by the planned action currently being held in memory. Recent research suggests that execution of an action, at least in some cases, can be adversely affected by a planned action currently held in memory.

Stoet and Hommel (1999) showed that withholding an action plan in memory for later execution can sometimes delay the

execution of another action. In their study, two different visual stimuli were presented sequentially. Participants were instructed to plan and withhold a sequence of keypresses with either their right or left hand on the basis of the identity of the first stimulus (Stimulus A). While withholding the action plan to Stimulus A, a second visual stimulus appeared (Stimulus B). An immediate keypress response with either the right or left hand was required on the basis of the identity of Stimulus B. After executing a speeded response to Stimulus B, the planned action to Stimulus A was executed. Results showed that the response to Stimulus B was longer when it required the same (compatible) hand as opposed to a different (not compatible) hand than Stimulus A. This delay in executing an action to the intervening stimulus (Stimulus B) when it shares a compatible feature with the action currently held in memory is referred to as *compatibility interference* (CI).

To explain CI, Stoet and Hommel (1999, 2002) proposed the code occupation hypothesis (COH), which was built on the foundations of the common coding hypothesis developed by Prinz (1990, 1997; for an overview, see Hommel, Müsseler, Aschersleben, & Prinz, 2001b). The COH assumes that intentional actions are cognitively represented in terms of the proximal and distal effects that this action produces, and hence these action–effect codes contain both one's internal actions and the anticipated or perceived effects in the environment (Hommel et al., 2001b; Müsseler & Hommel, 1997a). On the basis of these assumptions, action and perceptual features share a common representational domain that is consistent with the existence of mirror neurons (e.g., Gallese, Fadiga, Fogassi, & Rizzolatti, 1996) as well as visual-and-motor neurons (e.g., Sakata, Taira, Murata, & Mine, 1995; Taira, Mine, Georgopoulos, Mutara, & Sakata, 1990). An action feature can be a movement direction or the side of the body in which the effectors used to carry out an action are located (e.g., a

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movement to the right, a movement with the right hand), and a perceptual feature can be the orientation or movement direction of a stimulus (e.g., a right-pointing arrow, a stimulus moving to the right). To specifically account for CI, the COH assumes that all features (both perceptual and action features) controlling the planned action are bound together (perhaps due to temporary cell synchronizations between distributed sensory and motor areas of the brain; e.g., Roelfsema, Engel, Koenig, & Singer, 1997) into a common representation (action plan) that occupies the codes that represent it. This occupation of codes causes these codes to become temporarily less available for other actions or perceptions until the action plan is executed or abandoned (see also Prinz, 1997).

Thus, the COH predicts that a response will be delayed if there is partial feature code overlap with the action plan held in memory, due to code occupation. For example, if an action sequence is planned that requires the right hand, a *right* code will be occupied, delaying any additional actions that require the *right* code (e.g., the right hand) until the planned action is performed or released, which was the result obtained by Stoet and Hommel (1999). In accordance with the COH, Stoet and Hommel found that CI occurred only if a sequence of actions was planned in advance of the stimulus that required an immediate action. Furthermore, they found CI when effectors shared a side of the body (e.g., left hand and left foot that share the *left* code), although the effect was not as pronounced compared to when only one effector (e.g., left hand) was used for both responses. This finding suggests that it is not effector overlap but an overlap in the feature codes (e.g., right or left) that make up the action plan that causes CI. It also suggests that CI may be reduced if feature overlap is reduced.

The COH can also account for the findings by Müsseler and colleagues (Müsseler & Hommel, 1997a, 1997b; Müsseler, Steininger, & Wühr, 2000; Müsseler & Wühr, 2002; Müsseler, Wühr, & Prinz, 2000; Wühr & Müsseler, 2001), who showed that the perception of a stimulus was degraded when it had a perceptual feature that had a common (compatible) code with an action feature associated with a planned response. For example, they showed that planning or executing a keypress with the right hand during the brief presentation of a right-pointing arrow (i.e., both response and stimulus shared compatible feature codes of right) caused recognition accuracy of the arrow to decrease relative to when the keypress was planned or executed with the left hand (i.e., response and stimulus did not share feature codes). The COH predicts this result because the to-be-perceived stimulus and the planned action share feature codes (e.g., a right-pointing arrow [right code] and a right-hand response [right code]), and access to the code required to perceive the right-arrow stimulus is delayed because it is temporarily occupied by the planned action.

Taken together, these findings suggest that a planned action held in memory can interfere with the execution and/or perception of a later occurring event if there is partial, feature code overlap (in terms of action features and/or perceptual features). That is, activation of a feature code is delayed when the feature code is already involved in preparing or executing an action, consistent with the predictions of the COH. However, while much research has investigated conditions under which a response held in memory interferes with the perception of a stimulus (recognition interference; Müsseler and Hommel 1997a, 1997b; Müsseler et al., 2000; Müsseler & Wühr, 2002; Müsseler, Wühr, & Prinz, 2000; Oriet,

Stevanovski, Jolicœur, & Cowan, 2003; Stevanovski, Oriet, & Jolicœur, 2003), much less research has examined the conditions under which a response held in memory interferes with the execution of another response (execution delays; Stoet & Hommel, 1999, 2002).

In these latter studies, execution delays were found for keypress responses when selection of the appropriate keys was defined by the identity of a stimulus. For example, in the experiments by Stoet and Hommel (1999), the response held in memory to the first stimulus (Stimulus A) consisted of a sequence of finger keypresses based on stimulus identity, and the response executed immediately to the second stimulus (Stimulus B) required either a finger keypress or a foot keypress based on stimulus identity, regardless of its spatial position (e.g., a right-hand keypress to a red stimulus or a left-hand keypress to a green stimulus). Thus, it is unclear whether CI, and the assumptions of the COH, will generalize to situations in which the intervening stimulus (Stimulus B) requires a visually guided action to its location and/or when response selection is determined by stimulus detection as opposed to stimulus identification. Because people can execute a visually guided response to a stimulus location based on the identity of the stimulus (e.g., blue glass vs. green glass), the detection of a transient stimulus (e.g., the falling water glass example earlier), or a spatial location within the stimulus (e.g., the top of the glass), it is important to determine whether CI generalizes to these types of perception–action scenarios.

Tasks where responses are selected on the basis of stimulus identification as opposed to stimulus detection are known to take longer and are assumed to be more difficult and hence more demanding on limited cognitive resources (e.g., Lavie, 1995; Lavie, Hirst, De Fockert, & Viding, 2004). Also identifying the properties of a stimulus and detecting where a stimulus is located appear to impose different demands on the ventral and dorsal visuo-cortical pathways in the brain (e.g., Ungerleider & Mishkin, 1982). The ventral (occipitotemporal) pathway, often referred to as the *what* pathway, appears to play more of a functional role in analyzing and identifying properties of a stimulus (e.g., color, shape, or surface features of an object; e.g., Bridgeman, 2002; Bridgeman, Gemmer, Forsman, & Huemer, 2000; Jeannerod, 1997; Köhler, Kapur, Moscovitch, Winocur, & Houle, 1995). Recent research further suggests that executing actions that rely on identity, context (e.g., intrinsic spatial relations within or between stimuli), or a memory representation of the stimulus (including its location) requires the ventral pathway (Brown, Halpert, & Goodale, 2005; Goodale & Humphrey, 1998; Goodale & Westwood, 2004). That is, selection between actions where stimulus identity (e.g., color) or context (e.g., top area of a box, where the box serves as the context) is explicitly identified on the basis of a visual memory system involves the ventral pathway (e.g., Passingham & Toni, 2001; Milner & Goodale, 1995).

In contrast, the dorsal (occipitoparietal) pathway, often referred to as the *where* or *how* pathway, appears to play more of a functional role in detecting the location of a stimulus in space. Recent research further suggests that visually guided actions that are carried out online, such as reaching and grasping an object (i.e., where the location of the object is coded with respect to the observer and not with respect to other objects in the environment) that do not rely on identity, context, or a memory representation of an object are more dependent on the dorsal pathway (Culham et

al., 2003; Johnson & Grafton, 2003; Milner & Goodale, 1995; Goodale & Humphrey, 1998; but see Glover, 2002, and rebuttal to Glover by Meegan et al., 2004). This is consistent with the functional distinction originally proposed by Milner and Goodale (1995), which assumes that the dorsal pathway is more involved in visuomotor control where there is a spatial correspondence between the visual cues and the action, while the ventral pathway is more involved in visual perception for recognition. That is, visually guided actions with a short time constant to an object location (Rossetti, 1998), that do not involve perceptual recognition of the object, rely more on the dorsal pathway (Carey, Harvey, & Milner, 1996; Hu & Goodale, 2000; Rossetti & Pisella, 2002). There is also evidence that these actions can be dissociated from the identity-based actions associated with the ventral pathway (e.g., Aglioti, DeSouza, & Goodale, 1995; Bridgeman & Huemer, 1998; Bridgeman, Lewis, Heit, & Nagle, 1979; Culham et al., 2003; Dewar & Carey, 2006; Goodale, Milner, Jakobson, & Carey, 1991; Goodale, Pelisson, & Prablanc, 1986; Haffenden & Goodale, 1998; James, Culham, Humphrey, Milner & Goodale, 2003; Loomis, Da Silva, Fujita, & Fukushima, 1992; but see Dassonville, Bridgeman, Bala, Theim, & Sampanes, 2004; Franz, Bühlhoff, & Fehle, 2003).<sup>1</sup> Furthermore, research indicates that the dorsal and ventral pathways may be more dissociated in the left hemisphere than in the right (Radoeva, Cohen, Corballis, Lukovits, & Koleva, 2005) suggesting a functional specialization of the left hemisphere for visuomotor processing by the dorsal pathway (Gonzalez et al., 2006; Lavrysen, Elliot, Buekers, Feys, & Helsen, 2007).

According to Hommel et al. (2001b), the COH proposed to account for CI is restricted to offline action planning and preparation of arbitrarily selected actions (e.g., where the color of a stimulus is mapped to a particular keypress response) that “requires some kind of short-term memory capacity” (p. 915). Thus, it is meant to describe cognitively controlled actions only (e.g., associated with the ventral pathway). However, there is no empirical evidence to support this assumed limitation. In addition, the definition of the feature codes that become bound and occupied to form an action plan has been purposely underspecified (see Hommel et al., 2001a, 2001b; see also Kunde, 2001; Oriet, Stevanovski, & Jolicœur, 2001; Westwood & Goodale, 2001), and hence it is unclear under what types of action–perception scenarios the COH predicts CI should occur.

The present study investigated whether CI and the assumptions of the COH generalize to visually guided actions that require touching a stimulus location where selection of the appropriate motor schemas involve (a) identifying and localizing a stimulus, (b) detecting the spatial location of a stimulus, or (c) localizing a spatial area within a stimulus. According to the functional distinction between the visuocortical pathways proposed by Milner and Goodale (1995), the first and third selection schemes would impose more of a functional demand on the ventral pathway, and the second scheme would impose more of a functional demand on the dorsal pathway. The cognitive demands of the task would also be greatest in the first selection scheme, minimal in the second selection scheme, and more demanding in the third versus the second selection scheme. This study allowed us to examine whether CI is influenced by the different functional demands imposed on the ventral and dorsal pathways as well as the general cognitive demands of the perceptual-motor task.

Three experiments were conducted using the paradigm by Stoet and Hommel (1999) described previously. In all three experiments, the action held in memory to the first stimulus (Stimulus A) consisted of a sequence of three keypress responses based on stimulus identity. The information required to execute an immediate touch response to the second stimulus (Stimulus B) varied across experiments. Experiment 1 showed that CI occurred when touch responses to a stimulus location required stimulus identification. In Experiment 2, where touch responses to the stimulus were based on detecting the stimulus location, CI also occurred, but only for left-hand responses. Also, in Experiment 3, where touch responses were directed to a spatial location within a stimulus, CI was again found but only for left-hand responses. These findings, combined with other research on handedness and visuomotor control, suggest that CI and the COH generalize to visually guided actions that invoke cognitive control.

### Experiment 1

The purpose of this experiment was to determine whether CI would generalize to visually guided reach responses to a stimulus location where the initial selection of the response was dependent on the stimulus identity. Participants saw a visual stimulus (Stimulus A) and planned a set of right- or left-handed keypresses based on its identity. Then a second stimulus (Stimulus B) appeared that consisted of a red and green pound sign (#); one pound sign appeared to the left and the other to the right of the participant's body midline. Participants touched the stimulus location of either the red or green pound sign with the ipsilateral index finger of the right or left hand as quickly as possible. Afterward, the planned response to Stimulus A was executed. If the assumptions of the COH generalize to visually guided actions, then responses to Stimulus B should be delayed when Stimulus B and A require the same (compatible) response hand as opposed to different (not compatible) response hands.

### Method

**Participants.** Twenty-five undergraduate psychology students from Washington State University participated and received optional credit in their psychology courses. All participants had at least 20/40 visual acuity (assessed using a Snellen chart). Twenty-four participants met an accuracy criterion of 80% for both Stimulus B and A, and only their data are reported. On the basis of self-report, 21 of these participants were right-handed and 3 were left-handed.

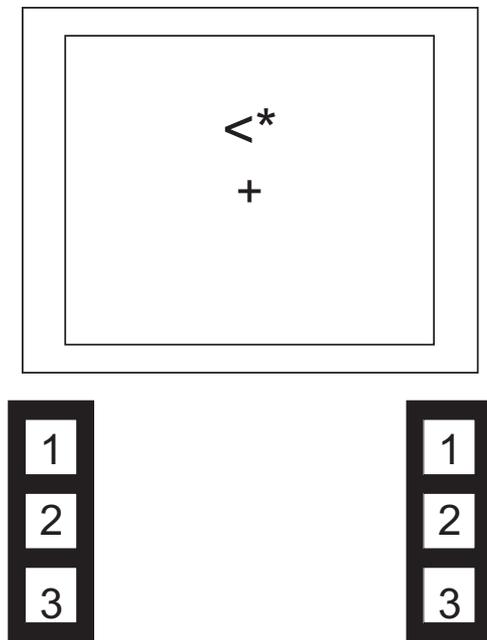
**Apparatus.** Stimuli were presented on a 17-in. (43.18-cm) MicroTouch touch-screen monitor that was approximately 44.5 cm from the participant. Responses to Stimulus B were executed by touching a stimulus location on the touch-screen monitor with the left or right index finger. Responses to Stimulus A were executed with the left or right index finger by pressing keys on one of two keypads. One keypad was located to the left and the other to the right of the participant's body midline. A distance of 22 cm

<sup>1</sup> Although these pathways are often assumed to be functionally distinct, it is also assumed that they interact and may interact more or less depending on the task requirements (see Bruno, 2001; Carey, 2001; Westwood, McEachern, & Roy, 2001).

separated the keypads. Each keypad had three keys (each were 1 cm × 1 cm in size, separated by 0.2 cm) oriented in a vertical array. The key in the middle of each keypad was designated as the home key.

*Stimuli and responses.* All stimuli were displayed on a black background. A white fixation cross (0.51° of visual angle) appeared in the middle of the screen before and during each trial.

*Stimulus A.* Stimulus A (0.97° of visual angle) consisted of a white arrowhead pointing to the left or right (< or >) and a white asterisk (\*) that appeared either to the left or right of the arrowhead. Stimulus A appeared 0.32° of visual angle above the fixation cross. Responses to Stimulus A were determined by its shape identity. The arrowhead direction (left/right) indicated the response hand (left/right), and the asterisk location (left/right) relative to the arrowhead indicated the movement direction of the index finger (key behind the home key/ key in front of the home key). For example: \*< indicated left-hand move to key behind home key, < \* indicated left-hand move to key in front of home key, \* > indicated right-hand move to key behind home key, and > \* indicated right-hand move to key in front of home key (see Figure 1). Responses began and ended by pressing down on the appropriate home key with the index finger.



*Figure 1.* A diagram of the response apparatus used to respond to Stimulus A in Experiments 1–3. Stimulus A consisted of an arrowhead (< or >) and asterisk (\*) that appeared to the right or left of the arrowhead. The arrowhead direction (< or >) indicated the response hand (left or right), and the asterisk location relative to the arrowhead indicated which keypress sequence to execute (asterisk to the right of the arrowhead indicated keypresses of 2-3-2, and the asterisk to the left of the arrowhead indicated keypresses of 2-1-2). For example, < \* required the left hand to press the key sequence of 2-3-2 on the left keypad, \* < required the left hand to press the key sequence of 2-1-2 on the left keypad, > \* required the right hand to press the key sequence of 2-3-2 on the right keypad, and \* > required the right hand to press the key sequence of 2-1-2 on the right keypad.

*Stimulus B.* Stimulus B consisted of a red and green pound sign (#), each subtending 0.51° of visual angle. Each pound sign appeared 0.32° of visual angle below the fixation cross with one pound sign appearing 17.39° of visual angle to the left and the other appearing 17.39° of visual angle to the right of the fixation cross. The location of the red and green pound sign occurred with equal frequency to the left or right of fixation in a random order. Participants had to identify the color of the pound sign in order to touch the correct stimulus location. Half of the participants were instructed to touch the red pound sign (red target), and the other half were instructed to touch the green pound sign (green target). Participants used the right index finger to touch the colored target to the right of the fixation and the left index finger to touch the colored target to the left of the fixation.

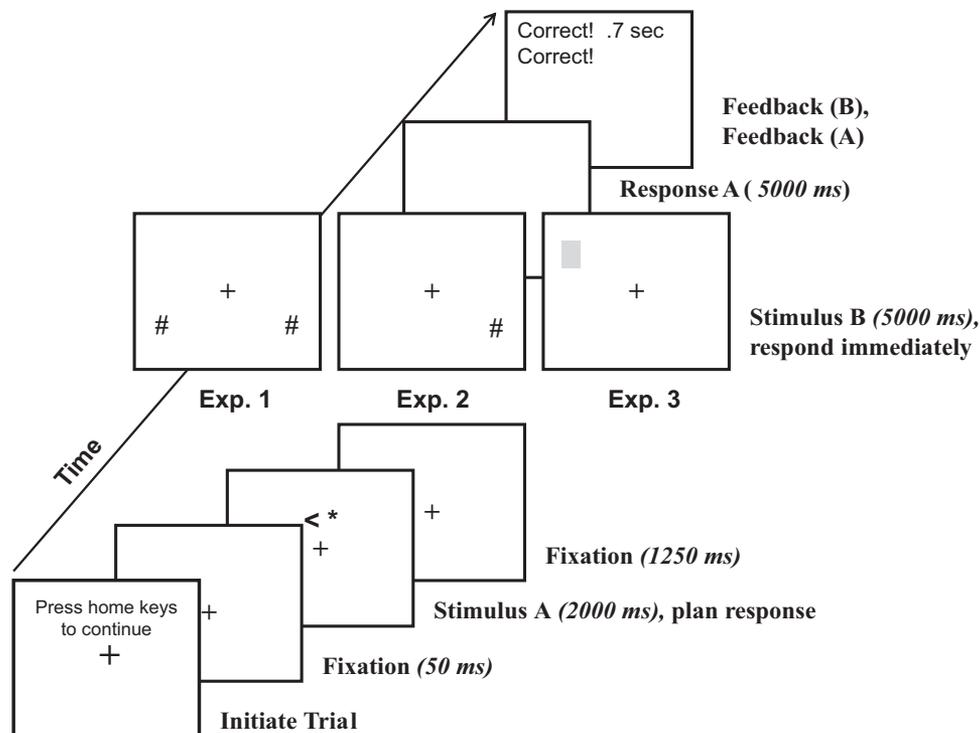
*Procedure.* At the start of each trial, an initiation screen appeared with a fixation cross and a message that read “press the home keys to continue” (see Figure 2). After participants pressed both home keys simultaneously (with their right and left index fingers), a fixation cross appeared for 50 ms. Next, Stimulus A appeared for 2,000 ms followed by a fixation cross for 1,250 ms. During the presentation of Stimulus A and the screen that followed, participants planned a response to Stimulus A. Stimulus B then appeared. Participants were instructed to respond to Stimulus B as quickly and accurately as possible. They were also instructed to keep their fingers on the home keys until Stimulus B appeared and they were ready to respond. Stimulus B appeared until a touch response on the touch screen was detected or until 5,000 ms elapsed, whichever occurred first. A touch response within a 5 × 5 cm area (6.4° visual angle) around the location of Stimulus B with the correct ipsilateral hand was recorded as correct. A response made outside this area was recorded as incorrect. After executing the response to Stimulus B, participants had 5,000 ms to execute the planned response to Stimulus A. Participants were instructed to emphasize accuracy, not speed, when responding to Stimulus A. Feedback indicating reaction time (RT) and accuracy for Stimulus B and accuracy for Stimulus A was then presented for 500 ms. After the trial ended, the initiation screen appeared and a new trial began when the participant was ready.

Either the same hand was used to respond to Stimulus B and A (compatible) or a different hand was used to respond to Stimulus B and A (not compatible). Response compatibility (compatible, not compatible) between Stimulus B and A occurred randomly and with equal probability of occurrence in each block of trials. Also, the four possible symbols for Stimulus A were equally paired with the two possible pound-sign colors for Stimulus B.

Participants completed one 90-min session consisting of one block of 32 practice trials followed by 12 blocks of 32 experimental trials. The RT to Stimulus B was measured from the onset of Stimulus B to the touch response detected on the touch screen.

## Results

The RTs slower than 1,500 ms for Stimulus B were excluded (3.2% of trials on average per participant). Also, the RT analysis for Stimulus B was restricted to trials in which responses to both Stimulus B and A were accurate. Figure 3 shows the mean correct RT and percentage error for Stimulus B based on compatibility and hand. As is evident in Figure 3, CI was found for both right- and left-hand responses. A two-way repeated measures analysis of



*Figure 2.* The sequence of trial events for Experiments 1–3. All events were similar across experiments except as follows. In Experiment 1, Stimulus B (left panel) consisted of a red and green pound sign (#); one pound sign occurred to the left and the other to the right of the fixation cross. A speeded touch response was made to the location of one of the colored pound signs. In Experiment 2, Stimulus B (middle panel) consisted of a single, white pound sign (#) that occurred to the left or right of the fixation cross. A speeded touch response was made to this stimulus location. In Experiment 3, Stimulus B (right panel), consisted of a single, white-filled rectangle that appeared at one of three different locations vertically arranged to the left or right of the fixation cross (six different locations total). A speeded touch response was made to the area inside the top half of the rectangle.

variance (ANOVA), with the factors of compatibility and hand, was conducted separately on correct RT and percentage error for Stimulus B and on percentage error for Stimulus A.

**Stimulus A.** The average error rate for Stimulus A was 5.3%. There was no significant difference in errors based on compatibility,  $F(1, 23) = 1.37$ ,  $MSE = 0.09$ ,  $p > .20$ , or hand,  $F(1, 23) < 1$ ,  $MSE = 0.11$ ,  $p > .40$ , and there was no significant interaction between compatibility and hand,  $F(1, 23) < 1$ ,  $MSE = 0.24$ ,  $p > .90$  (see Table 1).

**Stimulus B.** For mean correct RT, there was a significant main effect of compatibility,  $F(1, 23) = 7.98$ ,  $MSE = 890.77$ ,  $p < .01$ , and hand,  $F(1, 23) = 10.71$ ,  $MSE = 1645.15$ ,  $p < .01$ , and the interaction between compatibility and hand was not significant,  $F(1, 23) < 1$ ,  $MSE = 249.14$ ,  $p > .70$ . These findings show that accurate touch responses to Stimulus B were slower when the hand required to respond to Stimulus B was compatible, as opposed to not compatible, with that required for Stimulus A. This indicates that CI occurred for reach responses to a stimulus location based on stimulus identity. We also found that responses were overall faster when executed with the right hand ( $M = 774$  ms) as opposed to the left hand ( $M = 801$  ms). However, this difference in speeded execution found for hand did not influence the degree of CI observed; the difference in RT between the compatible and not compatible conditions were equivalent for right- and left-hand

responses. In terms of accuracy, there were no significant effects found for compatibility,  $F(1, 23) < 1$ ,  $MSE = 0.027$ ,  $p > .40$ , hand,  $F(1, 23) = 1.81$ ,  $MSE = 0.063$ ,  $p > .15$ , or the interaction between compatibility and hand,  $F(1, 23) = 3.46$ ,  $MSE = 0.01$ ,  $p = .08$ .<sup>2</sup> Thus, the RT interpretations above are not due to a speed–accuracy tradeoff.

### Discussion

Experiment 1 showed that CI occurred for a visually guided touch response to a stimulus location when selection of the response relied on stimulus identity information (i.e., color discrimination). Touch responses to a stimulus location were delayed when these actions required the same response hand as the action sequence held in memory. Touch responses executed with the compatible hand were approximately 17 ms slower than those executed with the hand that was not compatible. This is somewhat

<sup>2</sup> The trend toward a compatibility and hand interaction suggests there was a 1% decline in accuracy for compatible versus not compatible conditions for left-hand responses, while those for right-handed responses were identical. This insignificant difference in error rate is very small and hence should not have a significant impact on the mean RT interpretations across the different response hands.

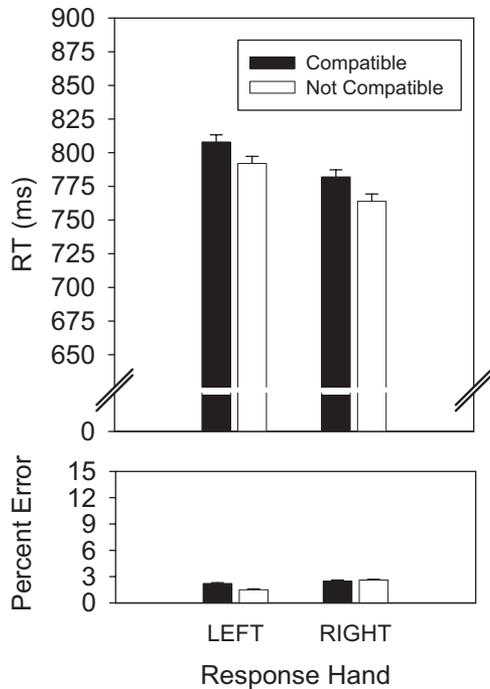


Figure 3. Experiment 1: Correct reaction time and percentage error for Stimulus B based on response hand (left, right) and hand compatibility (compatible, not compatible) with the response held in memory to Stimulus A. Error bars show one standard error of the mean.

smaller but comparable to the findings by Stoet and Hommel (1999), who found that manual keypress responses with the compatible hand were approximately 25 ms slower than those executed with the noncompatible hand when response selection was based on stimulus identity. The smaller CI effects found in our experiment may be due to less feature overlap in the motor actions required by the memorized and intervening responses (i.e., keypress and reach) relative to the motor actions required in Stoet and Hommel’s experiment (i.e., both responses required keypresses). Because CI occurred for visually guided actions to a stimulus location, this suggests that the COH is not limited to actions where the stimulus–response mapping is arbitrary (e.g., stimulus color is linked to a left or right keypress response).

### Experiment 2

Experiment 2 investigated whether CI generalizes to responses that are selected on the basis of detecting the spatial location of a stimulus without also requiring that the identity of the stimulus be discriminated. In this case, the cognitive resources required for response selection should be reduced relative to Experiment 1. Also, the dorsal pathway, as opposed to the ventral pathway, may play a more functional role in response selection in Experiment 2 relative to Experiment 1 because response selection in Experiment 2 requires detecting where a transient occurs as opposed to which of two stimuli have a specific attribute (e.g., Passingham & Toni, 2001). Research suggests that visually guided reach responses carried out online toward an object based on its spatial location (without requiring identification of stimulus properties) may im-

pose more of a demand on the dorsal pathway relative to the ventral pathway (e.g., Culham et al., 2003; Goodale & Humphrey, 1998).

The stimuli and procedures were the same as those in Experiment 1 except that the second stimulus (Stimulus B) was a single white pound sign (#) that was presented to the left or right of the participant’s midline. Participants touched this stimulus location with the ipsilateral index finger of the right or left hand as soon as it was detected. Stimulus B remained on the screen until its location was touched to ensure responses were not based on a memorized representation of the stimulus location, which may transform the response into an identity-based response (e.g., Goodale, Jakobson, & Keillor, 1994; Milner & Goodale, 1995). After participants responded to Stimulus B, the response held in memory to Stimulus A was executed. We were interested in whether responses to Stimulus B would be delayed when the response to Stimulus B and A required the same (compatible) response hand as opposed to different (not compatible) response hands.

### Method

**Participants.** Twenty-four undergraduate psychology students from Washington State University participated and did not take part in any of the other experiments. Visual assessment standards and participant compensation were the same as those in Experiment 1. All participants met an accuracy criterion of 80% for both Stimulus B and A. By self-report, 20 of these participants were right handed and four were left handed.

**Apparatus, stimuli, and procedure.** The apparatus, stimuli, and procedure were the same as those in Experiment 1 except as follows. Stimulus B consisted of a single white pound sign (#) that appeared 0.32° below and 17.39° of visual angle to the left or right of the fixation cross (see Figure 2). For all participants, a pound sign located to the right of body midline required a right index finger response, while a pound sign to the left of body midline required a left index finger response. As in Experiment 1, a touch response within a 5 × 5 cm area (6.4° visual angle) around the location of Stimulus B with the correct ipsilateral hand was recorded as correct. A response made outside this area was recorded as incorrect. Stimulus B appeared until a touch response was detected or 5,000 ms elapsed, whichever occurred first. Also, RT to Stimulus B was calculated from the onset of Stimulus B to the time at which the screen was touched.

Table 1  
Percentage Error (With SEM in Parentheses) for Stimulus A by Hand and Compatibility Condition for Experiment 1–3

Experiment	Left hand		Right hand	
	Compatible	Not compatible	Compatible	Not compatible
1	5.13 (0.11)	5.96 (0.11)	4.67 (0.11)	5.29 (0.11)
2	7.88 (0.14)	7.08 (0.14)	5.96 (0.14)	7.83 (0.14)
3	5.25 (0.05)	4.92 (0.05)	5.13 (0.05)	5.75 (0.05)

## Results

The RTs slower than 1,500 ms for Stimulus B were excluded (2.2% trials on average per participant). Also, the RT analysis for Stimulus B was restricted to trials in which responses to both Stimulus B and A were accurate. Figure 4 shows the mean correct RT and percentage error for Stimulus B based on compatibility and hand. As is evident in Figure 4, CI was found but only for left-hand responses. A two-way repeated measures ANOVA, with the factors of compatibility and hand, was conducted separately on correct RT and percentage error for Stimulus B and on percentage error for Stimulus A.

*Stimulus A.* The average error rate for Stimulus A was 7.2%. There was no significant difference in errors based on compatibility,  $F(1, 23) < 1$ ,  $MSE = 0.12$ ,  $p > .40$ , or hand,  $F(1, 23) = 1.02$ ,  $MSE = 0.08$ ,  $p > .30$ , and there was no significant interaction between compatibility and hand,  $F(1, 23) = 1.79$ ,  $MSE = 0.24$ ,  $p > .15$  (see Table 1).

*Stimulus B.* For mean correct RT, there was a significant main effect of compatibility,  $F(1, 23) = 4.37$ ,  $MSE = 630.19$ ,  $p < .05$ , and hand,  $F(1, 23) = 10.31$ ,  $MSE = 1834.07$ ,  $p < .01$ , and a significant interaction between compatibility and hand,  $F(1, 23) = 5.34$ ,  $MSE = 536.71$ ,  $p < .05$ . Planned comparisons (Tukey's honestly significant difference test) showed that responses executed with the left hand were delayed by 22 ms when the action held in memory required the left hand ( $p < .05$ ) but not the right hand ( $p > .90$ ). However, responses executed with the right hand were not differentially affected by the hand required to execute the action held in memory. Thus, CI only occurred for left-hand

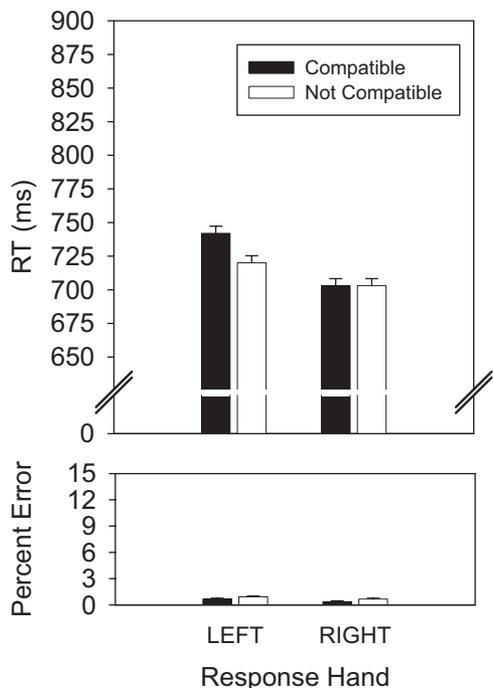


Figure 4. Experiment 2: Correct reaction time and percentage error for Stimulus B based on response hand (left, right) and hand compatibility (compatible, not compatible) with the response held in memory to Stimulus A. Error bars show one standard error of the mean.

responses. In terms of accuracy, there were no significant effects found for compatibility,  $F(1, 23) = 1.16$ ,  $MSE = 0.02$ ,  $p > .25$ , hand,  $F(1, 23) < 1$ ,  $MSE = 0.03$ ,  $p > .40$ , or the interaction between compatibility and hand,  $F(1, 23) < 1$ ,  $MSE = 0.02$ ,  $p > .90$ . Thus, the RT interpretations above are not due to a speed-accuracy tradeoff.

*Compatibility interference comparisons between Experiment 1 and Experiment 2.* To determine whether CI effects differed when response selection required stimulus identification (Experiment 1) as opposed to detection (Experiment 2), we conducted a mixed design ANOVA, with the between-participants factor of experiment (1 or 2) and the within-participant factors of compatibility (compatible or not compatible) and response hand (left or right), separately on mean correct RT and accuracy for Stimulus B. Importantly, there was a main effect of experiment,  $F(1, 46) = 4.11$ ,  $MSE = 57036.93$ ,  $p < .05$ , and a significant three-way interaction among the factors of experiment, compatibility, and hand,  $F(1, 46) = 4.52$ ,  $MSE = 392.93$ ,  $p < .05$ , found for RT. No significant effects were found for accuracy. These findings show that touch responses were approximately 70 ms slower when stimulus identification was required for response selection rather than stimulus detection. Moreover, CI occurred for both left- and right-handed touch responses when response selection involved stimulus identification (Experiment 1), but CI only occurred for left-handed touch responses when response selection was based on detecting the spatial location of a stimulus (Experiment 2). Because the difference between left- and right-hand response RTs and error rates were similar within Experiment 1 and 2 (i.e., there was no significant interaction between hand and experiment for RT or accuracy,  $F[1, 46] < 1$ ,  $ps > .30$ , respectively), the failure to find CI for right-hand responses in Experiment 2 was not due to a floor effect.

## Discussion

Experiment 2 showed that holding a planned action in memory (based on stimulus identity) delayed a visually guided action to a detected stimulus location but only when the two actions required the same left response hand. This suggests that CI can occur when visually guided actions are based on stimulus detection where demands on cognitive resources are relatively low. Importantly, however, CI effects were found only for left-hand touch responses. Because most of our participants were right-handed (by self-report), left-hand touch responses may have been more difficult and hence invoked more cognitive control than those executed with the right hand. Recall that participants were to touch the stimulus occurring to the left or right of body midline with the ipsilateral hand. If it is more natural for participants to reach and touch a stimulus (appearing within  $18^\circ$  of visual angle from fixation and body center) with their right hand, particularly if they are right-handed, reaching toward a stimulus with the left hand may require more cognitive control. Consistent with this interpretation, right-handers showed significantly faster and less variable right-hand responses ( $M = 701$  ms and  $\sigma = 127$ ) than left-hand responses ( $M = 730$  ms and  $\sigma = 161$ ):  $F(1, 19) = 8.11$ ,  $p < .05$ , and  $F(1, 19) = 9.35$ ,  $p < .01$ , for RT and  $\sigma$ , respectively. However, for the four left-handers, right-hand response trends were also less variable ( $M = 717$  ms and  $\sigma = 130$ ) than the left-hand responses ( $M = 741$  ms and  $\sigma = 172$ ), although the

faster RT trend found for the right hand ( $M = 710$  ms) versus the left hand ( $M = 754$  ms) occurred only when the response hand was compatible with the planned action held in memory. Taken together, these results suggest that left-hand responses may have invoked more cognitive control than right-hand responses for both our right- and left-handers (see also Elliot & Chua, 1996; Todor & Cisneros, 1985). Thus, CI may be restricted to responses that invoke cognitive control as opposed to those that invoke automatic visuomotor mechanisms.

Consistent with this latter interpretation, Gonzalez et al. (2006) suggested that visuomotor mechanisms encapsulated in the left hemisphere, which control the right hand, may play a special role in automatic visuomotor control for both right-handed and left-handed individuals. They also suggested that more deliberate actions (i.e., those carried out by the right hemisphere that controls the left hand) may not engage the automatic visual control mechanisms but may instead invoke cognitive control that is dependent on perceptual processing. To support this conjecture, they used pictorial illusions (the Ponzo and Ebbinghaus illusions), which have been shown to influence perceptual judgments that rely on visual identity but have little influence on visually guided, grasping responses (e.g., Aglioti et al., 1995; Bridgeman & Huemer, 1998; Dewar & Carey, 2006; Haffenden, Schiff, & Goodale, 2001; but see Dassonville et al., 2004; Franz et al., 2003; Franz, Gegenfurtner, Bülthoff, & Fahle, 2000; Meegan et al., 2004). They found that for both right- and left-handed individuals, precision grasping with the left hand, but not the right hand, was biased by the illusions. That is, regardless of handedness, only the left hand showed larger grip apertures when the target grasped was perceived as larger than the other target even though both targets were identical in size. Also, in a more natural setting where individuals had to pick up small objects to reproduce a puzzle as quickly and accurately as possible, left-handers used their nondominant hand significantly more often to pick up objects in both ipsilateral and contralateral space than right-handers (52% vs. 22%) suggesting that a left hemisphere advantage for grasping may have attenuated the use of the left hand. Such findings are consistent with the idea that left hemisphere (right hand) may engage in more automatic visual control, whereas the right hemisphere (left hand) may require more cognitive visual control.

Gonzalez et al. (2006) also cited neurological evidence from patients with optic ataxia who show differential impairments in target-directed movements depending on whether they have damage to the right or left posterior parietal cortex. Those with left-hemisphere damage show impairments with the right hand anywhere in space, while those with right-hemisphere damage show impairments with the left hand that is apparent only in the contralesional field (Fisk & Goodale, 1988; Gazzaniga, 2000; Koski, Iacoboni, & Mazziotta, 2002). Also, Radoeva et al. (2005) showed that patients with right-hemisphere damage showed a large dissociation between grasping and estimation illusions, whereas patients with left-hemisphere damage showed no detectable dissociation. On the basis of this neurological evidence and the illusion bias found for the left hand in both left- and right-handers, Gonzalez et al. (2006) suggested that visuomotor networks that mediate rapid target-directed movements may have evolved preferentially in the left hemisphere along with the well-established specialization of the left hemisphere for the selection of hand postures and other movements. Because reach or touch responses are also considered

to be visually guided and may require even less processing of object properties than that required for preshaping the hand during grasping (Culham et al., 2003; Jeannerod, 1981; Jeannerod & Decety, 1995; Johnson & Grafton, 2003; Tunik et al., 2005), these rapid target-directed movements may also have a left-hemisphere bias (e.g., Elliot & Chua, 1996; Todor & Cisneros, 1985; see also review by Lavrysen et al., 2007).

Our results, along with those of Gonzalez et al. (2006) and Radoeva et al. (2005), suggest that CI found for visuomotor responses may be limited to those that are under cognitive control as opposed to those that can invoke automatic visuomotor mechanisms. This finding is consistent with the COH account for CI, which assumes that CI should only occur for actions that are under cognitive control.

### Experiment 3

The purpose of Experiment 3 was to determine whether CI would also generalize to a visually guided response where response selection required detecting the stimulus location as well as a spatial location within the stimulus (i.e., the top area of the object). The stimuli and procedures were the same as those in Experiment 1 except that the second stimulus (Stimulus B) consisted of a single rectangle that was presented in one of three possible vertical locations to the left or right of the participant's midline. Participants were to touch the upper inside location of this rectangle with the ipsilateral index finger of the right or left hand as soon as it was detected.

This task should be less cognitively demanding than that in Experiment 1 where response selection was based on object discrimination, but it may be more cognitively demanding than that in Experiment 2 where response selection was based on detecting a global stimulus location. Also, a response based on locating part of an object may invoke perceptual identification of the object, putting more of a demand on the ventral pathway, because the relevant spatial location may be coded with respect to the object (i.e., an allocentric location) as opposed to the observer (i.e., an egocentric location; see reviews by Milner & Goodale, 1995; Goodale & Humphrey, 1998). However, initial selection of the right- or left-hand response may be based on the spatial location of the object relative to the observer, which may put more of a demand on the dorsal pathway. Thus, it is unclear whether the ventral or dorsal pathway would play a more functional role in this type of perceptual-motor task. We were interested in whether responses to Stimulus B, which require visually guided actions to a specific part of an object, would be delayed when the response to Stimulus A and B required the same (compatible) response hand as opposed to different (not compatible) response hands.

### Method

*Participants.* Twenty-five undergraduate psychology students from Washington State University participated and did not take part in any of the other experiments. Visual assessment standards and participant compensation were the same as those in Experiment 1. Twenty-four participants met an accuracy criterion of 80% for both Stimulus B and Stimulus A. By self-report, 22 of these participants were right-handed, and 2 were left-handed.

*Apparatus, stimuli, and procedure.* The apparatus, stimuli, and procedure (see Figure 2) were the same as those in Experiment

1 except as follows. Stimulus B was a single white filled rectangle that subtended 5.8° of visual angle vertically and 4.5° of visual angle horizontally. Stimulus B appeared at one of three different locations vertically arranged to the left or right of the fixation cross (six different locations in total; see Figure 5). The center-to-center distance between the fixation cross and the rectangle when the rectangle was located in the top, middle, or bottom vertical location was approximately 19.4°, 17.0°, and 20.3° of visual angle, respectively. Participants were instructed to make a speeded touch response to the inside top location of the detected rectangle as soon as it appeared. For all participants, a rectangle located to the right of body midline required a right index finger response, while a rectangle located to the left of body midline required a left index finger response. A touch response with the correct hand to the area inside the top of the rectangle (2.25° of visual angle) was recorded as correct. A response anywhere outside this area was recorded as incorrect. Stimulus B appeared until the screen was touched or 5,000 ms elapsed, whichever occurred first. Reaction time to Stimulus B was calculated from the onset of Stimulus B to the time at which the screen was touched.

**Results**

The RTs slower than 1,500 ms for Stimulus B were excluded (3.2% trials on average per participant). Also, the RT analysis for Stimulus B was restricted to trials in which responses to both Stimulus B and A were accurate. Figure 6 shows the mean correct RT and percentage error for Stimulus B based on compatibility and hand. Similar to Experiment 2, CI was found for left-hand responses. A two-way, repeated measures ANOVA, with the factors of compatibility and hand, was conducted separately on correct RT and percentage error for Stimulus B and on percentage error for Stimulus A.

*Stimulus A.* The average error rate for Stimulus A was 5.3%. There was no significant difference in errors based on compatibility,  $F(1, 23) < 1, MSE = 0.06, p > .70$ , or hand,  $F(1, 23) < 1, MSE = 0.03, p > .30$ , and there was no significant interaction between compatibility and hand,  $F(1, 23) < 1, MSE = 0.56, p > .40$  (see Table 1).

*Stimulus B.* For RT, there was a significant main effect of hand,  $F(1, 23) = 7.36, MSE = 1050.30, p < .05$ , but not com-

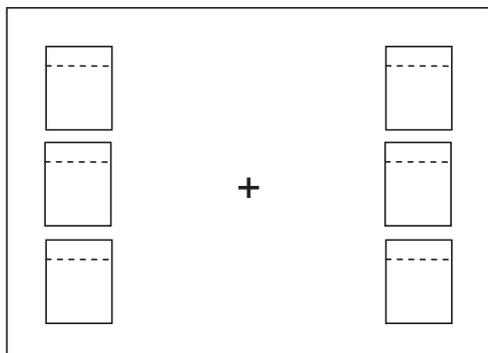


Figure 5. A diagram of the response apparatus used for Stimulus B in Experiment 3. Stimulus B appeared in one of the six possible locations indicated by the solid-line boxes. A correct response for Stimulus B was a touch response to the top portion of each box, denoted by the area above the dashed line within each box.

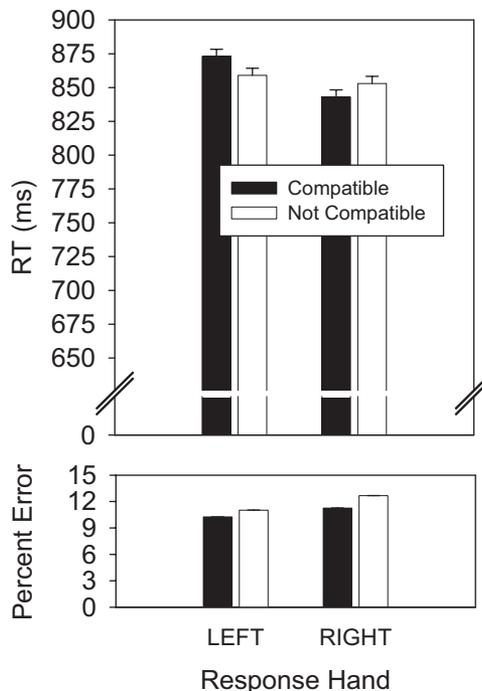


Figure 6. Experiment 3: Correct reaction time and percentage error for Stimulus B based on response hand (left, right) and hand compatibility (compatible, not compatible) with the response held in memory to Stimulus A. Error bars show one standard error of the mean.

patibility,  $F(1, 23) < 1, MSE = 1010.28, p > .80$ . Moreover, the interaction between compatibility and hand was significant for RT,  $F(1, 23) = 17.34, MSE = 202.96, p < .001$ . Planned comparisons (Tukey’s honestly significant difference test) showed that responses executed with the left hand were delayed by 14 ms when the action held in memory required the left hand as opposed to the right hand ( $p < .05$ ). In addition, responses executed with the right hand were facilitated by 10 ms when the action held in memory required the right hand as opposed to the left hand ( $p < .05$ ). This indicates that CI only occurred for left-hand responses, while compatibility facilitation occurred for right-hand responses. In terms of accuracy, there were no significant effects found for compatibility,  $F(1, 23) = 2.91, MSE = 0.10, p > .10$ , hand,  $F(1, 23) < 1, MSE = 0.56, p > .40$ , or the interaction between compatibility and hand,  $F(1, 23) < 1, MSE = 0.09, p > .60$ . Thus, the RT interpretations above are not due to a speed-accuracy tradeoff.<sup>3</sup>

*Compatibility interference comparisons between Experiment 2 and Experiment 3.* To examine whether CI effects were similar when responses were based on detecting the spatial location of a

<sup>3</sup> The trend toward a main effect of compatibility for response errors shows lower error rates for the compatible versus the not compatible condition, which is consistent with a speed-accuracy tradeoff interpretation for left-hand responses. However, because this trend is insignificant and because mean error RTs found for left-hand responses were no different between the compatible ( $M = 829$  ms) and the not compatible conditions ( $M = 823$  ms),  $F(1, 23) < 1, p > .70$ , this indicates that response execution was not more conservative for the compatible condition.

stimulus (Experiment 2) and determining a spatial location within a stimulus (Experiment 3), we conducted a mixed design ANOVA, with the between-participants factor of experiment (2 or 3) and the within-participant factors of compatibility (compatible or not compatible) and response hand (left or right), separately on mean correct RT and accuracy for Stimulus B. Importantly, the factor of experiment did not interact with the factors of compatibility or hand in terms of RT ( $ps > .35$ ) or accuracy ( $ps > .20$ ). Only a main effect of experiment was found for RT,  $F(1, 46) = 13.69$ ,  $MSE = 68,906.39$ ,  $p < .001$ , and accuracy,  $F(1, 46) = 98.15$ ,  $MSE = 0.56$ ,  $p < .0001$ , which indicates that RTs were 140 ms longer and error rates were 10% greater in Experiment 3 compared to Experiment 2. These differences likely reflected the higher demands on response precision in Experiment 3 where touch responses were restricted to an area of  $2.25^\circ$  as opposed to  $6.3^\circ$  of visual angle in Experiment 2. Although response difficulty varied between these experiments, a CI effect was found only for the slower left-hand response in both experiments. Also, the compatibility effects found for right-hand responses did not differ between Experiment 2 and 3, which suggests that the 10-ms compatibility facilitation reported for the right-hand response in Experiment 3 was not statistically reliable. To confirm this, we conducted a mixed design ANOVA on the factors of experiment and compatibility for right-handed response RT only. Results showed a significant main effect of experiment,  $F(1, 46) = 14.25$ ,  $MSE = 35,538$ ,  $p < .001$ , but no significant effect of compatibility,  $F(1, 46) = 1.81$ ,  $MSE = 388$ ,  $p = .19$ , and no significant interaction between experiment and compatibility,  $F(1, 46) = 1.67$ ,  $MSE = 388$ ,  $p > .20$ . Thus, visually guided actions executed by the right hand were not reliably influenced by the factor of compatibility.

### Discussion

Experiment 3 showed that CI occurred for a visually guided touch response to a location within a stimulus but only for left-hand responses. That is, holding a planned action in memory based on stimulus identity delayed a visually guided action to a location within a stimulus when the two actions required the same left response hand. These findings are similar to those obtained in Experiment 2 where response selection of the intervening stimulus was based on detecting the location of a stimulus. Also similar to the findings of Experiment 2, left-hand touch responses appeared more difficult and hence may have invoked more cognitive control than those executed with the right hand. Consistent with this interpretation, right-handers showed significantly faster and less variable right-hand responses ( $M = 849$  ms and  $\sigma = 126.46$ ) than left-hand responses ( $M = 869$  ms and  $\sigma = 134.07$ ):  $F(1, 20) = 10.30$ ,  $p < .01$ , and  $F(1, 20) = 5.30$ ,  $p < .05$ , for RT and  $\sigma$ , respectively. Also, this difference in response speed between the right and left hand was greater when the response hand was compatible versus not compatible with the planned action held in memory,  $F(1, 20) = 13.70$ ,  $p < .01$ . The 2 left-handers showed similar trends; right-hand responses were less variable ( $M = 845$  ms and  $\sigma = 116.52$ ) than left-hand responses ( $M = 850$  ms and  $\sigma = 127.96$ ), and responses were faster for the right hand ( $M = 835$  ms) relative to the left hand ( $M = 860$  ms) but only when the response hand was compatible with the planned action held in memory. These results, particularly the trends in RT variability,

suggest that left-hand responses may have invoked more cognitive control than right-hand responses for both our right- and left-handers. Again, it appears that CI may be restricted to responses that invoke cognitive control as opposed to those that invoke automatic visuomotor response mechanisms.

According to Milner and Goodale (1995), the ventral pathway should play a more functional role in visually guided actions to a stimulus location that is defined relative to an external stimulus as was the case in our Experiment 3. However, the response pattern obtained in Experiment 3 was more similar to those obtained in Experiment 2 (where selection required detecting a stimulus location relative to the observer; i.e., the dorsal pathway) as opposed to Experiment 1 (where selection required stimulus discrimination based on color identity; i.e., the ventral pathway). This could be because the selection of the appropriate response hand was based on the detection of the transient onset of the stimulus to the right or left of the observer (e.g., the egocentric location of the stimulus) similar to Experiment 2, with fine adjustments to the particular stimulus location carried out online, without requiring perceptual identification of the stimulus. Many studies investigating grasp responses have instructed participants to grasp a particular location within the object and have shown that these responses impose more of a functional demand on the dorsal stream as opposed to responses that require perceptual recognition (e.g., Culham, 2004; Culham et al., 2003). These findings suggest that executing touch responses to a stimulus location that requires discriminating stimulus identity (Experiment 1) is different from touch responses that rely only on determining the spatial location of a stimulus or the spatial location within a stimulus (Experiment 2 and 3, respectively); the latter two cases may invoke automatic visuomotor control, particularly when the response is executed with the right hand.

### General Discussion

This study showed that compatibility interference (CI), a delay in responding to a stimulus that has partial feature overlap with an action plan held in memory, can occur for visually guided actions that require touching a stimulus location. However, CI appears to be limited to actions that invoke cognitive control and does not appear to generalize to actions that invoke automatic visuomotor mechanisms. When response selection involved identifying and localizing a stimulus (Experiment 1), CI was observed for both right- and left-hand touch responses. This indicates that CI can occur for visually guided touch responses to an object location that requires evaluation of the stimulus's identity, linked to the ventral pathway (e.g., Bridgeman, 2002; Culham et al., 2003; Milner & Goodale, 1995; Jeannerod, 1997; Ungerleider & Mishkin, 1982). In contrast, when response selection did not require discrimination of stimulus identity but involved detecting the spatial location of a stimulus (Experiment 2) or the spatial location within a stimulus (Experiment 3), CI was observed for left-hand responses but not for right-hand responses. Because the left hemisphere (which controls right-hand responses) may play a special role in automatic visuomotor control linked to the dorsal pathway (Gonzalez et al., 2006; Radoeva et al., 2005), our results suggest that CI does not occur for automatic visuomotor responses where the dorsal pathway plays a special role. However, CI does occur for similar visually guided responses that are directed by the right hemisphere

(which controls left-hand responses), which is thought to invoke more cognitively controlled responding linked to the ventral pathway (Gonzalez et al., 2006). In general, these findings are consistent with the code occupation hypothesis's (COH) account for CI (Hommel et al., 2001a, 2001b; Stoet & Hommel, 1999).

The COH assumes that CI originates at a level of processing between late perceptual and early response (Hommel et al., 2001b). That is, where memory plays a role in feature-code generation of the action plan (late perceptual) and before the appropriate motor programs are selected to execute the action (early response). Feature codes may be best described as cognitive codes (e.g., Hommel et al., 2001b; Müsseler & Hommel, 1997a; Wühr, 2006), which may include meaning-based representations of action operations or schemata (e.g., the code *right* for right-hand response) as well as meaning-based representations of a stimulus (e.g., the code *right* for a right-pointing arrow). In accordance with these assumptions, the bound cognitive codes representing the action plan can be used to select the appropriate motor plans in order to execute an overt response. If this action plan is held in memory to allow immediate execution of another action, the COH assumes that execution of the intervening action will be delayed if it shares a feature code with that occupied by the action plan in memory (CI). Also, because memory is assumed to play a critical role in feature-code generation and code occupation, the COH predicts that CI will only occur for actions that invoke cognitive control. Only actions that invoke cognitive control would possibly require a feature code that is occupied by an action plan held in memory.

Consistent with the COH, our results indicate that CI occurs before the generation of motor responses and is likely restricted to actions that invoke cognitive control. If activation or occupation of specific motor programs contributed to CI, we would have consistently observed CI when the intervening response required the same hand as the action plan held in memory. This was clearly not the case. Compatibility interference was found for left-hand responses but not for right-hand responses when the information required to select and execute the correct response involved detecting the location of a stimulus, without also requiring stimulus discrimination. Furthermore, because right-hand responses were typically faster and less variable than left-hand responses and likely invoked automatic visuomotor mechanisms under these stimulus–response conditions (e.g., Gonzalez et al., 2006; see also Elliot & Chua, 1996; Todor & Cisneros, 1985), these findings suggest that actions that invoke automatic visuomotor mechanisms are immune to CI. Thus, CI appears to be restricted to actions that invoke cognitive control, in accordance with the assumptions of the COH.

In general, our results are consistent with the functional distinction between the ventral and dorsal visuocortical pathways and in particular with the framework proposed by Milner and Goodale (1995) and Gonzalez et al. (2006). According to this framework, both the dorsal and ventral pathways play a role in visual guidance to the correct stimulus location (e.g., Westwood & Goodale, 2001), but the ventral pathway plays a more significant role in actions linked to cognitive representations of stimuli, and the dorsal pathway is linked more strongly to automatic visuomotor mechanisms (i.e., associated with the left hemisphere) where there is a spatial correspondence between the visual cues and the action (e.g., Gonzalez et al., 2006). Consistent with this framework, we found

a dissociation between the ventral and dorsal pathways in terms of CI.

We showed that whether an action plan held in memory interfered with the execution of an intervening, visually guided action was dependent on the functional role of the pathway associated with the intervening action. That is, withholding an action plan in memory (ventral pathway) led to CI for visually guided actions that were dependent on cognitive representations of stimuli (ventral pathway). These included actions that required discrimination of stimulus identity (Experiment 1) and actions that did not invoke automatic visuomotor responses to a detected stimulus location (i.e., visually guided left-hand responses to a detected stimulus location that were slower and more variable than right-hand responses; Experiments 2 and 3). According to Gonzalez et al. (2006), both types of responses should invoke perceptual-motor processing associated with the ventral pathway. However, withholding the same action plan in memory (ventral pathway) did not lead to CI for visually guided right-hand actions toward a detected stimulus location assumed to be under automatic visuomotor control linked to the dorsal pathway. The dissociation between these two pathways in terms of CI was found by holding the physical actions to the planned and intervening stimulus constant and varying the response hand as well as the information required to select the appropriate, intervening response.

Although participants were instructed to withhold a planned action to the first stimulus (e.g., “left hand move upward”) in memory, it is possible that participants instead withheld a perceptual representation of this stimulus (e.g., “left-pointing arrowhead with left asterisk”) in memory that was later translated into a response. This possibility does not pose a problem for the COH account for our CI results since cognitive code overlap may reflect perceptual features as well as action features associated with the events (e.g., Hommel et al., 2001b). Moreover, it does not threaten our conclusion that CI may be restricted to cognitively controlled actions. However, it would undermine our assumption that participants were withholding an action plan in memory, and it was the cognitive codes representing the memorized action plan (as opposed to cognitive codes representing the perceptual aspects of the stimulus) that determined whether the intervening action was delayed.

There are three reasons why we believe that an action representation to the first stimulus (Stimulus A) was withheld in memory, as opposed to a perceptual representation. First, Stoet and Hommel (1999) obtained CI when the withheld action to the first stimulus was based on the letter *X* or *O* that could only share an action code (left or right based on a left- or right-hand response) and not a perceptual code with the intervening stimulus that consisted of a red or green square. This suggests that when participants are instructed to plan and withhold an action to the first stimulus, they generally comply. Second, although other research (e.g., Stoet & Hommel, 2002) indicates that instructing participants to withhold a perceptual representation of the stimulus (particularly in terms of the spatial characteristics of the stimulus) can lead to CI, our participants were explicitly instructed to plan and withhold an action to the stimulus. Detailed debriefing in a recent study conducted in our laboratory using the same paradigm and a similar stimulus (i.e., right- or left-pointing arrowhead with an asterisk above or below the arrowhead) confirmed that an action planning strategy was used—at least for 95% of the participants. The

strategies used by participants to remember the withheld action were reported to be based on a verbal description of the action (e.g., “left up”) 85% of the time, visualization of motor execution with correct hand and finger 10% of the time, or a mental picture of the stimulus (e.g., “left above”) only 5% of the time.

Third, if a perceptual representation was withheld in memory in the experiments reported here, we would expect the CI effect to depend on the perceptual representation characterizing Stimulus A (i.e., arrowhead direction [left or right] and asterisk location [left or right] relative to the arrowhead). For example, when the arrowhead direction (left or right) and asterisk location (left or right) were similar (i.e., \* < and > \*), the spatial representation of each symbol should cause a left code or a right code to be activated and occupied. In turn, only one of the two possible actions for Stimulus B (left-hand or right-hand action) would require the occupied left or right code. This would result in longer Stimulus B RTs for our action-defined compatible condition compared to our not compatible condition (CI). In contrast, when the arrowhead direction (left or right) and asterisk location (left or right) differed (i.e., < \* and \* >) causing both the left code and the right code to be activated and occupied, all actions required for Stimulus B (i.e., left- and right-hand responses) should be delayed. This would result in equivalent Stimulus B RTs for our action-defined compatible and not compatible conditions (no detectable CI). However, we failed to find statistical evidence that CI was dependent on the perceptual representation associated with Stimulus A as outlined above.<sup>4</sup> This suggests that our CI effects were not based on the perceptual representation of Stimulus A but on an action representation. Thus, on the basis of the three reasons provided, it is very likely that that our participants withheld a representation of the action plan to the first stimulus (Stimulus A) and that the CI effects obtained were based on this withheld action representation.

In summary, action features (codes) held in memory (e.g., corresponding to the response hand) may not affect responses that invoke automatic visuomotor mechanisms but can affect other visually guided actions that invoke cognitive control. Because automatic visuomotor actions are translated into motor responses online and directly during response execution (Bridgeman, 2002; Culham et al., 2003; Gonzalez et al., 2006; Milner & Goodale, 1995), withholding an action plan in memory should not interfere with the execution of such actions. Our results provide empirical evidence that CI, and the COH account for CI, may only apply to actions that invoke cognitive control (i.e., Hommel et al., 2001a, 2001b). That is, withholding an action plan, such as series of keypresses to the remote control (ventral stream), may hinder one’s ability to perform an immediate action, such as reaching for a red coffee cup among other colored coffee cups (ventral stream) when both actions require the same hand. However, one’s ability to reach for a falling water glass when both actions require the same hand may only be hindered if this action is executed with the left hand, where visually guided actions invoke cognitive control (ventral stream), but not if this action is executed with the right hand, where visually guided actions may invoke automatic visuomotor mechanisms (dorsal stream).

<sup>4</sup> Perceptual codes were assumed to reflect mappings of arrowhead direction (left or right) and asterisk location relative to arrowhead (left or right) as represented in the instructions. These codes are assumed to be the

simplest codes that could be used to extract the correct response mappings required when executing the response to Stimulus A.

A within-subjects ANOVA, with the perceptual factor (both symbol codes similar vs. different) and the factors of compatibility and hand, was conducted on Stimulus B RTs separately for each experiment. There was no main effect or interactions associated with this perceptual factor in Experiment 1 and 2 (all  $ps > .20$ ). However, the Perceptual  $\times$  Compatibility  $\times$  Hand interaction approached significance ( $p = .062$ ) in Experiment 3 demonstrating a data trend of left-handed CI effects when perceptual codes of both symbols were similar and different, with a larger CI trend for different perceptual codes—which is the opposite of that predicted above. This indicates that the perceptual coding scheme described above was not used in this study.

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