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KINEMATIC PROPERTIES OF VISUALLY AND HAPTICALLY GUIDED ACTIONS

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KINEMATIC PROPERTIES OF VISUALLY AND HAPTICALLY GUIDED ACTIONS

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Abstract

We compared the contribution of the visual and haptic modalities in action and perception tasks. We also investigated whether or not the dissociation between action and perception found in vision can be duplicated in haptics. For both a grasping and perceptual estimation task, performance based on haptics alone showed greater uncertainty than vision alone. When congruent information from both senses was available simultaneously, performance was no different than with vision alone. When conflict was introduced between the senses, however, an influence of haptic cues emerged. Investigation of Weber's law in haptics revealed that, like vision, the law was upheld in the perceptual task, but violated in the action task. An experiment utilizing a haptic version of a visual illusion also provided evidence for an action-perception dissociation. Taken together, this work suggests that although there are significant differences between vision and haptics, the action-perception distinction may be common to both modalities.

Keywords: vision, touch, haptics, grasping, manual estimation, perception, action, kinematics, multisensory integration, illusions

Co-Authorship

All of the research contained within this thesis was conducted in collaboration with my supervisors, Dr. Jody C. Culham and Dr. Melvyn A. Goodale. Dr. Culham and Dr. Goodale contributed to all aspects of the projects (e.g. experimental design, interpretation, manuscript preparation). The written material in this thesis is my own work, but both of my advisers (Dr. Culham and Dr. Goodale) provided assistance with editing and revisions.

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CHAPTER 1: General Introduction

While there is a wealth of research studying the contributions of vision to the control of action, relatively little research has examined contributions from other sensory modalities. In particular, the role of touch, or haptics, in everyday movements has received considerably less attention than that of vision. The purpose of this work is to lay a foundation for understanding the basic contribution of touch during human interactions with objects and to compare these findings to what is known about vision. To begin, it is necessary to discuss the framework with which visually guided actions are typically understood.

1.1 The dual pathway model of vision

Early studies on neuropsychological patients suggested a potential dissociation between our ability to perform actions based on visual information and our ability to form visual percepts of objects. In particular, patients with damage to their occipito-temporal cortex have difficultly perceiving the shape, orientation and size of objects, but can nonetheless perform accurate hand movements toward such objects (Goodale et al. 1991). The collection of inputs that stem from primary visual cortex (V1) and travel to areas in occipito-temporal cortex is referred to as the ventral visual stream. The ventral visual stream contains regions that are particularly important for discerning the identity of objects. In other words, the ventral stream processes visual 'what' information. Conversely, patients with damage to their posterior parietal cortex are able to perceive object identity, but fail at acting on external objects (Goodale and Milner 1992). Inputs travelling from area V1 to the posterior part of parietal cortex are collectively referred to as the dorsal visual stream. This processing stream is crucial for transforming visual inputs into information used for action preparation. As such, the dorsal stream is credited for processing the 'where' and 'how' content of visual information. Thus, there appears to be functionally distinct and spatially separated neural circuitry mediating visually guided action and visual perception (Milner and Goodale 1995). This theory has been supported by both monkey neurophysiology and human neuroimaging. However, a considerable number of studies have also been able to observe this action-perception dissociation in normal subjects performing simple laboratory tasks. These tasks typically involve having participants perform actions and perceptual judgments in special contexts that are designed to tease apart the capabilities of the dorsal and ventral visual steams. However, before discussing these experiments, we will begin by outlining how actions and perceptual judgments are typically measured in a laboratory setting.

1.2 The kinematics of grasping and manual size estimation

One method that is used to dissociate the capabilities of the dorsal and ventral streams involves grasping vs. perceptually estimating the size of different stimuli. While people perform these tasks, researchers place infrared emitting diodes (IREDs) at key positions on the participant's hand (typically the index finger, thumb and knuckle). Infrared light emitted from these markers is recorded by cameras mounted to the wall, which reconstruct the three dimensional movements of the hand through time. When grasping, one of the most important and most commonly reported measures derived from this data is the maximum aperture of the grip as participants reach out to pick up an object. The maximum opening between the finger and thumb typically scales to the size of the object being grasped. Although one might think this size-dependent opening of the hand is related to the perceived size of the object, in fact, studies on neuropsychological patients suggest otherwise (Goodale et al. 1991; Goodale and Milner 1992). In particular, patients with lesions to the dorsal visual stream show no size-dependent scaling of grasp aperture, yet these patients are able to accurately report the perceived size of the same stimuli. Conversely, patients with lesions in the ventral visual stream are unable to distinguish between differently sized stimuli, yet show accurate grip scaling when performing a grasp. Thus, it appears that the dorsal stream, which is critical for action preparation, has a unique representation of size that is separate from the conscious perceptual representation of size generated in the ventral visual stream. As a result, by having normal participants perform both grasping and perceptual estimation tasks, researchers can selectively engage the distinct processing streams.

There are a number of different ways in which a person can perform a perceptual judgement of size. However, one technique that is common to many studies requires participants to use their dominant hand and indicate size by opening their fingers to the perceived size of the object (Goodale et al. 1991; Goodale and Milner 1992; Aglioti et al.

1995; Haffenden and Goodale 1998; Hu and Goodale 2000; Haffenden et al. 2001; Westwood and Goodale 2003). In this task, rather than reaching out to grasp the object, participants keep their hand stationary and simply open their grip to the extent they believe would be sufficient to hold the object. This measure is akin to the typical magnitude estimation paradigms used in conventional psychophysics, but with the virtue that the manual estimation makes use of the same effector that is used in the grasping task. It is predominantly a perceptual task in that it requires the participant to show the experimenter how big he or she thinks the object is without interacting with the object in any way. Studies on neuropsychological patients suggest that grasping and manual estimation rely on fundamentally different representations of size (Goodale et al. 1991; Goodale and Milner 1992). Specifically, the dorsal visual stream is thought to be predominantly responsible for grasping actions, whereas the ventral visual stream is thought to be crucial for manual estimates of size. Consequently, when testing normal subjects, the maximum aperture when grasping can be compared to the aperture in manual estimation in order to investigate the involvement of the dorsal and ventral visual streams.

1.3 Grasping in the context of perceptual illusions

One clever method of revealing this functional dissociation between the dorsal and ventral visual streams is to have normal subjects interact with real objects that are presented in the context of a visual illusion (Aglioti et al. 1995; Haffenden and Goodale 1998; Hu and Goodale 2000; Goodale et al. 2004; Ganel et al. 2008; Goodale 2008). There are numerous visual illusions such as the Ebbinghaus illusion, the Müller-Lyer illusion or the Ponzo illusion that are designed to distort our perception of size. When asked to judge the size of objects placed in the context of such illusions, estimates typically reflect the illusory size, not the real size of the object. However, when participants are asked to reach out and pick up these objects, their performance shows no influence of the illusion. That is, people generally scale their grip aperture to the real size of the object. This result is interpreted as a demonstration of the separable influences of the dorsal and ventral steams on visual processing. Since the ventral visual stream is responsible for generating our conscious perception of visual objects, it is fooled by the illusory context in which the object is presented. Therefore, subsequent judgments of size based on these representations are flawed in the direction of the illusion. The dorsal stream, on the other hand, is responsible for using visual information for action preparation. The absence of an illusory effect in grasping actions suggests that this processing steam does not rely on the same mechanisms or representations as those of the ventral stream. Instead, the dorsal stream processes information in a more automatic fashion, concentrating on the real metrics of the target and ignoring the irrelevant context.

Although the finding that visual illusions can reveal dissociations between action and perception is not without controversy (e.g., Pavani et al. 1999; Franz 2001; Glover 2002; Franz et al. 2009), most visual illusion experiments report results that are consistent with the dual-pathway model of vision. Interestingly, a number of experiments are able to demonstrate an illusory effect in grasping, but only under certain conditions. In particular, some investigators have asked participants to grasp an object placed in an illusory context, but without visual feedback (Hu and Goodale 2000; Westwood et al. 2001; Westwood and Goodale 2003; Ganel et al. 2008). That is, just prior to initiating a reach-to-grasp movement, participants would lose vision of the object and then perform the action without visual feedback. In this scenario, grasp aperture is suddenly influenced by the illusory context. However, this result is not considered to be a criticism of the dual-stream hypothesis, but rather a demonstration of it. Once visual feedback is removed, the online visual information that is necessary for dorsal stream processing is lost. Thus, in order to prepare for action, we must rely on a perceptual memory of the size and location of the stimulus. Since this perceptual representation was generated through ventral stream processing, it will be distorted by the illusory context. As a result, any action plan based on such a representation will be similarly affected by the illusion.

Although a considerable amount of effort has been spent investigating this dissociation in the visual domain, very little work has been done on other sensory modalities. In particular, our sense of touch, or haptics, can also be used to perceive the size, orientation and location of objects. As a result, many of the questions asked of vision can also be asked of haptics. However, in order to start investigating this dissociation in the haptic domain, it would be useful to know how the two senses compare on both action-oriented and perception-oriented tasks.

1.4 Comparisons between vision and haptics

Research comparing size perception in haptics with that in vision has been somewhat sparse and inconsistent. The inconsistency observed between studies may stem from inconsistency in how size perception is measured. There are a number of ways to measure size perception and the choice of method typically depends on the question being asked. Studies that investigate grasping as well as perceptual estimates typically rely on the manual estimation technique described earlier. However, perceptual judgments can also be made in the context of matching experiments, through the arbitrary assignment of numbers, or in a 1-back same or different task. Early findings on visual and haptic size perception indicated that size perception is more accurate when vision is available than when relying on haptics alone (Teghtsoonian and Teghtsoonian 1970). However, in a more recent study, Chieffi and Gentilucci (1993) suggested that the two modalities are comparable at a majority of object sizes, with haptics showing less accuracy at representing the size of smaller objects. In addition to investigating how each modality performs separately, other studies have examined performance when information is provided to both senses simultaneously.

When examining sensory integration between vision and haptics in a size perception paradigm, researchers have utilized both real and virtual objects to show that, in fact, both modalities contribute to perceptual judgments (Ernst and Banks 2002; Helbig and Ernst 2007). However, by creating a discrepancy between the visual and haptic information, the weighting of the visual information is shown to be higher than that of the haptic information. That is, when judging size, people tend to rely more on vision when both vision and haptics are available. This result may not be surprising considering previous findings on the relative accuracy of visual estimates of size, as well as how often vision is used to judge object size in everyday life. Interestingly, when the visual signal is degraded (either through noise or blurring), people begin to rely more on haptics when estimating size (Ernst and Banks 2002; Helbig and Ernst 2007). Thus, it appears that the weighting of the senses is dynamic and sensitive to the particular context of the observer. However, the question of whether this result generalizes to the motor system has yet to be answered.

Similar to the dorsal-ventral distinction in the visual system, recent evidence in haptics has illuminated a potential distinction between neural circuits mediating action-oriented and perception-oriented capabilities (Dijkerman and de Haan 2007; Anema et al. 2009). As a result, investigations into the relation between vision and haptics may benefit from utilizing separate action and perception tasks. That is, findings in perceptual tasks, such as size estimation, may not generalize to motor tasks, such as grasping. However, very few studies have investigated haptically guided grasping actions, resulting in little evidence for a potential action-perception dissociation in haptics. Those studies which have investigated haptically guided actions such as grasping are not typically framed to uncover such a dissociation (Chieffi and Gentilucci 1993; Gentilucci et al. 1998; Kritikos et al. 2002; Coats et al. 2008). Instead, these studies are aimed at investigating how haptic information, either from previous trials or from the current trial, affects visually guided grasping actions. The general finding from this line of research is that haptic information can influence grasping behavior in tasks that were previously thought to rely solely on vision. However, the specific conditions under which haptic information is incorporated in visual tasks remains to be investigated. Furthermore, whether this incorporation is dependent on the type of task (action-oriented or perception-oriented) is still unknown.

1.5 Motivation for experiments

The purpose of this body of work is to first conduct a comprehensive analysis of how vision and haptics compare in both a grasping task and a manual estimation task. In doing so, we hope to describe any of the baseline differences between the senses in performing these tasks. We will use this information to help inform our secondary goal, which is to investigate the potential dissociation between action-oriented tasks and perception-oriented tasks in the haptic domain.

Experiment 1 in Chapter 2 seeks to address our first goal by having participants perform a grasping task and a manual estimation task based on vision alone, haptics alone and a combination of both senses. The purpose of the multimodal condition was to see how the two sense modalities interact when information is received simultaneously. Never has this been done with both an action and a perception task in a single experiment. With this data, we hope to answer the question of whether the incorporation of haptics into traditionally visually-dominated tasks depends on whether an action-oriented or a perception-oriented task is being performed. Experiment 2 in Chapter 2 examines cross-modal integration further by making the two sources of information (vision and haptic) incongruent. This creates the opportunity for a greater and potentially more noticeable influence of the available haptic information.

Chapter 3 proceeds by describing an experiment that investigates the action-perception distinction in haptics by duplicating a traditionally vision-based illusion called the size-contrast illusion. In this visual illusion experiment, participants are required to view two blocks of different sizes then grasp or estimate the size of one of the blocks. This scenario creates an illusion where the presence of a differently-sized block influences the perception of the size of the block to be acted upon. However, only perceptual estimations of size are fooled by the illusion, with grasping behaviour remaining relatively unaffected. For this chapter, we created a purely haptic version of the visual size-contrast illusion in order to investigate the action-perception dissociation in the haptic domain. In this version of the illusion, participants first use the non-dominant hand to explore the sizes of the two objects, then they use their dominant hand to perform either a grasp or manual estimation on one of the objects. As mentioned previously, grasping actions are typically less influenced by illusory contexts than perceptual estimations of size. However, when grasping follows a delay, wherein vision is typically removed, suddenly grasp apertures show influences of the illusion. This change after the introduction of a delay is believed to reflect a switch between reliance on dorsal stream processing to ventral stream processing. We duplicate this paradigm by introducing a delay into a haptic version of the visual size-contrast experiment, where participants release their non-dominant hand form the target object prior to grasping or estimating. We hope that the information gathered from this experiment and those described previously will further our understanding of the relation between vision and haptics in the context of the action-perception debate.

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CHAPTER 2: Integration of haptic and visual size cues in perception and action revealed through cross-modal conflict[1]

Introduction

The aim of the present study was to determine how haptics and vision interact when people are simultaneously presented with congruent or incongruent information from the two senses. Previous research has shown that both haptics and vision play important, but sometimes unequal roles, in our perception of object size (Ernst and Banks 2002; Helbig and Ernst 2007). For example, when participants were asked to indicate the length of a range of block sizes by assigning numbers, estimates based on vision alone were more accurate than estimates based on haptics alone (Teghtsoonian and Teghtsoonian 1970). In addition, when both vision and haptics were available, length estimates were more characteristic of the vision alone condition (Teghtsoonian and Teghtsoonian 1970). However, that is not to say that haptic information asserts no influence when performing estimations based on information from both modalities. For instance, the introduction of noise and blurring into visual images of virtual and real objects results in a greater reliance on haptic information when estimating the size of a stimulus (Ernst and Banks 2002; Helbig and Ernst 2007).

Although haptics and vision can have different influences on the perception of size, these effects do not necessarily generalize to actions that rely on size information, such as grasping Indeed, separate systems are said to mediate perception and action (Goodale and Milner 1992); thus the conditions under which haptics influences judgments of size may not parallel those which dictate action. Although some results suggest that vision completely dominates when the two senses are put in opposition during a perceptual task (Rock and Victor, 1964), more recent findings on action have demonstrated otherwise (Gentilucci et al. 1995; Chieffi and Gentilucci 1993). For example, when participants grasped objects that changed physical size from trial to trial but had a constant visual size, grip aperture automatically adjusted to the haptic feedback from previous trials (Gentilucci et al. 1995). Thus, even the small amount haptic

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interaction involved while securing a grasp is automatically integrated into visuomotor programs for subsequent reach-to-grasp movements. When grasping based on haptic information alone, participants consistently opened their hands wider than when relying on visual information alone (Chieffi and Gentilucci 1993; Coats et al. 2008). However, participants did not show the same trend when asked to manually estimate the size of objects presented either haptically or visually. Therefore, it is unlikely that the observed difference between haptics and vision during grasping reflects differences in perception between the two modalities.

In addition to the previous studies that have examined incongruent sensory information across trials, other studies have examined incongruent sensory information within trials (Gentilucci et al. 1998; Kritikos et al. 2002). In these studies, however, the available haptic information has been irrelevant to the task. For example, when one hand is reaching toward a target while the other hand is simultaneously manipulating a totally different object, haptic feedback from the non-reaching hand influences the motor behavior of the reaching hand (Gentilucci et al. 1998). Another study separated target and distracter objects not only in space but also in time such that potential cross-modal interference could not be attributed to concurrent activation of two motor programs (Kritikos et al. 2002). They also found that the haptic stimulus influenced the grasp aperture of the reaching hand. In sum, even when irrelevant to the task, haptic information is incorporated into visuomotor programs when executing reach-to-grasp movements.

Here, we used a single paradigm to investigate both action (grasping) and perception (manual size estimates) based on haptics alone, vision alone, or both senses together. The manual size estimate technique was used because it provides measurements that can be directly compared to those of grasping, but which rely on distinct perceptual systems, as revealed by neuropsychological dissociations (Goodale et al. 1991) and studies on perceptual illusions (Aglioti et al. 1995; Haffenden and Goodale 1998; Hu and Goodale 2000; Haffenden et al. 2001; Westwood and Goodale 2003). When performing tasks based on both senses, simultaneously available haptic and visual information pertained to a single target object, ensuring that both types of information were relevant to the task (unlike earlier studies: Gentilucci et al. 1998; Kritikos et al.

2002). In addition, the information from the two senses could be either congruent (Experiment 1) or incongruent (Experiment 2). Although we had expected that congruent cross-modal information in Experiment 1 might improve performance relative to either sense alone, in fact we found that performance was best with vision, regardless of whether or not haptic information was available. This finding provided the motivation for Experiment 2, which made haptic and visual information incongruent to examine whether the simultaneously available haptic information was being considered at all. Furthermore, while visual information decays quickly with the introduction of a delay (Westwood et al. 2001; Westwood and Goodale 2003; Hu and Goodale 2000), the effects of delay on haptic information are less certain. Delay has been shown to interact in different ways with grasping and manual size estimations based on haptic information (Pettypiece et al. 2009). That is, introducing a delay prior to grasping resulted in the consideration of previously encountered haptic information, whereas introducing a delay prior to estimating eliminated such a reliance on previous haptic information. Crucially, however, the present study examines cross-modal interactions whereas the previous study was limited to investigating real-time and memory-driven performance based on uni-modal cues. Thus, in Experiment 2, we also examined grasping and estimation both with and without a brief (2 s) delay to determine whether the relative contribution of the senses changed over time. Finally, recent evidence has shown that with visual cues, manual estimation but not grasping follows Weber's law. That is, with vision, variability of manual estimates increases as a function of object size but variability of grasping remains constant regardless of object size (Ganel et al. 2008). Here, we also investigated whether, with haptic cues and combined haptic and visual cues, the same dissociation is observed.

Methods

Participants

Twelve people (2 male; mean age of 24.7) participated in Experiment 1 and a different group of 17 people (2 male; mean age of 21.9) participated in Experiment 2. All participants were right-handed, had normal or corrected-to-normal vision and received monetary compensation for their participation. Participants provided informed consent in accordance with the local institutional guidelines for ethical research practices.

Experiment 1

We employed a 2 x 3 design in which the kinematics of the right hand were measured while participants either grasped or manually estimated six sizes of wooden blocks under three different experimental conditions: haptics only (H), vision only (V) and haptics and vision (HV). Participants could see one block presented atop an elevated platform and/or use the left hand to feel a second block presented beneath the platform in the same spatial location (Figure 2-1).

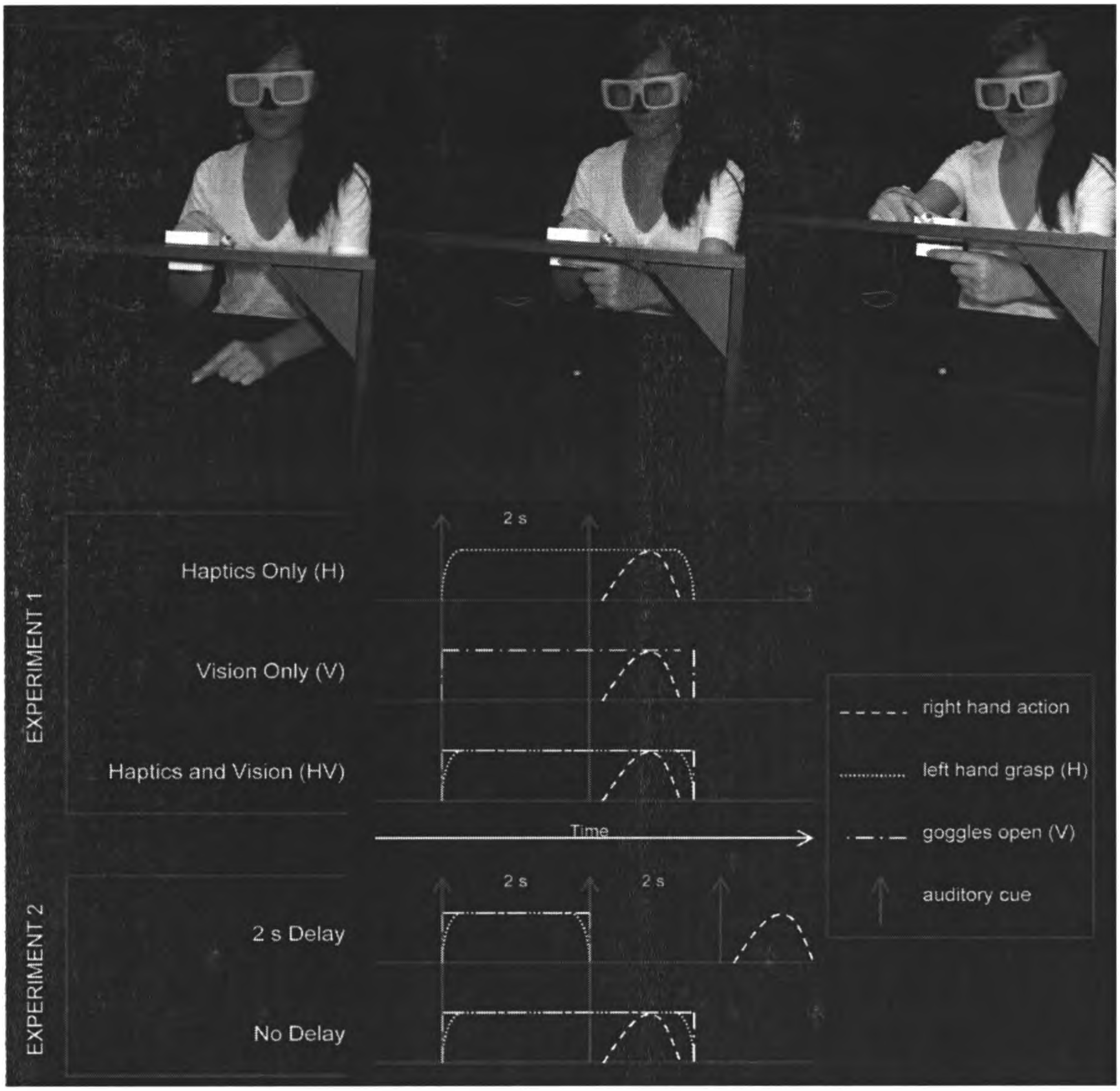

Figure 2-1 *Apparatus and protocols for Experiments 1 and 2.* Blocks were mounted in corresponding positions on the top and bottom surfaces of an elevated platform. Blocks were connected via doweling that passed through the centre of the platform. In the haptic conditions, participants used the left hand to grasp the block mounted to the underside of

the platform to receive size information. The right hand was used to either grasp or estimate the size of the block mounted to the top of the platform. For vision conditions, goggles opened to allow participants to view the block mounted to the top of the platform. Every condition in Experiment 2 involved both haptics and vision. Pictured above is the sequence of one no delay grasping trial of Experiment 2. Here, the participant is using both haptics and vision to guide a reach-to-grasp toward the visual target while unaware of the discrepancy between the haptic and visual information. For estimation trials, the right hand remained at the start location and participants separated their index finger and thumb to the perceived size of the block. Below, conceptual diagrams illustrate each of the relevant conditions in Experiments 1 and 2. Arrows indicate when participants received auditory cues to look or act on objects. Dashed curves signify the action of the right hand (grasping or manual estimation) in response to the preceding auditory cue

The stimulus array consisted of six sets of wooden blocks. Each set contained two square blocks of equal size, one attaching to the top surface of the platform and the other to the bottom surface of the platform. Blocks were 15 mm high and 10, 20, 30, 40, 50 or 60 mm in both length and width. Participants wore Liquid Crystal Display (LCD) goggles (PLATO, Translucent Technology, Toronto Canada) to control vision of the top block.

During grasping trials, participants were required to reach toward the block mounted on the top surface of the platform and grasp the block by placing the index finger and thumb of the right hand on the back and front surfaces respectively. When estimating, participants were instructed to match the opening between their index finger and thumb to the perceived size of the target object. When participants believed they had achieved the correct size, they notified the experimenter who then initiated data collection. Participants were instructed to move as quickly and as accurately as possible when performing all actions.

In the H condition, participants began trials with their right index finger and thumb pressed together on the start button, which was located on the top surface of the platform. Participants rested the left hand in the same posture on a table directly beneath the position of the right hand. The LCD goggles remained closed for the entire duration of each H trial. An auditory beep cued participants to grasp and hold the block mounted on the underside of the platform using their left index finger and thumb. Following a 2-s delay, a second beep signaled participants to initiate either a reach-to-grasp or a manual estimation with the right hand. Participants completed the movement while still holding the block mounted on the underside with the left hand. In the V condition, the hands started in the same positions, but the left hand remained on the table top. Instead of using the left hand to receive size information, the goggles opened simultaneously with the first beep, allowing participants to see the block mounted on top of the platform. After viewing for 2-s, participants received the second beep, which again cued the right-handed grasp or estimation. The goggles remained open during the course of the action and closed afterward in preparation for the next trial. The HV condition was a simply a combination of the two previous conditions. Participants both viewed the top block and held the bottom block with the left hand for a 2-s period following the first beep. Participants then performed the action at the sound of the second beep while still viewing the top block and holding the bottom block with the left hand. Accordingly, sensory information for both haptic and visual cues was available throughout the movement; in other words, all actions were performed in closed-loop.

Hand movements were recorded using an OPTOTRAK 3020 system (NDI, Waterloo, ON, Canada). Infra-red emitting diodes (IREDs) were positioned on the index finger, thumb and index knuckle of the right hand. IRED positions were sampled at 200 Hz for 4 s following the auditory cue to act. Grasping actions were sampled based on the velocity of the knuckle IRED. Movement onset and offset were said to occur when velocity exceeded 20 mm/s and fell below 20 mm/s for five consecutive data points (or 25 ms).

Trials were presented in blocks for each of the six conditions (grasping or estimating under H, V, or HV guidance). The order of the two tasks (grasping and estimation) was counterbalanced between participants. The order of the three experimental conditions within each task (H, V, or HV guidance) was determined pseudo-randomly. For each of the six conditions, the six possible stimulus sizes were presented in random order with four repetitions of each. This amounted to 24 grasping trials and 24 estimation trials in each experimental condition, for a total of 144 trials. At the end of the experiment, seven calibration trials were collected to measure the distance between each participant's finger and thumb IREDs in the starting posture and when holding each of the six block sizes. The value for the initial closed grip was subtracted from all aperture measures for each participant to help reduce the variability due to IRED positioning.

Experiment 2

We employed a 2 x 3 x 2 design in which the kinematics of the right hand were measured while participants either grasped or manually estimated the size of wooden blocks for which the relative haptic size (felt by the left hand) was smaller than, larger than, or the same as the visual size, under conditions of no-delay or a 2-s delay. Participants were unaware of the potential differences in relative size.

The stimulus array consisted of two visually presented target blocks (50 and 60 mm blocks from Experiment 1), which were mounted on top of the platform, and five haptically presented blocks (45, 50, 55, 60, and 65 mm), which were mounted in a corresponding position on the underside of the platform. Only trials with combined haptic and visual information were presented, similar to the HV trials from Experiment 1. However, in this experiment, the top and bottom blocks were mismatched on two-thirds of the trials such that the block viewed on top was either 5-mm larger or 5-mm smaller than that which was felt with the left hand. In addition, half of the actions in this experiment were made after a 2-s delay where participants lost both vision (via the closing of the goggles) and haptics (by returning their left hand to the start position). A final beep cued participants to perform right-handed reach-to-grasp actions or right-handed estimations using the techniques described in Experiment 1.

Block sizes were chosen based on the results of a separate pilot experiment where participants had to explicitly identify the mismatched set of blocks in a two-alternative forced-choice paradigm. A relative size difference of 5 mm between the seen and felt blocks produced near chance performance in this paradigm and was thus adopted in Experiment 2. At the outset of the experiment, participants were explicitly told that the block they were seeing was the same size as that which they felt underneath. As part of the experimental debriefing, participants were asked a series of questions aimed at determining whether they noticed the discrepancy between seen and felt blocks. Indeed, none of the 17 participants were aware of the mismatch, though each was informed of the deception afterward.

Conditions were pseudo-randomized to control for potential order effects. Within each of the conditions, the two target sizes (50 and 60 mm) alternated to make it less likely that the participants would notice the changes in haptic block size. Relative haptic size varied randomly between trials. Within each combination of task (grasping or manual estimation) and delay (no-delay or 2-s delay), there were six possible stimulus pairs (two visual sizes with three relative haptic sizes), with four repetitions of each. This amounted to 24 trials in each condition, for a total of 96 trials. At the end of the experiment, three calibration trials were collected to measure the distance between participants' finger and thumb IREDs in the start posture and when holding each of the target blocks. Again, the value for the initial closed grip was subtracted from all aperture measures for each participant to help reduce the variability due to IRED positioning.

Data analysis

Grip aperture was calculated by computing the difference between the three-dimensional positions of the IREDs on the index finger and thumb (resultant grip aperture). Peak grip aperture was the largest value assumed by the grip aperture measurement during the 4-s time series. Other kinematic measures reported include time to maximum aperture, peak velocity, time to peak velocity and movement time. Since movement time varied in consistent and important ways between conditions, time was not normalized for measures of time to maximum aperture and time to peak velocity. For estimations, aperture was taken to be the difference between the positions of the index finger and thumb IREDs during the first time point collected after participants verbally reported completing the estimation. In addition to examining mean grip aperture, we also examined variability of grip aperture using standard deviations. Data were analyzed using a repeated-measure analysis of variance (ANOVA). Only significant differences between means ($p < 0.05$) and trends toward significance ($p < 0.1$) are reported. Where main effects or interactions were found to violate sphericity, reported values for degrees of freedom and the F-statistic were based on a Greenhouse-Geisser correction. Significant interactions were followed-up with tests for simple main effects and subsequent pairwise comparisons were adjusted using Tukey's honestly significant difference (HSD) correction.

Results

Experiment 1

It is widely known that both maximum grip aperture and estimation aperture scale with object size. Here, we investigated not only size scaling, but how scaling varies as a function of the type of sensory information used to program the movement. Refer to Figure 2-2a for a depiction of the raw aperture data averaged across all participants. For the purpose of analysis, lines of best fit were applied to the data for each of the three experimental conditions (H, V and HV) and values for slope and *y*-intercept were analyzed using separate ANOVAs for grasping and estimation trials. The ANOVA contained a single factor (modality) with three levels (H, V and HV). Figure 2-2b and 2-2c display slope and *y*-intercept values averaged across all participants. Correlation coefficients were calculated for each individual, averaging 0.95 for grasping actions (range 0.59 to 0.99) and 0.98 for manual estimations (range 0.92 to 0.99).

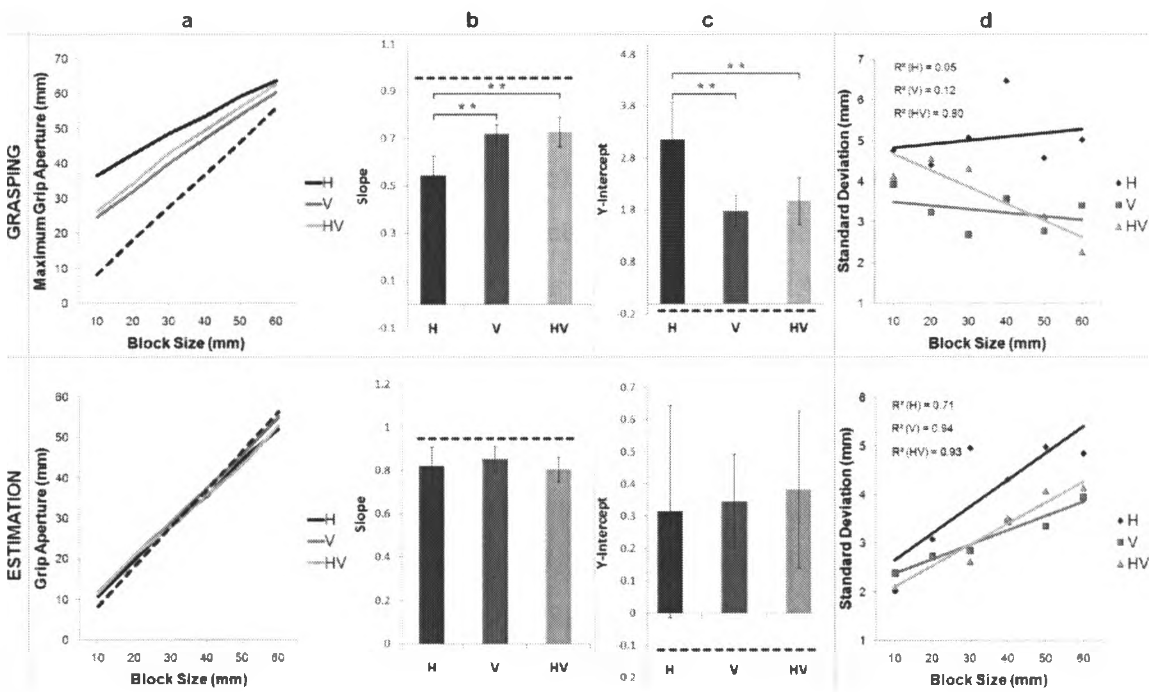

Figure 2-2 *Experiment 1 results.* Panel *a* illustrates the averaged raw data for grasp aperture and estimation aperture for each of the three experimental conditions (vision only, haptics only and haptics and vision) and for calibration trials, represented by the

dotted line. Calibration trials measured the distance between participants' finger and thumb positions while they held each of the six block sizes (10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 60 mm). Panels *b* and *c* depict the averaged slope and *y*-intercept values for regression lines fitted to each experimental condition for each participant. Again, dotted lines signify the averaged values of the slopes and *y*-intercepts for calibration trials, and error bars represent the 95% confidence interval around the mean. Panel *d* depicts standard deviations of grip aperture averaged across subjects, with separate regression lines and corresponding coefficients of determination for each experimental condition. (*$p < 0.05$, **$p < 0.01$)

In all conditions, maximum grip apertures for grasping were larger than the object size and scaled with object size; however, participants opened their hands wider in the H condition than in the V or HV conditions, which were comparable to each other. The *y*-intercept reflects the degree to which subjects oversized their grip relative to the final grip aperture (when contacting the object) indicated by the calibration line. There was a significant effect of modality on *y*-intercept values ($F_{(1,14)} = 15.65$, $p < 0.01$). Post hoc tests revealed significant differences between the H and V conditions ($t_{(11)} = 4.15$, $p < 0.01$) and the H and HV conditions ($t_{(11)} = 4.22$, $p < 0.01$), but not the V and HV conditions. A higher *y*-intercept for the H condition suggests that participants were opening their hands wider, which is a common characteristic of the uncertainty demonstrated when grasps are made without visual feedback. A positive slope indicates that grip aperture scaled with object size, as it did for each of the three conditions. However, there was also a difference in slope between the H condition and both the V and HV conditions. Specifically, there was a significant effect of modality on the slope ($F_{(2,22)} = 13.43$, $p < 0.001$), where post hoc tests revealed significant differences between the H and V conditions ($t_{(11)} = 4.05$, $p < 0.01$) and the H and HV conditions ($t_{(11)} = 4.65$, $p < 0.01$), but not the V and HV conditions. Significant differences between slopes indicate an interaction between modality and object size, whereby the larger grip apertures observed in the H condition approached aperture values observed in the V and HV conditions as object size increased. Given that increased grip apertures are typically thought to reflect the uncertainty of the grasp (Wing et al. 1986; Loftus et al. 2004), these patterns suggest that uncertainty was greatest for the haptic conditions and comparable for the two conditions in which vision was available. Greater uncertainty in the H condition was demonstrated by the significantly higher *y*-intercept in the linear model describing grip aperture as a function of object size.

When estimating, on the other hand, participants showed no differences between any of the experimental conditions. Indeed, the lines representing each of the experimental conditions overlapped with one another and with that of the calibration trials, suggesting that estimation aperture scaled almost perfectly with actual object size. Importantly, however, grip aperture for grasping reflects the margin of error that participants allow for uncertainty, but grip aperture for estimation simply reflects the accuracy of the estimate. In other words, uncertainty in an estimation task is not reflected in the aperture, but rather its variability. To investigate whether uncertainty was higher for H than V and HV conditions (as it was for grasping), we evaluated the standard deviations (SDs) for the estimation task (Figure 2-2d). These were calculated for every block size and experimental condition for each subject and were submitted to an ANOVA with separate factors for object size and modality. Results showed a main effect of modality ($F_{(2,22)} = 4.86, p < 0.05$) with estimations in the H condition showing significantly more variability than those in both the V ($t_{(11)} = 2.84, p < 0.05$) and HV ($t_{(11)} = 3.09, p < 0.05$) conditions. Thus, as with grasping data, uncertainty for estimation was highest for the H condition, compared to the V and HV conditions. Similarly, when we investigated SDs for the grasping task, we also found a main effect of modality ($F_{(2,22)} = 9.91, p < 0.01$), where, again, grasps in the H condition showed more variability than those in both the V ($t_{(11)} = 3.78, p < 0.01$) and HV ($t_{(11)} = 2.86, p < 0.05$) conditions.

In order to address the dissociation in Weber's law between perception and action advanced by Ganel et al. (2008), it is useful to consider the effect of size on SDs for each of the two tasks. For estimation, there was a main effect of size ($F_{(5,55)} = 11.17, p < 0.001$) such that variability was greater for larger blocks, however there was no interaction. Thus, haptically guided estimation (and the combination of haptically and visually guided estimation) follows Weber's law, as does visually guided estimation. For grasping, there was no main effect of size; however, there was an interaction between size and modality ($F_{(10,110)} = 2.1, p < 0.05$). Post hoc analysis of the interaction revealed no effect of size in either the H or V conditions, indicating that haptically guided grasping, like visually guided grasping, does not follow Weber's Law. Surprisingly, we found a significant main effect of size in the HV condition ($F_{(5,55)} = 2.88$, $p < 0.05$) such that variability decreased with increasing size. It is necessary to note that assessing adherence to Weber's Law through examination of standard deviations is not a standard test for Weber's Law. By describing the pattern of variability across object sizes, we are merely testing whether participants are conforming to the general trend that Weber's Law describes, which is decreasing sensitivity to changes in object size as the magnitude increases. We do not determine whether this decreasing sensitivity is proportional to changes in object size.

Kinematic measures associated with grasping actions also showed no differences between the V and HV conditions (Figure 2-3). Movement time, which began at liftoff and ended with object contact, showed main effects of both size (Means: 10 mm, 670 ms; 20 mm, 697 ms; 30 mm, 662 ms; 40 mm, 654 ms; 50 mm, 644 ms; 60 mm, 643 ms; $F_{(5,55)} = 3.78$, $p < 0.01$) and modality (Means: H, 722 ms; V, 632 ms; HV, 625 ms; $F_{(2,22)} = 14.27$, $p < 0.001$). Post hoc analysis of the main effect of modality showed that participants took significantly longer in the H condition than in both the V ($t_{(11)} = 3.77$, $p < 0.01$) and the HV ($t_{(11)} = 5.22$, $p < 0.001$) conditions. However, there was no difference between the movement times of the V and HV conditions. Qualitative inspection of the main effect of size suggested that participants took longer to grasp blocks of a smaller size. Peak velocity showed a significant main effect of both size (Means: 10 mm, 789 mm/s; 20 mm, 789 mm/s; 30 mm, 801 mm/s; 40 mm, 809 mm/s; 50 mm, 827 mm/s; 60 mm, 830 mm/s; $F_{(5,55)} = 9.83$, $p < 0.001$) and modality (Means: H, 759 mm/s; V, 815 mm/s; HV, 848 mm/s; $F_{(1,14)} = 5.36$, $p < 0.001$). Post hoc tests on the main effect of modality revealed that participants had higher peak velocities in the HV condition than in the H condition ($t_{(11)} = 5.78$, $p < 0.001$). Velocities in the V condition fell in between those of the other two conditions, but they were not significantly different from either. Qualitative analysis revealed that as blocks became larger, participants moved faster, which is consistent with the decreased movement time that followed increases in block size. Time to peak velocity also showed a significant main effect of modality (Means: H, 287 ms; V, 274 ms; HV, 266 ms; $F_{(2,22)} = 3.58$, $p < 0.05$), but no effect of size. Similarly, post hoc tests revealed a difference only between the H and HV conditions ($t_{(11)} = 3.59$, $p < 0.05$), with peak velocities occurring later in the H condition. Time to peak aperture did not show any significant main effects, although size showed a trend toward significance ($p = 0.079$). Qualitative analysis of this effect showed that as the size of the block increased, participants appeared to take longer to reach maximum grip aperture. Finally, there was no interaction between modality and size for any of the variables listed above.

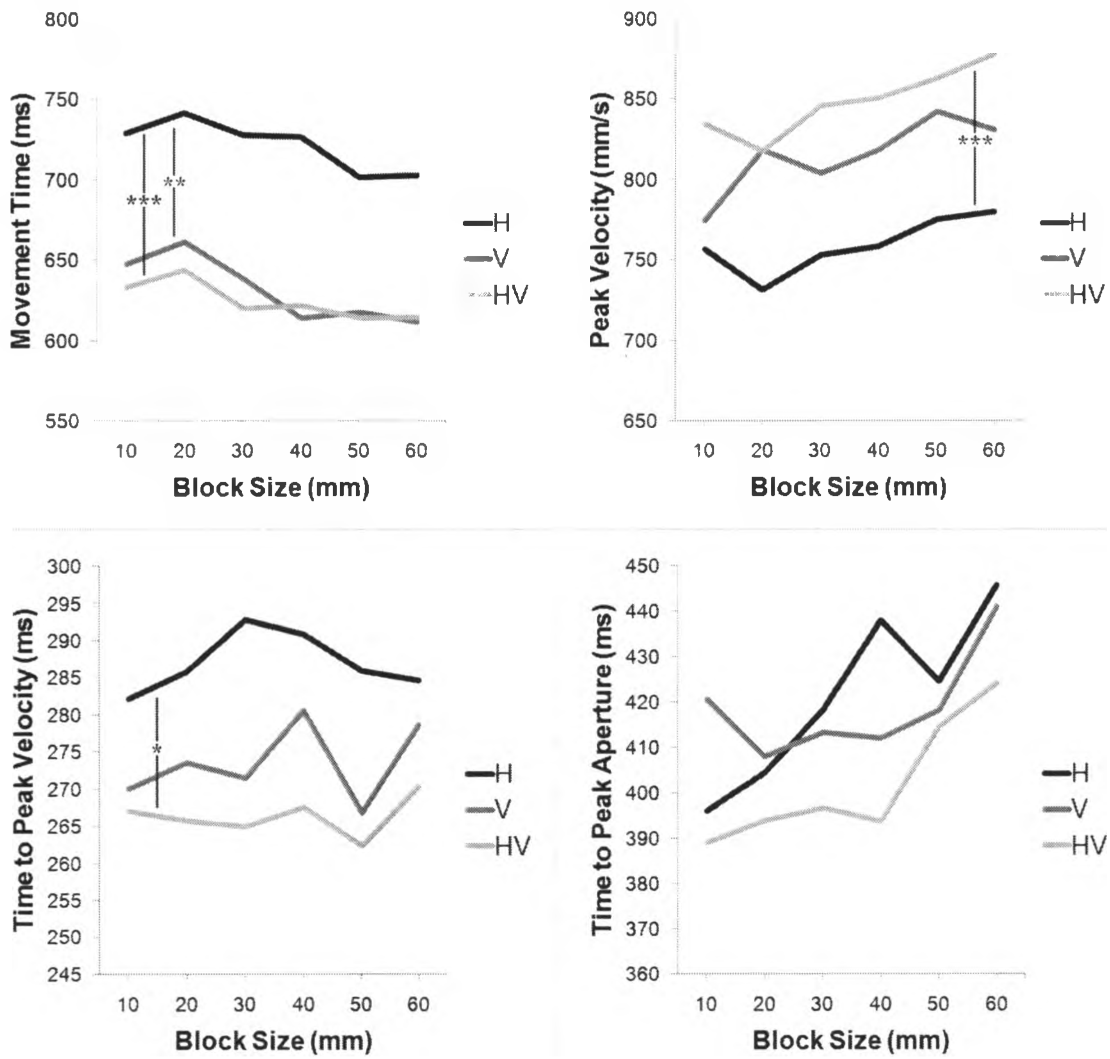

Figure 2-3 *Experiment 1 grasping kinematics.* Movement time, peak velocity, time to peak velocity and time to peak aperture as a function of block size. (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$)

In summary, analysis of kinematic variables strengthens the conclusion that the combination of haptic and visual information does not produce a significant difference in either grasping or estimation when compared to performance under visual guidance alone. Furthermore, when under the guidance of haptics alone, participants generally open their grip wider, take longer and move slower than in the other conditions.

Experiment 2

Data were analyzed using separate ANOVAs for grasping and estimation trials. Each ANOVA contained factors for delay (no-delay, 2-s delay), visual size (50, 60 mm) and relative haptic size (smaller, same, or larger than visual size). Refer to Figure 2-4a for averaged grasp and estimation apertures as a function of relative haptic size. When grasping, there was a main effect of relative haptic size ($F_{(2,32)} = 5.77, p < 0.01$) where participants opened their grasp wider for target blocks paired with the larger haptic blocks than targets paired with either the same sized block ($t_{(16)} = 3.28, p < 0.05$), or a haptic block of a smaller size ($t_{(16)} = 3.46, p < 0.05$). There was also a significant main effect of delay, where the introduction of a 2-s delay caused people to open their grasp wider than in the no-delay condition ($F_{(1,16)} = 8.21, p < 0.05$). However, there was no interaction between delay and relative haptic size. As expected, participants opened their grip wider for blocks of a larger visual size ($F_{(1,16)} = 78.03, p < 0.001$), yet the interaction between visual size and relative haptic size was also not significant. Participants also showed a main effect of relative haptic size when estimating ($F_{(2,32)} = 3.40, p < 0.05$). Post hoc tests revealed that participants estimated target blocks paired with larger haptic blocks to be larger than targets paired with smaller haptic blocks ($t_{(16)} = 2.46, p < 0.05$); however, neither condition differed significantly from the intermediate condition in which target blocks were the same size as haptic blocks. Unlike grasping, participants did not show a main effect of delay. In addition, there was no interaction between delay and relative haptic size. Analysis revealed a predictable main effect of visual size ($F_{(1,16)} = 134.22, p < 0.001$) , where the larger 60-mm target block was estimated to be larger than the 50-mm target block. However, this effect of visual size did not interact with relative haptic size or delay.

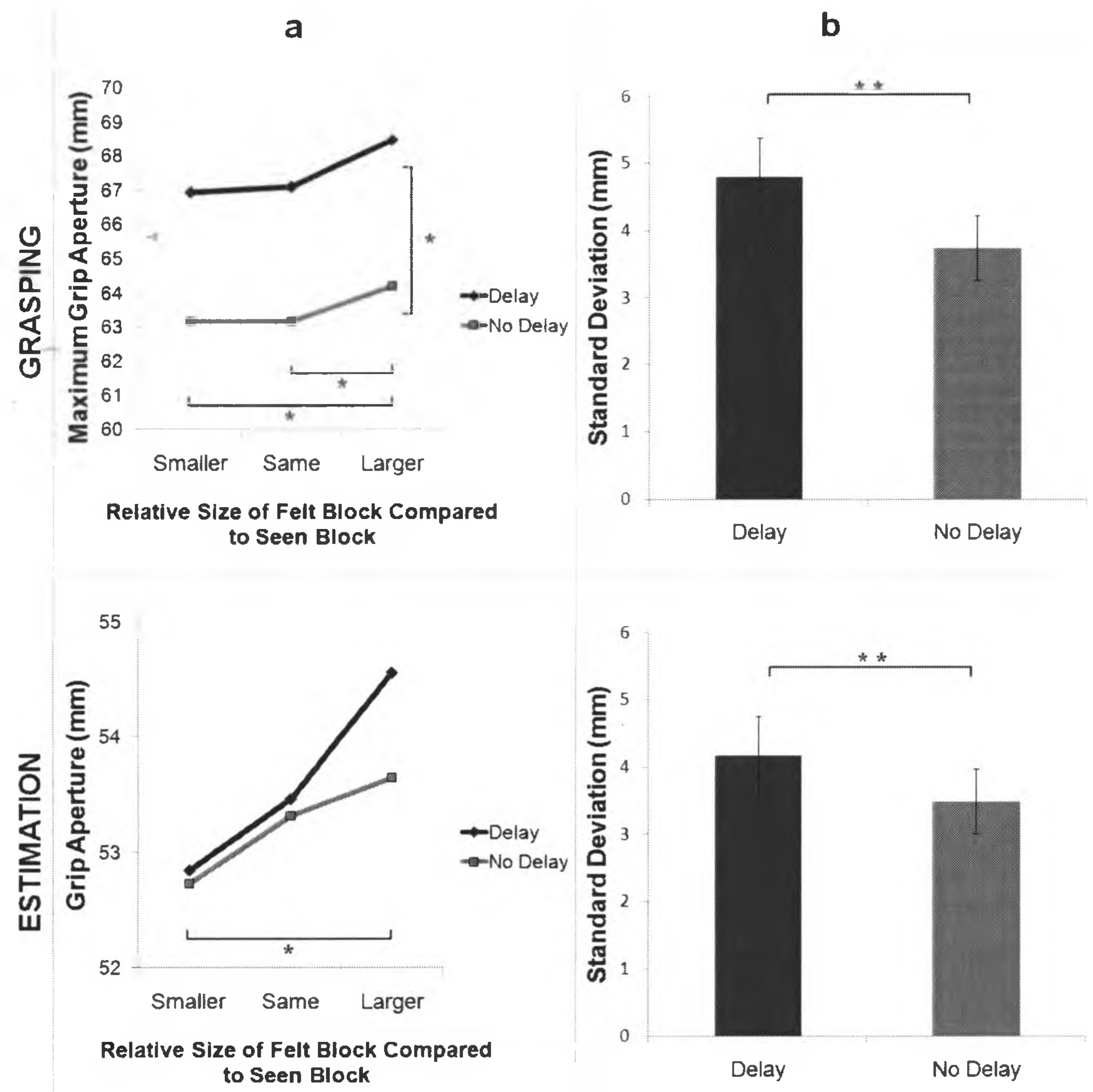

Figure 2-4 *Experiment 2 results.* Panel *a* depicts the grasp aperture and estimation aperture for real-time and delayed performance as an effect of the relative size of the felt block compared to the seen block. Data are collapsed across the 50 mm and 60 mm target sizes. Although only grasping showed a main effect of delay, separate lines for the 2 s delay and no delay conditions are shown for estimation as well. Panel *b* illustrates standard deviations of grip aperture averaged across subjects for the 2 s delay and no delay conditions. (*$p < 0.05$, **$p < 0.01$)

Again, an analysis of standard deviations was conducted on grip apertures for both grasping and estimation data to determine (1) whether estimations showed the same increase in uncertainty following a 2 s delay that can be inferred from the main effect of delay in grasping and (2) whether the introduction of incongruence between haptic and visual stimuli results in more variable grip apertures (Figure 2-4b). Analyses indicated a main effect of delay in both grasping ($F_{(1,16)} = 14.8, p < 0.01$) and estimation ($F_{(1,16)} = 11.21, p < 0.01$), with participants producing more variable grip apertures following the delay. However, there was no effect of relative haptic size in either grasping or estimation, suggesting that certainty was unaffected by the manipulation of congruency.

Other measured kinematic variables showed no sensitivity to either relative haptic size or visual size. However, the introduction of delay produced a longer overall movement time (Means: 2-s delay, 705 ms; no-delay, 619 ms; $F_{(1,16)} = 48.27, p < 0.001$), a lower peak velocity (Means: 2-s delay, 712 mm/s; no-delay, 825 mm/s; $F_{(1,16)} = 45.39$, $p < 0.001$), and caused the time of peak velocity (Means: 2-s delay, 290 ms; no-delay, 274 ms; $F_{(1,16)} = 4.55, p < 0.05$) and of maximum grip aperture (Means: 2-s delay, 434 ms; no-delay, 402 ms; $F_{(1,16)} = 6.31, p < 0.05$) to occur later in the movement.

Discussion

When haptic and visual information about object size is congruent, both perceptual and grasping performance based on the combination of the two senses is no better than performance under vision alone. When the information from the two senses is incongruent, however, the influence of haptic information is revealed. Since responses based on haptics alone show a larger degree of uncertainty than those based on vision alone, we might conclude that, for redundant information, the relative contribution of the senses when in combination is weighted by the certainty associated with each modality, such that vision appears to dominate. But despite the lesser degree of certainty provided by haptics, when the sensory cues are in conflict, an influence of haptic information becomes apparent.

Our results help to reconcile inconsistent results from past studies. When vision and haptics are veridical and consistent, vision influences performance more than haptics (Teghtsoonian and Teghtsoonian 1970; Rock and Victor 1964), but when the quality of visual information is degraded (Ernst and Banks 2002; Helbig and Ernst 2007) or inconsistent with haptics (Gentilucci et al. 1995, 1998; Kritikos et al. 2002) available haptic information does indeed affect performance. Here, we have directly compared cases in which the cues either agree or disagree and found that the conclusions depend critically on this variable. Moreover, we have found that this is not simply a carryover from previous trials (as in Gentilucci et al. 1995); it also occurs when information from the two senses is available simultaneously. Furthermore, we show that integration between vision and haptics occurs when multi-modal information comes from the two hands interacting with an object at a single location rather than two disparate locations (Gentilucci et al. 1998; Kritikos et al. 2002). However, one remaining question concerns the strength of this effect when the two sensory percepts belong to a single object versus multiple objects.

Surprisingly, in Experiment 1, we found few differences between the senses and their integration on perception versus action tasks. Maximum grip aperture is larger when grasping objects based on haptic cues alone than visual cues alone or combined cues, indicating that participants allow a greater margin of error when grasping under only haptic guidance. Consistent with the reduced certainty implied by increased grasp apertures, the purely haptic condition also yields lower peak velocities and longer movement times than the purely visual and combined conditions. Although no increase in grip aperture was observed for manual estimates of size (as reflected by the *y*-intercept), greater perceptual uncertainty should produce more variable estimates rather than larger estimates. Indeed, variability was greatest for haptically guided estimations (as well as for haptically guided grasps). Thus, we can conclude that the haptic modality provides significantly less certain information than does vision, providing a plausible explanation for why haptics appeared to assert no influence in the HV condition of Experiment 1.

However, the incongruent cues introduced in Experiment 2 revealed a distinct influence of haptic information on both perceptual and action tasks, even though participants were entirely unaware of the inconsistency. For real-time performance, both perception and action showed comparable influences of incongruent haptic information. That is, participants were taking into consideration both the haptic and visual size cues when scaling their grasp and estimation apertures. We therefore suggest that haptic and visual information is integrated at some stage of sensorimotor processing; however, our work alone cannot determine the stage at which the information is combined. Although our purely behavioral data cannot speak directly to this question, there is ample evidence from neurophysiology and neuroimaging that show areas within parietal cortex, such as a grasp-related area in the anterior intraparietal sulcus (Grefkes et al. 2002), as well as areas in the temporal cortex (Amedi et al. 2001) that contain inputs from both modalities. Given that these regions are important for discerning the location and shape of objects, it would be surprising if information from haptics and vision did not converge prior to the generation of motor commands.

One important difference between the results for grasping and those for estimation is that estimates showed a steady increase in grip aperture as relative haptic size changed from smaller to same and from same to larger (though these differences did not quite reach significance), while maximum grasp aperture did not appear to change as relative haptic size moved from smaller to same, but only when moving from same to larger. We suggest that this result not only provides support for the notion that haptic and visual information is being integrated, but also that haptics and vision are being integrated in an optimal fashion when considering the goal of the task. When participants reach-to-grasp an object that is accompanied by a haptic block of a relatively smaller size, they appear to err on the side of scaling their grip to the larger of the two objects, permitting extra "room for error". In other words, if they were to scale their grip toward the smaller haptic size, then they run the risk of failing at grasping the object. Of course, participants are not making this decision consciously, as they believe the blocks are the same size. Thus, it is an unconscious decision made by the motor system to utilize the information that promises a greater probability of success. This interpretation is also consistent with the increase in aperture that we observe when grasping a target paired with a haptic block of a relatively larger size. Finally, we would not expect such a trend when estimating size because the goal of the task has changed; rather than having to successfully perform a grasp, participants only had to accurately represent object size. This likely involves a combination of the information provided by both haptics and vision, rather than a more strict decision about which source to use.

We also hypothesized that the weighting of haptic and visual information might change after the introduction of a 2-s delay. If it is the case that haptic information persists to a greater degree than visual information, we might expect to see greater deviations from the visual target's size when the target is paired with an incongruent haptic block in 2-s delay condition versus the no-delay condition. Although there was a trend in this direction for both grasping and estimation (with greater discrepancies between apertures in the incongruent vs. congruent trials following the delay), there was no significant interaction between delay and relative haptic size in either grasping or estimation tasks. However, delay did affect the magnitude of grip apertures for grasping, but had no influence on manual estimates of size, consistent with previous research (Westwood et al. 2001; Westwood and Goodale 2003; Hu and Goodale 2000). Delay also led to greater variability for both grasping and size estimation. As in Experiment 1, uncertainty was manifested in different variables for the two tasks (increased grip apertures for grasping and increased grip variability for estimations), but uncertainty was always greatest when guided by haptics alone for both perception and action tasks.

Although not an original goal of our experiment, the data was amenable to investigating Weber's law in the haptic domain. In Experiment 1, we found that with haptics alone, as with vision alone (Ganel et al. 2008), Weber's law is upheld by perceptual estimates of size (i.e., variability increases with size) but violated when size is used to guide grasping (i.e., variability remains constant across sizes). However, when performing under the guidance of both modalities simultaneously, we observed a surprising decrease in the variability of grasp aperture with increasing size, while estimation apertures showed a predictable increase in variability following increases in object size. In the variability measures for our second experiment, we did not find an interaction between object size and delay during haptically guided grasping, as found with vision (Ganel et al. 2008); however, only two similar sizes were tested and the design was not optimal for addressing this question.

Altogether, our results show that haptic processing follows similar principles (including Weber's law) to vision, albeit with less sensitivity in general. Because of its weaker sensitivity, the addition of haptics to vision has a negligible effect on performance when the two senses agree; however, when a cross-modal discrepancy is introduced, the influence of haptics becomes apparent.

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CHAPTER 3: Differential effects of delay upon visually and haptically guided grasping and perceptual judgments[2]

Introduction

Converging evidence suggests that there are two dissociable streams of visual projections in the cerebral cortex of the primate brain: a dorsal 'action' stream and a ventral 'perception' stream (Milner and Goodale 1995). Although the early evidence for this dissociation came from neuropsychological studies of patients and neurophysiological studies in the macaque monkey, researchers have also used visual illusions to investigate the separable functions of the dorsal and ventral streams in normal observers. Thus, people show accurate scaling of their grasp when picking up objects presented within the context of size–contrast illusions such as the Ebbinghaus or Ponzo illusion, scaling the opening of their grip in flight to the real and not the perceived size of the object (Aglioti et al. 1995; Haffenden and Goodale 1998; Ganel et al. 2008). Of course, when they use their hands to simply estimate the size of the object, they fall victim to the illusion, presumably because this manual estimate is based on their perception of the object's size. Although not without controversy, the literature on grasping in the context of illusions is largely consistent with the dual pathway model (Goodale et al. 2004; Goodale 2008).

Although the dorsal stream appears to play a major role in the programming and control of visually guided actions in real time, things change when a delay is introduced between seeing the target object and initiating the action. When targets are presented in the context of a size–contrast illusion, and a delay is introduced between seeing the display and reaching out and grasping the target, the scaling of grip aperture becomes susceptible to the illusion. Specifically, participants opened their grasps wider when the target object was presented with a smaller flanker object after a delay and narrower when the target object was presented with a larger flanker object (Hu and Goodale 2000; Westwood and Goodale 2003a). The authors argued that in delayed grasping, participants were forced to rely on their perceptual memory of the target's size which was

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[2] A version of this chapter has been published (Pettypiece, C. E., Culham, J. C., & Goodale, M. A. (2009). Differential effects of delay upon visually and haptically guided grasping and perceptual judgments. Experimental Brain Research, 193(3), 473-479).

influenced by the perception of the relative difference in size between the target and the flanker object. These observations, together with findings from a broad range of studies, have led to the idea that the planning of movements after a delay relies on perceptual mechanisms in the ventral stream, which make use of relational metrics in a scene–based coordinate frame (Goodale et al. 2004; Bruno et al. 2008; but see, Franz et al. 2009).

More recently, researchers have begun to explore possible dissociations between action and perception in other sense modalities. Westwood and Goodale (2003b) investigated whether haptically guided grasping showed the same resistance to size–contrast illusions as visually guided grasping. In their study, participants were first asked to hold two blocks one after the other with their left hand while keeping their eyes closed. Participants were then asked to use their right hand to either grasp or estimate the size of the second block, referred to as the target block, while continuing to hold it with their left. The first block, referred to as the flanker block, was either the same size, larger, or smaller than the target block. Westwood and Goodale (2003b) observed a pattern of results that mirrored those of the visual size–contrast illusion. Specifically, participants' grasps were unaffected by flanker size, whereas their estimates were often influenced by the difference in size between the flanker and the target block. Based on these results, Westwood and Goodale (2003b) argued that haptic perception like visual perception employs relative metrics, while haptically driven actions, like their visually driven counterparts, make use of the real metrics of the world.

But how far does this parallel between haptics and vision extend? For example, would haptically guided grasping after a delay show the same sensitivity to size–contrast illusions as visually guided grasping does? There is certainly evidence that using somatosensation to identify the shape of objects and their location involves neural circuits that are distinct from those mediating the somatosensory control of actions (Anema et al. 2009; Dijkerman and de Haan 2007). One might expect therefore that haptically guided grasping after a delay will rely on a memory of the goal object's size that is laid down by the somatosensory networks involved in object identification rather than in action control. Westwood and Goodale (2003b) showed that haptic perception of size, just like visual perception of size, uses relative rather than real–world metrics. Consequently, delayed grasping driven by perception–based somatosensory memories should be as susceptible to size–contrast illusions as delayed grasping driven by perception–based visual memories.

The present study sought to investigate this question by building upon the methods of Westwood and Goodale (2003b) and introducing a delay prior to initiating either a grasping movement or a manual estimation of the target object's size. In the delay condition, participants were instructed to release their left hand from the target object 2 s before grasping or estimating the size of the object with their right hand. A delay time of 2 s was chosen because 2 s has previously been shown to produce a robust effect when grasping in the context of visual illusions. In parallel with the haptic experiment, we also ran a visual experiment–but to make the two more comparable, the visual study had to be modified from the usual way such experiments are carried out. In the typical visual size–contrast experiment, both the target object and the flanker are presented simultaneously. But in the visual experiment in our study, the target and flanker were presented sequentially, just like they were in the haptic experiment.

Methods

Participants

Twenty right–handed undergraduate students (7 male; mean age of 18.7) with normal or corrected–to–normal vision participated, and received credit towards an introductory psychology course for their participation. Participants provided informed consent in accordance with the local institutional guidelines for ethical research practices. Participants were randomly assigned to one of two experimental groups of ten participants. One group used vision to guide all of their actions, while the other relied on haptics to guide their movements.

Stimuli and Recording of Hand Movements

The stimulus array consisted of two sets of wooden blocks. Each set contained two blocks of equal size, one attaching to the top surface of the apparatus and the other to the bottom surface of the apparatus. Refer to Figure 3-1 for a detailed depiction. The set of blocks presented on the left were considered flanker objects and the set of blocks on the right were the target objects. Target objects were either 5 cm x 5 cm or 7 cm x 7 cm in size and flanker objects were either 4 cm x 4 cm, 5 cm x 5 cm, 6 cm x 6 cm, 7 cm x 7 cm, or 8 cm x 8 cm blocks. Target objects were paired with flankers that were the same size, 1 cm larger or 1 cm smaller in both dimensions. Put another way, there were six possible combinations of sizes: 5 cm target paired with 4 cm, 5 cm or 6 cm flankers; 7 cm target paired with 6 cm, 7 cm or 8 cm flankers. Participants were never told how many objects were used in the study. Target and flanker sizes were varied randomly within trial-blocks, with an equal number of trials for each of the six possible stimulus arrays.

Hand movements were recorded using an OPTOTRAK 3020 system (NDI, Waterloo, Ontario, Canada). Infra–red emitting diodes (IREDs) were positioned on the index finger, thumb and index knuckle of the right hand. IRED positions were sampled at 100 Hz for 5 s following the auditory cue to grasp or estimate. Grasping actions were sampled based on the velocity of the knuckle IRED. Movement onset and offset were said to occur when velocity exceeded 20 mm/s and fell below 20 mm/s for five consecutive data points (or 50 ms).

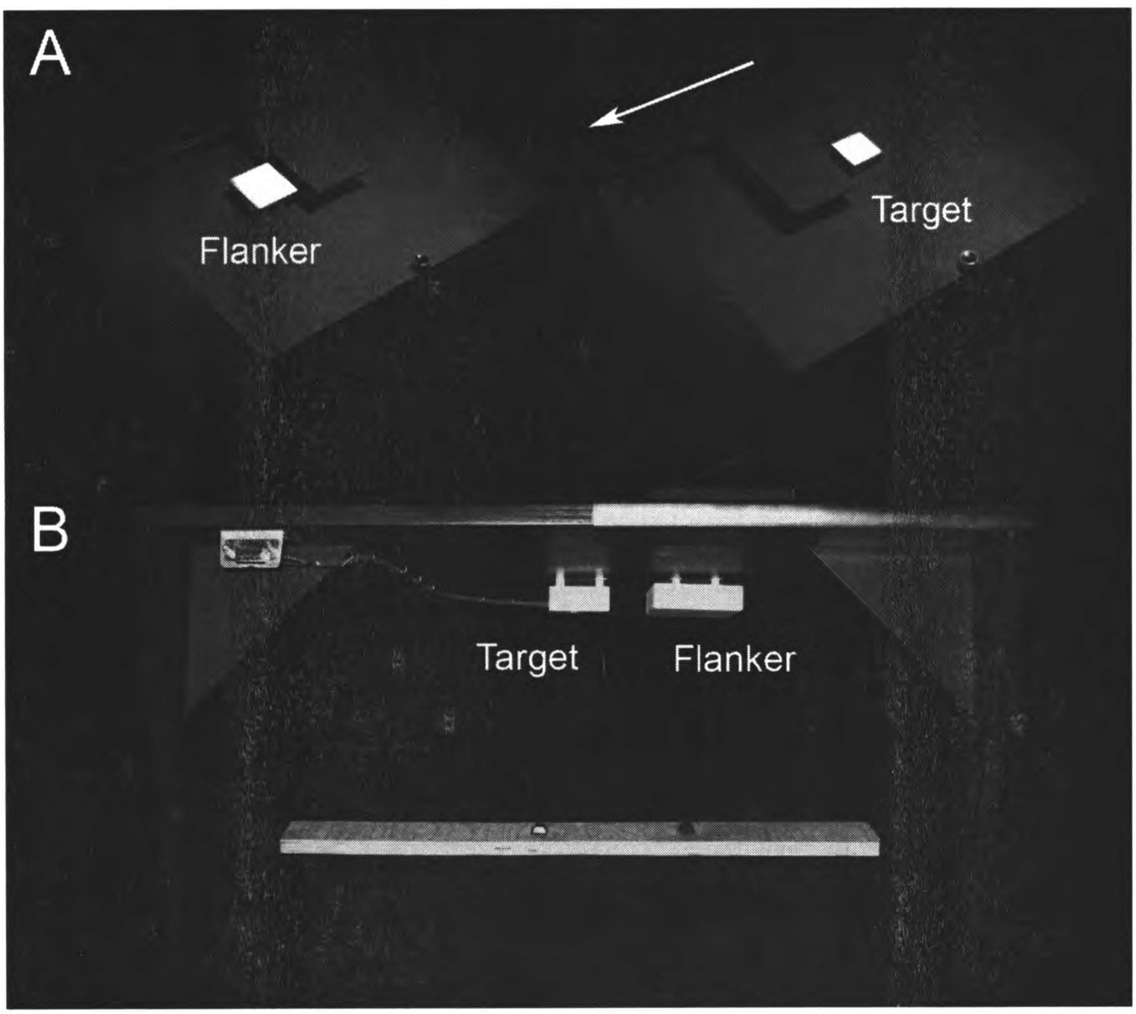

Figure 3-1 *Table apparatus, based on the design used in Westwood and Goodale (2003).* Two sets of blocks (*left* side, flankers; right side, targets) were mounted on the top and bottom surfaces of an elevated table apparatus. Panel A depicts the top surface of the apparatus, while Panel B shows the experimenter's view from behind the apparatus. The right hand was used to either grasp the target block on top of the apparatus, or estimate the size of the target block using the thumb and index finger. In the haptic version of the experiment, the left hand was used to sequentially grasp the blocks underneath the table (first the flanker, then the target) in preparation for the right handed grasp or estimation of the target block. The position of the blocks on the top surface corresponded directly to the position of the blocks on the bottom surface by means of doweling that connected the objects through holes in the table apparatus. In the vision experiment, the participants simply rested the left hand beneath the table while viewing the blocks on the top surface, which were revealed sequentially by the moving a sliding cover depicted in Panel A

Task

In a 2 (no-delay/delay) x 2 (grasp/estimate) design, one group of participants used visual information and the other used haptic information to guide their right-handed actions. In the haptic experiment, participants began trials with their eyes closed with their right index finger and thumb pressed together on the start button and their left hand resting in the same posture directly beneath the flanker object. Participants' eyes remained closed for the entire duration of the trial. An auditory beep cued participants to grasp and hold the flanker object on the underside of the table using their left index finger and thumb. After a 2 s delay, a second beep signaled participants to move their left hand over to the right and grasp and hold the target block for another 2 s. In the no-delay grasping trials, a go–signal beep of a higher pitch signaled participants to execute a right–handed reach–to–grasp of the target block on the top surface of the apparatus (while still maintaining the left–handed grasp directly underneath). In the delayed grasping trials, a third beep signaled participants to release their left–handed grasp of the target object, close their grip, and rest the left hand at a specified position directly beneath the target block. After a 2 s delay, participants heard the go–signal beep, which was their cue to perform the right–handed grasp of the target object. Participants were instructed to move as quickly and as accurately as possible when performing all grasps. The sequence of events for estimation trials was similar. Participants performed right–handed estimations of the size of the target block either while still grasping the target block with their left hand, or after having released the target block for a delay of 2 s. Manual estimations were performed by releasing the start button and, with the right hand still resting on the table apparatus, matched the opening between the index finger and thumb to the perceived size of the target object. When participants believed they had achieved the correct size, they gave the experimenter a verbal signal, at which point the experimenter collected aperture data. Participants were instructed to perform the estimation as quickly and as accurately as possible.

In the vision experiment, participants wore liquid crystal display (LCD) goggles that controlled when they were able to see the stimulus array. Each trial began with the goggles closed (opaque) with the right hand on the start button and left hand resting in their lap (where it remained throughout the experiment). On the first beep, the goggles opened (became transparent) and participants could see the flanker object mounted on the top surface of the table apparatus. After a 2 s delay, a second beep signaled the experimenter to move a sliding cover to hide the flanker block and reveal the target block. Participants viewed the target block for 2 s. In the no-delay grasping trials, the go–signal beep instructed the participants to reach out and grasp the target block with their right hand. The goggles remained open during the grasp. In the delayed grasping trials, a third beep coincided with the closing of the goggles. After a 2 s delay, the go–signal beep instructed the participants to reach out and grasp the target block with their right hand, but in this case without vision. Again, participants were instructed to move as quickly and as accurately as possible when performing all grasps. The sequence of events for estimation trials was the same, and the method used to estimate mirrored that of the haptic experiment. Importantly, in the no-delay estimation trials in the vision experiment, participants were able to see the shaping of their right hand as well as the target block while they were estimating. In the delayed estimation trials, participants saw neither.

In each experiment, the four conditions were blocked and pseudo–randomized such that participants never experienced two grasping blocks or two estimation blocks in a row. Within each block, the six possible stimulus arrays were presented in random order with four repetitions of each. In addition, there were three extra stimulus arrays in each block (6 cm target paired with either a 6, 5 or 7cm flanker), which were repeated only once and made it less likely that the participant would know how many block sizes there were. This amounted to 27 trials in each block, for a total of 108 trials. Participants were also given approximately five practice trials before every block. At the end of each experiment, a calibration trial was recorded to measure the distance between participants' finger and thumb IREDs in the start posture. This value was subtracted from the aperture measures for each participant.

Data Analysis

Grip aperture was calculated by computing the difference between the three-dimensional positions of the IREDs on the index finger and thumb (resultant grip aperture). Peak grip aperture was the largest value assumed by the grip aperture measurement during the 5 s time series. Other kinematic measures were taken but none of these showed any significant differences between conditions within each experiment and will not be discussed further. For estimations, aperture was taken to be the difference between the thumb and index finger IREDs during the first time point collected after participants verbally reported completing the estimation. Data were analyzed using a 2 (no-delay/delay) x 2 (target size) x 3 (flanker size) repeated–measures analysis of variance (RM–ANOVA), alpha = 0.05. Where main effects or interactions were found to violate sphericity, reported values for degrees of freedom and the F–statistic were based on a Greenhouse–Geisser epsilon multiplier. Significant interactions were followed up with tests for simple main effects and all pairwise comparisons were corrected using Bonferroni.

Results

As expected, participants opened their hands wider when grasping the 7 cm target blocks than they did when grasping the 5 cm target blocks in both the haptic experiment (7 cm: $M = 71.67$, $SE = 1.99$; 5 cm: $M = 62.21$, $SE = 2.79$; $F_{(1,9)} = 36.72$, $p < 0.001$) and the vision experiment (7 cm: $M = 81.53$, $SE = 1.46$; 5 cm: $M = 70.54$, $SE = 1.57$; $F_{(1,9)} = 296.84$, $p < 0.001$). Similarly, participants opened their hands wider when estimating the size of the 7 cm target blocks than they did when estimating the size of the 5 cm target blocks in both the haptic experiment (7 cm: $M = 66.27$, $SE = 1.64$; 5 cm: $M = 48.88$, $SE = 2.06$; $F_{(1,9)}=175.96$, $p < 0.001$) and the vision experiment (7 cm: $M = 73.68$, $SE = 1.29$; 5 cm: $M = 55.97$, $SE = 1.67$; $F_{(1,9)} = 424.52$, $p < 0.001$). Participants in the vision experiment had wider peak apertures (vision: $M = 76.04$, $SE = 1.48$; haptic: $M = 66.94$, $SE = 2.30$; $t_{(18)} = 3.33$, $p < 0.01$) and opened their hands wider when estimating (vision: $M = 64.82$, $SE = 1.43$; haptic: $M = 57.58$, $SE = 1.74$; $t_{(18)} = 3.22$, $p < 0.01$) compared to participants in the haptic experiment. However, there were no significant differences in the peak velocity (vision: $M = 674.55$, $SE = 29.65$; haptic: $M = 639.23$, $SE = 34.26$; $t_{(18)} = 0.78$, *ns*) or the time of peak velocity (vision: $M = 41.77$, $SE = 0.88$; haptic: $M = 42.42$, $SE = 1.47$; $t_{(18)} = 0.38$, *ns*) of the grasping movements between the visual and haptic paradigms. Therefore, participants were performing grasps in roughly the same fashion in the two experiments.

In the vision experiment, flanker objects had no effect on either the peak grip aperture (smaller: $M = 76.51$, $SE = 1.67$; same: $M = 75.66$, $SE = 1.45$; larger: $M = 75.94$, $SE = 1.44$; $F_{(2,9)} = 0.98$, *ns*) or the size estimation (smaller: $M = 65.22$, $SE = 1.34$; same: $M = 65.29$, $SE = 1.26$; larger: $M = 63.95$, $SE = 2.00$; $F_{(2,9)} = 0.88$, *ns*). In addition to the lack of main effects, there were no interactions between flanker size and delay or flanker size and target size.

In the haptic experiment, there was a main effect of flanker size for grasping (smaller: $M = 67.15$, $SE = 2.33$; same: $M = 67.47$, $SE = 2.14$; larger: $M = 66.21$, $SE = 2.44$; $F_{(2,9)} = 5.27$, $p<.05$) but not for estimation (smaller: $M = 58.13$, $SE = 1.61$; same: $M = 57.69$, $SE = 1.68$; larger: $M = 56.92$, $SE = 2.08$; $F_{(2,9)} = 1.18$, *ns*). But there was also a significant interaction between flanker size and delay in peak grip aperture ($F_{(2,9)} = 9.88$, $p < 0.01$) and a nearly significant interaction in the estimation task ($F_{(2,9)} = 3.23$, $p = 0.06$). [Although the latter interaction did not quite reach significance, delay and no-delay estimation performance was examined in post-hoc tests in order to assess agreement with previous studies on visual estimation that show size-contrast effects for both delay and no-delay estimation.] Tests for simple main effects revealed flanker effects in no-delay estimation trials ($F_{(2,9)} = 3.67$, $p < 0.05$) and in delayed grasping trials ($F_{(2,9)} = 13.57$, $p < 0.001$), but no flanker effects in delayed estimation trials ($F_{(2,9)} = 0.30$, *ns*) and no-delay grasping trials ($F_{(2,9)} = 2.74$, *ns*). It appears that the factors driving the interaction in grasping trials and those driving the interaction in estimation trials are exactly opposite: peak grip aperture was affected by flanker size only in the delay condition, whereas estimations were affected by flanker size only in the no-delay condition. Although participants' grasps in the no-delay condition were unaffected by flanker size, they tended to estimate targets paired with a smaller flanker as being larger than targets paired with the same sized flanker (smaller: $M = 58.66$, $SE = 1.80$; same: $M = 56.99$, $SE = 1.97$; $t_{(9)} = 3.96$, $p < 0.01$). These results are consistent with the findings of Westwood and Goodale (2003b), who demonstrated that the presence of flankers produced an effect on perceptual estimations but not on grasping.

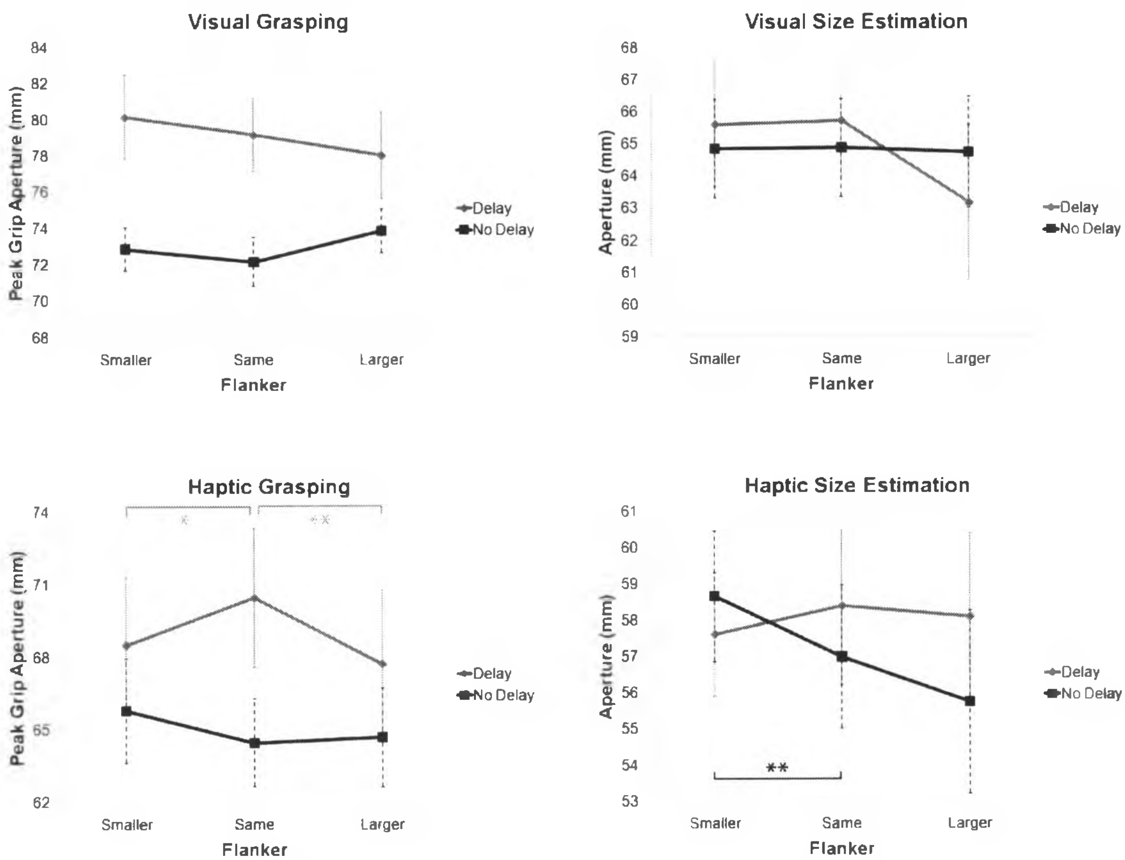

Figure 3-2 *Results.* The effects of flanking objects on grip scaling and estimation in the haptic and visual experiments for real time and delayed performance. Data are collapsed between 5 and 7 cm square targets. Flankers could be the same size or 1 cm smaller or larger in both dimensions. Error bars indicate standard error of the mean within each group of participants (* $p < 0.05$, ** $p < 0.01$)

In the delay condition of the haptic experiment, the effect of flanker size on estimation disappeared. Participants' estimates reflected only the size of the target object, showing no modulation for the size of the flanker objects. In haptic grasping trials, however, participants' peak grip aperture was smaller for targets paired with flankers of a different size, which was the case for both the smaller (smaller: $M = 68.50$, $SE = 2.83$; same: $M = 70.47$, $SE = 2.88$; $t_{(9)} = 3.56$, $p < 0.05$) and the larger flankers (larger: $M = 67.72$, $SE = 3.06$; $t_{(9)} = 5.22$, $p < 0.01$). There was no difference in peak aperture between the large and small flankers ($t_{(9)} = 1.42$, ns). Taken together, these results suggest that in the haptic experiment, delay produces a different effect when grasping than it does when estimating (Figure 3-2).

Discussion

We found clear differences between the way in which exposure to flanker objects affected haptically driven grasping and size estimation as compared to visually driven grasping and size estimation. We will discuss each of these differences in turn.

First, we found no evidence for a size–contrast effect in the visual experiment, either on grasping or on estimation. In other words, seeing a smaller (or larger) flanking object before seeing the target itself had absolutely no effect on the scaling of the grasp or on the estimation of size. This was true whether or not the grasp (or estimation) was made while still viewing the target or after a delay. This is in striking contrast to the findings of a number of experiments showing (1) that estimates of object size show size–contrast effects and (2) that delayed grasping but not real–time grasping also shows sensitivity to size–contrast illusions (Hu and Goodale 2000; Westwood and Goodale 2003b). But there was a crucial difference between our experiment and earlier ones. In order to make the visual and the haptic experiments as similar as possible in our study, we presented the flanker and target objects sequentially rather than simultaneously. This meant that (in contrast to the typical visual experiment of this sort) participants never saw the flanker object and the target object at the same time. Taken together, this suggests that size–contrast illusions in the visual domain only emerge when the flanker and the target stimulus are both present in the array.

There are a few possible explanations for this phenomenon. Since there is no direct visual comparison between the two blocks, there may not be an opportunity for our perception of the size of one block to be influenced by viewing the other block. It also may be the case that for the delay conditions, our perceptual memory for the display contains only the target block, which was the one most recently viewed prior to the delay. This could explain why a size–contrast effect was not observed in either the delayed grasping or the delayed estimation. With regard to the no-delay trials, it may be that participants used only the visual information in front of them to complete the actions, rather than relying on irrelevant perceptual memories of the concealed flanker block.

We also investigated whether or not the introduction of a delay in the haptic experiment would produce a similar effect to that observed in vision. When a delay is introduced in a typical visual size–contrast experiment, participants scale their grasps to the perceived rather than the real size of the target object (Hu and Goodale 2000; Westwood and Goodale 2003b). The results of our haptic experiment, however, seem to indicate important effects of delay on both grasping and estimation. When grasping after a delay, participants did not open their hands as wide when reaching for a target paired with a flanker of a different size. Although this cannot properly be called a size–contrast effect since we observed no difference between the large and small flanker, we can still conclude that when a delay was introduced, the size of the flanker became important to the shaping of the grasp. It is possible that this effect reflects some uncertainty about the remembered size of the target. Indeed, grip aperture tended to be larger overall on delayed grasping trials.

For no-delay estimation trials, participants showed a similar size–contrast effect to what was observed in Westwood and Goodale (2003b). That is they overestimated the size of targets paired with a smaller flanker. When we introduced a delay between when participants saw the target object and when they performed the estimation, the effect disappeared. This may be because our perceptual memory for haptic objects only lasts for a small period of time, or that there is a limit to how many haptic objects can be kept in working memory at once. Taken together, it appears that a delay eliminates the effect of the flanker object when estimating, but creates one when grasping.

The reasons for these differences are unclear. It could be the case that haptic memories do not last very long–and therefore differences in the temporal constraints of the estimation and grasping tasks could have been a factor. Data collection for the manual estimates of object size was always initiated after the participants indicated that they were satisfied with their estimate. As a consequence, much more time would have passed since they last felt the flanker and the target object than would have been the case in the grasping task. In other words, it is possible that the delayed manual estimates of object size were based on a much 'weaker' memory than the delayed grasps. Further examination into the longevity of haptic memory for size information is clearly required.

Even though the real–time haptic results in our experiment and the earlier one by Westwood and Goodale (2003b) appear to map well onto the traditional perception–action distinction for vision, the story begins to unravel when a delay is introduced. The very fact that participants in the vision experiment opened their hand wider on both grasping and estimation trials than did participants in the haptic experiment already points to differences in the way in which these two sensory modalities engage action and perception. Finally, the delay results could reflect important differences in the way in which haptic and visual memories are laid down and/or accessed, but this must remain speculation until further experiments are carried out.

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CHAPTER 4: General Discussion

4.1 Summary of major findings

The experiments outlined in Chapter 2 were meant to both describe the difference between visually and haptically guided grasping and estimation tasks, and investigate how the two modalities are used in combination while grasping and estimating. The main finding of the first experiment in Chapter 2 was that participants performed with greater uncertainty and more variability in both the haptically guided grasping task and the haptically guided manual estimation task when compared to when only vision was available. Uncertainty in grasping was demonstrated by larger maximum grip apertures and uncertainty in estimation was demonstrated by increased variability in apertures. In addition, participants performed no differently in the condition in which both vision and haptics were available in comparison to when only vision was available. This suggested that participants may not be incorporating the additional haptic information in the multimodal tasks. However, when information from vision and haptics was made incongruent in the second experiment, we observed a clear influence of the added haptic information in both grasping and manual estimation tasks. As a result, we concluded that available haptic information is automatically incorporated into visually guided action and perception tasks.

The experiments outlined in Chapter 3 sought to determine whether or not a haptic version of a typically visual illusion could provide further evidence for a dissociation between action and perception in haptics. Our experiment duplicated the results for haptically guided real-time grasping and estimation (Westwood and Goodale 2003a). That is, we found that grasping behaviour was unaffected by the illusion, whereas manual estimations of size showed a clear influence of the illusory context. However, when delayed performance was tested, the neat parallel between vision and haptics began to break down. In typical visual illusion studies, a delay will create an illusory effect in grasping and leave performance in the estimation task relatively unchanged (Hu and Goodale 2000; Westwood and Goodale 2003b). However, when a delay was introduced into our haptic size-contrast experiment, an illusory effect was created in grasping, but eliminated in estimation. Furthermore, the effect in delayed grasping could not properly be interpreted as a size-contrast effect. As a result, the issue of how far the action-perception dissociation can extend into the haptic domain is still unclear.

4.2 Comparison between visual and haptic performance

Chapter 2 demonstrated a clear difference in how visually guided tasks and haptically guided tasks are performed. We suggested these differences reflect the inherent uncertainty associated with haptically guided actions and perceptual judgements. There are a number of potential explanations for this observed increase in uncertainty. For instance, people have a relatively large amount of practice in performing actions based solely on vision, but very little experience with exclusively haptic movements. That is not to say that our sense of haptics is unimportant in our daily lives. Indeed, the results discussed in Chapter 2 suggest that haptics likely plays a role in many movements we may have previously considered to be entirely visual. Instead, we suggest that relatively few actions are performed with our hands in the absence of any visual feedback. Since our participants are not specially trained and only receive a minimal number of practice trials before the experiment, we would expect them to behave with a little less certainty when vision is absent. One might also argue that the sensory receptors in the hand are less precise than those in the eye. As a result, haptics would have greater difficulty in consistently representing size. Of course our estimation data suggests that vision and haptics have equal accuracy in representing size. However, precision, as measured by standard deviation, is certainly lower in haptics.

One caveat of Chapter 2 concerns the conclusion that available haptic information was being automatically incorporated in both experiments; when vision and haptics were congruent and when vision and haptics were incongruent. We concluded that incongruence revealed an influence of haptics, which was likely to be present even when no conflict existed. The mechanisms would likely be the same in both experiments because participants were unaware of the congruency manipulation. Thus, we believed the explanation that haptics was being incorporated all along to be more parsimonious than the suggestion that the incorporation of haptic information was dependent on whether the senses were put in conflict, even without participants' awareness. However, we find it necessary to point out that none of the data collected can properly distinguish between these two potential explanations. Therefore, there may be a mechanism that is sensitive to information from multiple modalities, which, in some situations, will combine information from the different senses and in other circumstances will not. In addition, this switching mechanism must operate unconsciously, as congruency was manipulated without awareness. Since much of what the brain does to perform actions is unconscious, the presence of an unconscious mechanism for multimodal integration is not entirely unfeasible. However, further research would be necessary to rule out this possibility.

Chapter 3 demonstrated that only certain findings from visual size-contrast illusion experiments could be generalized to the haptic modality. Considerable effort was spent to make the haptic version of the size-contrast illusion maximally similar to the classically visual paradigm. However, since the hand can only receive haptic information from one object at a time, the haptic version of the experiment was necessarily sequential, departing from the usual simultaneous design in vision. As a result, we designed a visual size-contrast experiment with sequential object presentation to mirror that of the haptic version. We found that changing the visual presentation of stimuli in this fashion completely eliminated all previously reported size-contrast effects. Reasons for the disappearance of the illusory effect were considered in the preceding discussion. However, it might be interesting to speculate on why a size-contrast effect is possible in a sequential haptic design, but not in a sequential visual design. One possibility is that this difference between modalities may result from how heavily the senses depend on online control. For vision, when online information is available, participants seem to rely only on that information, rather than memory representations of previously encountered objects. In a real-life scenario, we typically have all the necessary visual information present in order to guide our actions. Haptics, on the other hand, may rely on previously encountered information to a greater extent, as movements driven by haptics alone are rare in our everyday lives. It may also be the case that haptic size representations persist for a longer period of time, allowing for the size-contrast effect to emerge. Indeed, trends in this direction were observed in the experiments of Chapter 2.

Taken together, our experiments begin to shed some light on the similarities and differences between our sense of vision and our sense of touch. Considering the vast differences in how the two modalities receive and transduce information, one might expect major differences in performance based on the two senses. Indeed, we do find that certain aspects of grasping and manual size estimation are significantly different between the senses. However, there are a number of remarkable similarities between vision and haptics, including, most notably, an almost identical ability to represent size. This could be a result of the relatively high density of receptors in both the retina and the hand, allowing for highly accurate size representations for objects small enough to be haptically explored. In addition, it may be that information from the two sensory systems is processed by similar structures and mechanisms, leading to similar perceptual representations. Considering how undeniably important coordination between the hand and the eye would be during the course of human evolution, one might not be surprised that the two sensory systems demonstrate these similarities.

4.3 Action-perception distinction in haptics

In Chapter 2, one may be tempted to interpret the main effect of modality in grasp aperture and lack of main effect of modality in estimation aperture as evidence for a dissociation between action and perception. More specifically, one might assume that the different modalities are being utilized in fundamentally different ways when grasping, but in similar ways when estimating. However, when we consider the effect of uncertainty that was discussed in the previous section, we find a clear explanation for the discrepancy between the grasping and estimation results. That is, uncertainty in grasping would manifest as an increase in grasp aperture, whereas uncertainty in the estimation task would produce more variable estimates, consistent with our results.

Again, looking at the results in Chapter 2, we discussed the possibility of a goal-dependent incorporation of haptic information in the grasping and estimation tasks. In particular, we observed a trend where grasp aperture did not appear to be affected by the incongruent, haptically-smaller size, whereas the estimation aperture was. Thus, it appeared that in a multimodal scenario, haptic information might only be utilized if it is relevant to the completion of the task. Although we cannot make this argument from our statistics alone, the potential trend sparked some interesting speculation that could be investigated in future studies.

Some of our strongest evidence for a dissociation between action and perception in haptics came from our investigation of Weber's law. More specifically, haptics showed the same pattern as vision, with variability in manual estimates upholding Weber's law and variability in grasping violating Weber's law. This suggests that, as with vision, there is a fundamentally different way in which size is computed for action tasks and perception tasks. It appears that action relies on a representation of size that more closely follows the absolute metrics of the target stimulus. We also examined multimodal performance in the context of Weber's law and found that, again, Weber's law was upheld when estimating, but violated when grasping. However, when grasping based on both vision and haptics, we observed a trend exactly opposite to what Weber's law would predict. That is, variability in grip aperture decreased as a function of object size. We had considerable difficulty in trying to interpret this result. However, for the sake of speculation, it may be the case that for the smaller objects, haptics has more of an influence on the grasping behaviour, and for larger objects vision has a greater influence. Indeed, Figure 2-2 shows that the line describing the multimodal condition begins with variability close to that of the haptic condition at smaller sizes, and ends with variability close to that of the vision condition at larger sizes. Unfortunately, our data are not ideal for probing further into this possibility, again leaving room for future investigations.

The results of Chapter 3 experiments appear to confuse the story of a dissociation between action and perception in haptics. Although the real-time data replicate what was shown in previous haptic illusion studies, delayed performance proved more difficult to interpret. In particular, delay created some sort of flanker effect in grasping, but eliminated the size-contrast effect in estimation. There are two clear difficulties with this result. The first is that the size-contrast effect is typically preserved in delayed visual estimation, but has disappeared in our haptic version of the task. However, this discrepancy could be explained by the nature of our estimation task. After haptically exploring the flanker and target blocks, participants had as much time as they needed to indicate the perceived size of the target block with their right hand. This amounted to a self-induced delay period, wherein information for flanker size would likely begin to decay. Thus, one could argue that our real-time estimation task actually included a short delay, and our delayed estimation task simply involved an even longer delay. Therefore, we are resisting over-interpretation of the lack of a size-contrast effect in delayed haptic estimation. However, the second problem still remains; the strange flanker effect observed in delayed haptic grasping. Although it cannot properly be interpreted as a size-contrast effect, it is clear that delay caused some sort of consideration of the size of the flanker object. This result still lends support to the idea that delay changes how size information was processed and used to guide action in haptics. However, the exact nature of this change and the mechanisms involved are unclear.

4.4 Future Research Directions

Although this body of work makes some significant contributions to our understanding of how vision and haptics guide actions and perceptual judgements, there is still much progress to be made. Indeed, the issue of whether a distinction between action and perception can even be made in the haptic domain is still unsettled. Our experiments also raise a number of interesting questions that provide opportunities for further investigation.

In Chapter 2, for both visual and haptic performance, we found that Weber's law was upheld when estimating but violated when grasping. Previous findings in vision show that once a delay is introduced into the action task, grasping behaviour subsequently follows the predictions of Weber's law (Ganel et al. 2008). This is interpreted as a switch from dorsal stream computations to ventral stream computations, as behaviour begins to mirror that of the size estimation task. Thus, the next logical step in our investigation of haptics would be to test whether haptically guided grasping after a delay upholds Weber's law. If this is indeed the case, we will have additional evidence for the dissociation between action and perception in haptics. Furthermore, it would also be interesting to investigate multimodal grasping performance on this task, as our results in Chapter 2 were somewhat puzzling. As mentioned previously, the pattern of results when both senses are available could be explained by a size dependent incorporation of visual and haptic information. Therefore, in order to investigate this hypothesis, we could design an experiment that combines elements from both Experiment 1 and Experiment 2 of Chapter 2. That is, we could test multimodal grasping on a large range of block sizes with an additional congruency manipulation. As a result, we could see whether the incongruent haptic information has a greater influence at smaller block sizes, which could be predicted from the pattern of results observed in Chapter 2.

In Chapter 3, introducing delay into a haptic version of the size-contrast illusion resulted in confusing results for both grasping and estimation performance. In particular, the most puzzling result was the elimination of the size-contrast effect after delay in the estimation task. However, we suggested that a flaw in our design could explain this result. Thus, another potential direction we could take would be to repeat the experiment, but fix the flaw in the estimation task. In particular, rather than have participants determine the duration of the manual estimation, we would specifically control the length of the task to be comparable to that of the grasping task. Furthermore, since our estimation data is somewhat inconclusive, it might also be useful to repeat the sequential visual size-contrast experiment with the same rigid controls on the estimation task.

Finally, though not connected directly with this body of work, we are also interested in using functional magnetic resonance imaging (fMRI) to investigate whether haptic representations of shape can be localized in the dorsal and ventral visual streams. In particular, we are interested to see whether, in some cases, vision and haptics share the same patterns of activation for the same classes of stimuli.

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APPENDIX A: Ethics Approval

Ethics Approval for Chapter 2 Experiment

Western

Department of Psychology The University of Western Ontario
Room 7418 Social Sciences Centre,
London, ON. Canada N6A 5C1
Telephone: (519) 661-2067Fax: (519) 661-3961

Use of Human Subjects - Ethics Approval Notice

Review Number	08 12 06	**Approval Date**	08 12 10
Principal Investigator	Mel Goodale/Charlie Pettypiece	**End Date**	09 05 01
Protocol Title	Grasping based on simultaneous visual and haptic information		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

The PREB is a sub-REB of The University of Western Ontario's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement and the applicable laws and regulations of Ontario. (See Office of Research Ethics web site: http://www.uwo.ca/research/ethics/)

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the University's periodic requests for surveillance and monitoring information.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the PREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of research assistant, telephone number etc). Subjects must receive a copy of the information/consent documentation.

Investigators must promptly also report to the PREB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to the PREB for approval.

Members of the PREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the PREB.

Clive Seligman Ph.D.

Chair, Psychology Expedited Research Ethics Board (PREB)

The other members of the 2008-2009 PREB are: David Dozois, Bill Fisher, Riley Hinson and Steve Lupker

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Ethics Approval for Chapter 3 Experiment

Western

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Room 7418 Social Sciences Centre,
London, ON, Canada N6A 5C1
Telephone: (519) 661-2067Fax: (519) 661-3961

Use of Human Subjects - Ethics Approval Notice

Review Number	09 05 01	**Approval Date**	09 05 05
Principal Investigator	Mel Goodale/Charlie Pettypiece	**End Date**	
Protocol Title	Psychometric properties of visually and haptically guided actions		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

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Clive Seligman Ph.D.

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The other members of the 2008-2009 PREB are: David Dozois, Bill Fisher, Riley Hinson and Steve Lupker

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APPENDIX B: Publishing Consent

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