Disconnected Connections: Extending Peripersonal Space

with a Virtual Hand

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Arts
in
Psychology

Waterloo, Ontario, Canada, 2009

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Author's Declaration

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Abstract

Peripersonal (reachable) and extrapersonal (beyond reach) space is linked to hand perception. Using a tool to reach farther than normal recalibrates previously unreachable space as peripersonal, evidenced by Intraparietal Sulcus (IPS) activity related to hand perception and lateral biases during line bisection. The current study looked at the role of a visual connection between the hand and body in the ability to manipulate objects within the extended area of reach. In an immersive virtual environment, participants bisected lines using a connected hand (via arm), a disconnected hand, or a floating dot. A rightward shift in bisection was seen only for the dot condition for far lines, indicating that it was the only "tool" incapable of extending peripersonal space.

Acknowledgements

A hearty thanks needs to go to Colin Ellard for being an encouraging and otherwise wonderful advisor. My readers, James Danckert and Mike Dixon, also deserve a thanking for their help and support.

To the various members from the Ellard lab who helped create the final thesis, thanks a million: Gloria Sicuro for testing participants, Deltcho Valtchanov for technical assistance, and Kevin Barton for helping all along the way.

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Introduction

Hands play an important role for interactions with our surroundings. If you are thirsty, how else are you going to get a glass of water to your mouth? Similarly, a surgeon relies on his hands when operating on a patient -- though indirectly by using tools. To better understand some of the perceptual mechanisms that play a role in these self-world interactions, this study used an immersive virtual environment to manipulate the visual presentation of the hand and arm during a manual line bisection task.

Two aspects of hand perception are of primary concern. First is the contribution of visual perception of the hand, which the current study manipulates. Second is the ability of the hand to interact with objects in the external environment.

Perceiving Macaque Hands

When considering the area around one's body, a distinction can be made between peripersonal (near) space and extrapersonal (far) space. This separation arises from different neural control systems (e.g., Ladavas, 2002). Many studies with macaque monkeys have helped develop our knowledge about peripersonal space. Iriki, Tanaka, and Iwamura (1996) took electrophysiological recordings from multimodal neurons in the intraparietal sulcus (IPS) related to hand perception. Receiving input from both sensory and visual cortex (c.f. Iriki et al., 1996), these neurons showed activity as a small paintbrush touched the monkey's hand or as an experimenter's hand (holding a pellet of food) moved toward the monkey's hand. Visual receptive fields (RF) of these neurons are non-retinotopic, following the spatial coordinates of the monkey's hand rather than being localized to a specific region of the retina. Other than the IPS, Rizzolatti, Scandolara, Matelli, and Gentilucci (1981) found multimodal neurons in postarcuate cortex (area 6) that respond specifically to stimuli within peripersonal space. Keeping in mind that these and other areas outside of the IPS are involved in the complete processing of peripersonal representations, the IPS is an early aspect of the perceptual processing and most relevant to later discussion in this paper.

Other than identifying the neural activity related to multimodal integration, Iriki et al. (1996) also showed how tools interact with peripersonal space. As the experimenter held a pellet within reaching distance of the monkey, the neurons labeled as "proximal" and "distal" responded. No similar activity arose from pellets held beyond the monkey's reach. Training with a rake then allowed monkeys to extend their reach and retrieve previously unreachable pellets. For pellets held beyond the reach of the monkeys' hands but within reach of the rake, *proximal* and *distal* neurons in the IPS started responding. In effect, peripersonal space had been extended to include a wider region as the tool allowed the monkey to interact with this space previously coded as extrapersonal. This demonstration of the network involved in peripersonal encoding also shows that the same neurons that process hand perception are recruited for processing the rake.

Neurons in the IPS show activity during other hand movements, including times when the arm is not visible (Iriki, Tanaka, Obayashi, & Iwamura, 2001), indicating that peripersonal perception does not require a visual connection between the body and the hand. Iriki et al. (2001) showed this by having macaques watch their hands through a television screen (occluded from direct view). Visual RFs of IPS neurons continued to show activity, as well as the expected extension effects from tool use, while monkeys reached for food pellets during this indirect viewing procedure.

Likewise, the visual RFs can continue to follow the hand even in the absence of vision (Obayashi, Tanaka, & Iriki, 2000). To test this, the researchers trained monkeys to reach for a food pellet under a display that would turn from transparent to opaque. About half of the recorded neurons with corresponding visual RFs continued to respond as the monkey moved its hand, following the spatial location throughout movement. Response in the IPS diminished after prolonged severance of visual input, showing that some visual input is necessary along a timescale.

Positron Emission Tomography (PET) scanning has confirmed that the IPS is active while using a basic tool (Obayashi et al., 2001). It has also shown activities as monkeys remotely controlled a mechanical arm with a joystick (Obayashi et al., 2004) or by rotating two knobs (Obayashi et al., 2007). The specificity of PET does not help distinguish whether this activity is related to the visual RFs responding to the mechanical arm movement or merely linked to the monkeys' hands operating the controls. However, given that the visual RFs are active when using a stick or viewing hands on a television screen (i.e., Iriki et al., 1996; Iriki et al., 2001), it is plausible that some of the IPS activation was evoked by the mechanical arm. Assuming that the IPS activity is properly attributed to the mechanical arm, this is another example of peripersonal perception while lacking a visual connection between body and tool.

Perceiving Human Hands

In humans, functional Magnetic Resonance Imaging (fMRI) results have confirmed IPS activity related to seeing a ball approach the hand of participants compared to the same action performed beyond reach (Makin, Holmes, & Zohary, 2007). Lending further credence to the suggestion that mechanical arms/hands might evoke a response, a similar pattern of activity was evoked when using a dummy hand. Studies of human tool-use have also confirmed IPS activity when measured by PET (Inoue et al., 2001) and fMRI (Higuchi, Imamizu, & Kawato, 2007). More importantly, studies with human participants have helped pin-down the scope of peripersonal space by finding when peripersonal space will and will not extend. An ability to interact and manipulate the external environment appears to be one crucial factor for peripersonal extension. As many of the studies have reported, the effect only appears during active tool use (e.g., Farne, Iriki, & Ladavas, 2005; Farne & Ladavas, 2000; Iriki et al., 1996; Witt, Proffitt, & Epstein, 2005); passively holding the tool with no intent to use it will not extend peripersonal space. However, effects that can last minutes might take only seconds to induce (Holmes, Calvert, & Spence, 2007).

Further evidence that active interaction is crucial to peripersonal extension comes from studies using patients with cross-modal visual-tactile extinction. A typical behavioral symptom of extinction is that patients will ignore a stimulus presented near their contralesional hand when a second stimulus is simultaneously presented near their ipsilesional hand. Farne and Ladavas (2000) showed that tool use could lead to the expected extinction results (ignoring stimuli near a tool in the contralesional hand) as if the tool were a patient's hand. Importantly, extinction only occurred after using a tool. Merely pointing toward out-of-reach objects with their hands or tools that were too short did not induce extinction. This evidence suggests that arm movement toward distant objects is insufficient for extending peripersonal space. In a later study, Farne et al. (2005) compared extinction for a 60 cm tool to extinction for a "hybrid" tool that stretched 60 cm but only functioned to retrieve objects that were an extra 30 cm away.

For objects placed 60 cm from the ipsilesional hand, the tool with the 60 cm reach induced extinction as expected. However, the hybrid tool did not induce extinction at 60 cm despite the fact that it was also 60 cm in length (visually). This suggests that peripersonal extension is primarily driven by the functional reach of a tool, not merely its visible length. Another tool that reaches without allowing manipulation of the environment is a laser pointer. These fail to extend peripersonal space, as seen in many of the line-bisection tasks described shortly.

Effects on Action

A number of behavioral consequences arise from this differential encoding of peripersonal and extrapersonal space. In a simple study of distance estimation, Witt et al. (2005) had participants estimate the length from one hand to a point of light briefly projected onto the table. Estimates of distance, whether through active pointing or verbal judgments, were shorter when participants held a conductors baton instead of merely using their fingers. These results suggest that expanding peripersonal space creates a compression of all nearby space; that is, reachable distances are perceived as shorter. A second experiment confirmed these underestimates with perception matching; participants estimated the distance to the point of light by adjusting the width of two separate circles.

Many studies have investigated the consequences of the peripersonal-extrapersonal boundary with line-bisection tasks. Manual line-bisection typically calls for the participant to indicate the center of a horizontal line. The most striking effects come from patients with hemi-spatial neglect who ignore half of their visual field (most commonly the left) due to right-parietal lesions (e.g., Bisiach & Luzzatti, 1978). Since neglect patients do not notice the full length of the line, they tend to point considerably right-of-center. Some studies have found that for some neglect patients, this rightward bias only occurred if the line was in peripersonal space. Pointing with their finger, patients showed the typical rightward bias associated with neglect (Berti & Frassinetti, 2000; Halligan & Marshall, 1991; Pegna et al., 2001). However, using a laser pointer to bisect lines beyond reach reduced the rightward bias and significantly improved accuracy; different encoding of the lines in extrapersonal space seemingly spared their ability to represent these lines. Using a stick to bisect these distant lines led patients to revert to the rightward bias as if they were using their finger. In effect, the perceptual processing induced by use of the stick led to an automatic reincorporation of the lines into peripersonal space. A reversal of this is also possible, whereby the far lines are subject to the bias and close lines are accurately bisected (Cowey, Small, & Ellis, 1994). Lesion studies with macaques induced these differential bisection patterns by lesioning parts of postarcuate cortex (area 6) to elicit strong rightward biases in peripersonal space, and prearcuate cortex (area 8) to elicit the biases in extrapersonal space (Rizzolatti, Matelli, and Pavesi, 1983).

Healthy participants show less drastic biases in peripersonal versus extrapersonal bisection performance, yet still exhibit a subtle bias. Longo and Lourenco (2006; 2007) found that line bisection in peripersonal space was the same whether participants used a stick or a laser pointer. Performance showed high accuracy but a consistent bias to point leftward for closer lines, ending up slightly left-of-center for the closest lines. For trials with the line placed beyond arm's reach, a different pattern emerged. With a stick, the leftward bias remained. Though the lines lay beyond arm's reach, they were presumably encoded as being within peripersonal space due to the extension provided by the stick.

Distant lines bisected with a laser pointer saw participants shift their judgments of center to the right. Also, absolute error from the midpoint was somewhat larger when these distant lines were bisected with a laser pointer (though no statistics were run to confirm this difference). Based on previous human neuropsychological studies, Longo and Lourenco (2006) concluded that the peripersonal representations become weaker as lines move further away, and that these different activation patterns drive the change in behavior. Taking the macaque literature into consideration, a similar conclusion can be reached: that IPS activation is associated with the slight leftward biases, whereas rightward biases would likely show up during IPS inactivity. As to what drives the IPS, there is converging evidence that functionality of a tool plays a role in its ability to extend peripersonal space given that the rightward shift only happens when participants used the laser pointer. As mentioned earlier, a laser pointer does not allow manipulation of the objects it can reach.

In a replication of the findings by Longo and Lourenco (2006), Gamberini et al. (2008) showed the same pattern of leftward-rightward shift. All bisections performed with a stick (both near and far) showed the slight leftward bias, while using a laser pointer showed a discrete rightward shift for lines beyond reaching distance. Again, accuracy declined with the absolute errors being larger for distant lines bisected by laser pointer (though no statistics were run to confirm this difference). Similar results came from their second experiment carried out in virtual reality. Participants wore a head-mounted display to view a computer-rendered line bisection task. Holding a small stick for tactile feedback and wearing a glove that recorded their movements for the computer, participants showed the same leftward bias while visually aligning a virtual stick. For the laser pointer condition, participants controlled a virtual dot with a joystick. Despite a slightly different control mechanism, the leftward/rightward shift appeared for lines that were close/far away, respectively. One minor difference between the replicated and original results is that Gamberini et al. (2008) found a sharp switch from peripersonal to extrapersonal space. In contrast, Longo and Lourenco (2006; 2007) had found a gradually increasing rightward shift as lines continued further into extrapersonal space. Together with the imaging and macaque data, these behavioral studies lend credence to the hypothesis that decreased activity in the IPS and its related network is related to impoverished internal representation and less accurate actions toward external objects.

Understanding the Mechanisms

Many researchers agree that this literature affirms long-standing claims (Head & Holmes, 1911) that tools are integrated into the body schema (for reviews, see: Giummarra, Gibson, Georgiou-Karistianis, & Bradshaw, 2008; Knoblich, Thornton, Grosjean, & Shiffrar, 2006; Maravita & Iriki, 2004). More specifically, it appears that shared neural mechanisms in the IPS process tools and hands. This overlap appears to play a role in creating perceptual and behavioral differences related to peripersonal versus extrapersonal space.

When considering how reaching with tools extends peripersonal space, it is important to note the properties of these tools. In typical circumstances, a continuous physical (and visibly salient) connection exists between the part of the tool that manipulates external objects and the hand (e.g., the tines of a rake, which manipulate objects, are connected to the hand by the pole of the rake). Some tools, such as laser pointers, lack this connection between the hand and the dot projected at a distance.

Although the failure of laser pointers to extend peripersonal space has been attributed to the fact that they cannot manipulate external objects (only point to them), they also lack the physical connection between the hand and the end point of the tool (the dot). To conclusively determine whether being able to manipulate objects is crucial for functionally extending peripersonal space (and not merely a product of extra visual input provided by a connection extending all the way to the tip), it would be important to show that peripersonal space can be extended by a tool that is still effective for manipulation but lacking the connection. Indirect evidence from the macaque studies mentioned earlier (i.e., Iriki et al., 2001; Obayashi et al., 2007; Obayashi et al., 2004) suggests that there is no need for a visual connection. Recall that there was activation of the IPS even when viewing hands through a monitor (lacking a visual connection to the body).

Current Study

With humans, there is currently no evidence that peripersonal space can be extended with a hand that is not connected to the user's body. Neither human nor macaque studies have tested a simple laser-pointer-like dot that affords the same ability to manipulate surrounding objects for extending peripersonal space. With a virtual environment allowing these unconventional manipulations, the current study asked whether a visual connection between the body and hand is necessary to extend peripersonal space. Controlling a virtual representation of their hand, participants bisected lines presented either near or far away. Depicted in Figure 1, visual representation included a hand connected to the body by an arm (arm), a disconnected hand floating in space with no arm (hand), or a small dot floating in space (dot).

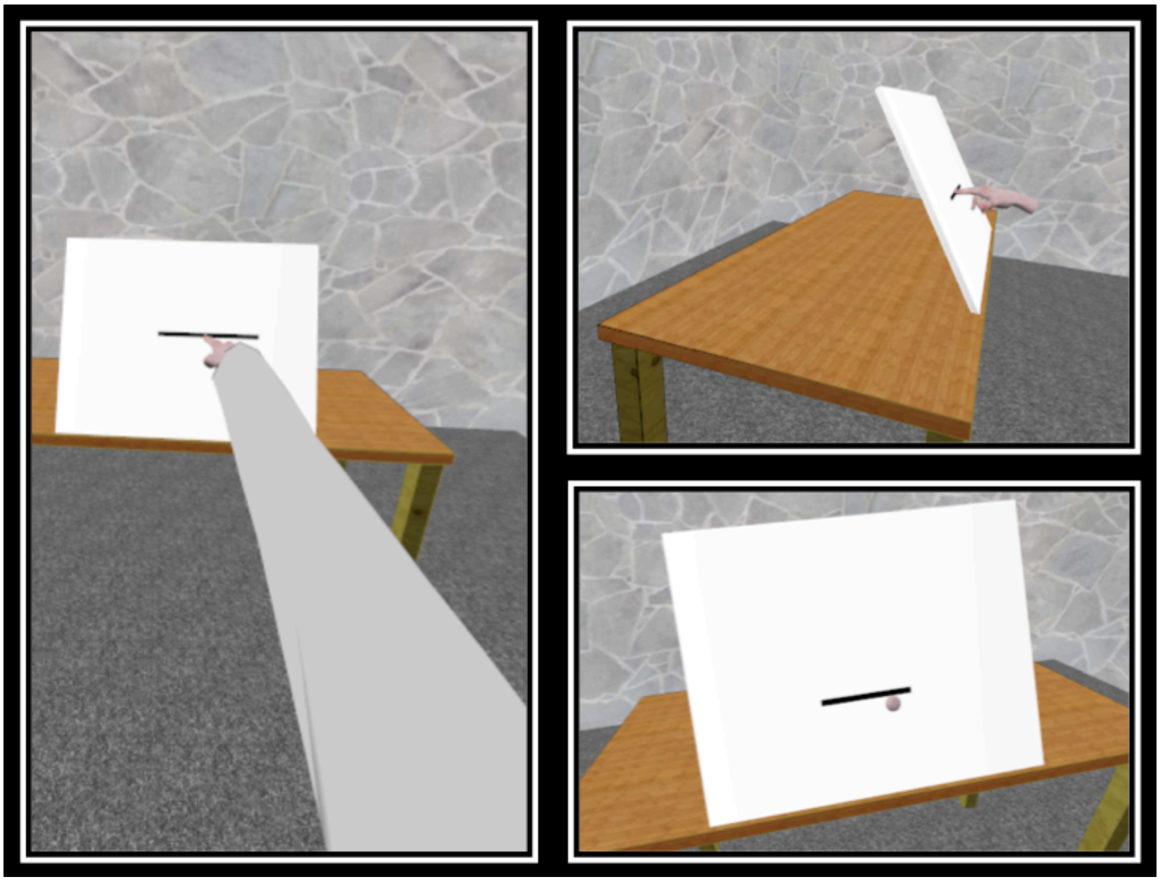

Figure 1. The visual representation provided inside the virtual environment of the (a) arm (b) disconnected hand and (c) dot.

Experiment 1

It was predicted that controlling the arm within the virtual environment would be the same as if they were using their own hand, or at worst a hand-like tool, to interact with the real world. Therefore, participants ought to show a minor leftward bias during bisection indicating an extension of peripersonal space. The key contrasts in this experiment were for hand and dot performance in far space relative to the arm, which were expected to follow one of four scenarios. If the ability to manipulate objects is the key factor in the extension of peripersonal space, then both would continue to show the leftward bias for distant lines. Conversely, if the visual connection is primarily responsible for driving peripersonal extension then both were expected to exhibit a rightward shift when used to bisect far lines. If one served to extend peripersonal space but not the other, then it would show that manipulation alone is not sufficient; instead there is some interaction with the visual properties of the tool (or in this case, the representation of the hand). Lastly, if peripersonal space exhibits a graded shift when approaching extrapersonal space, as Longo and Lourenco (2006; 2007) suggest, then it was expected that the limited visual representation by the dot would show the strongest rightward shift, while the hand might show a lesser rightward shift.

Method

Participants. Twenty-four undergraduates (13 males and 11 females; ages 18-26) from the University of Waterloo participated for course credit. All had normal or corrected to normal vision. Right-handedness (or ambidexterity) was preselected with the question "With which hand do you write?" One participant was removed from the dot condition for procedural errors.

Design. Both distance from the bisection line (near vs. far) and mode of bisection (arm, hand, dot) were manipulated as independent variables. Trials were blocked on distance and mode (e.g., a participant would complete a block of near-hand trials before moving on to the block of far-hand trials). A completely within subjects design was planned, but major order effects resulted from switching modes, so only the first block of bisection mode is included in further analyses. The resulting mixed design had mode as a between subjects factor and distance analyzed within subjects. Counterbalancing meant that half of the participants performed near bisections first and half performed the far bisections first.

The dependent variable was line-bisection performance as measured by mean distance away from the true midpoint (error) across trials.

Participants completed both the Immersive Tendencies Questionnaire (ITQ) and Presence Questionnaire (PQ), developed by Witmer and Singer (1998), as a check for similarity across groups and to find the extent to which immersion and presence may have played a mediating role.

Apparatus and Stimuli. A computerized version of the ITQ and PQ required participants to use the mouse to indicate their responses on a standard computer screen. All other tasks took place inside the virtual environment.

The physical setup (Figure 2) comprised a table measuring approximately 75 by 120 cm, a tilting lectern approximately 45 cm long and 60 cm wide on the surface (resting at either zero degrees parallel with the table, or tilted 60 degrees off the table tilted away from the participant), the chair for participants, and the computer equipment.

Participants saw a 150 degree field-of-view (88 degree height) of the virtual environment rendered on the *Fakespace Labs Wide-5* Head Mounted Display (HMD). Simulating a 3D view with 6 cm disparity, separate 400 by 300 pixel viewpoints were presented on the LCD in front of each eye. To control the hand, participants wore the *Fifth Dimension Technologies Data Glove* (Figure 2). Sensors ran along the length of the fingers to register bending. The dot was specifically linked to the tip of the pointer finger to keep the actions matched across conditions. Other movement (rotations and linear movements) used the same devices as the HMD.

Capturing rotations of the head and hand were separate *Inertia Cube 2* tracking devices affixed at the top of each. Movements in the x, y, and z directions were recorded through an infrared motion tracking system (*WorldVis PPT.8*) with one emitter on each device (glove and HMD).

Made with *Google SketchUp Pro 6*, the virtual environment contained a mostly-empty room, the desk and lectern at which participants performed the tasks (drawn to scale), and most of the other virtual objects used throughout the experiment. Scripting and online rendering was done through the *Vizard VR Toolkit*, which was also the source of the virtual hand that participants controlled. An average-sized Caucasian hand floated in space (extending just behind the wrist) or had a visual connection to the user's body provided by a light-gray sleeve (in the arm condition). For the dot, a floating sphere was created with the same graphic texture as the hand and matched to the size of the fingertip (Figure 1).

Black lines for bisection were drawn directly on the white surface of the lectern. Each measured 1 cm in height and cycled randomly through widths of 16, 20, 24, 28, and

32 cm (each width appearing once before cycling through the list again). The center of the line fell randomly within a 5 by 5 cm region on the surface of the lectern to minimize the effect of muscle-memory on the visual task. Participant arm length determined their distance from the lines, ranging from 30 to 75 cm for the near condition. Visual manipulation made everything appear 60 cm further than normal for the far condition, thus having a range from 90 to 135 cm.

Procedure. Upon arrival to the lab and signing the informed consent, participants completed the ITQ. They then moved to the table while the experimenter helped them don the cyber-glove and the HMD. To maximize presence in the virtual environment while minimizing external cues and distractions, overhead lights were turned off. Participants then learned basic control of the arm/hand/dot.

Participants had two minutes to familiarize themselves with using the glove for control while also developing an association between the virtual environment and the ability to manipulate objects. A batch of 15 virtual bricks laid on the table in two rows. Bricks could be moved by reaching out and squeezing the fingers of the hand together, as if grabbing, and released again by opening the palm. Due to technical limitations, there was no sensory feedback other than the tabletop, no gravity (bricks would hover wherever placed instead of falling), and no collision of objects (one brick could pass right through another or be placed within the table). Participants used whichever visual representation (arm, hand, dot in near or far space) was upcoming for their first block of bisection trials.

Continuing to the experiment, the virtual lectern and corresponding real lectern were tilted up to the 60-degree position in front of the participant. To establish sitting distance and emphasize the tactile feedback, participants were asked to reach forward and place their hand on the lectern. The experimenter drew the first line on the lectern, instructing participants to point as close to the center of the line as they could and to hold their hand in that position. No time limit was enforced. A key-press by the experimenter made the line disappear and recorded positions to the data file. To draw the next line, participants pushed a button that appeared beside the lectern alternating between left and right. After all 20 line bisections in that block, this procedure continued for the remaining blocks. As mentioned before, only the first two blocks are included in the analyses, each participant contributing both near and far for one modality (arm, hand, or dot).

Figure 2. The setup with lectern, Head Mounted Display (HMD), and the glove used to control the arm, hand, and dot.

Results and Discussion

Measurements were taken from the tip of the virtual index finger or the center of the dot. Error in cm was then converted to percent of line length (positive values reflect a tendency to point rightward whereas negative values reflect positions to the left). Judgments within a 3 cm strip (±2 standard deviations) were considered valid, leading to removal of one participant's data for consistently large errors (on both sides of the midpoint). All others had no more than two values removed for any given set of line lengths (five lengths at two distances) with only five participants missing more than one.

From a two-way analysis of variance, no main effects were found for distance, $F(1, 20) = .009$, n.s., or mode, $F(2, 20) = .584$, n.s. The interaction between these two variables was not significant, $F(2, 20) = 1.77$, $p = .196$. With differences only expected to arise between the arm and hand and/or between the arm and dot conditions when presented far, planned contrasts tested these comparisons. There were no differences for arm versus hand, $F(1, 14) = .092$, n.s., but a trending difference emerged for arm versus dot, $F(1, 13) = 3.144$, $p = .10$. As can be seen in Figure 3, the far dot condition elicited rightward bisections (M = 0.59%) whereas the far condition for the arm (M = -0.78%) and the hand (M = -0.51%) continued to show the slight, leftward bias.

In defense of the weak *p*-values, it is noted that extra noise in the precision of measurements likely came from the fact that the width of the fingertip and dot were both approximately one centimeter wide. A laser pointer or stick might only spread a few millimeters. Without a fine tip, it is assumed that extra error will arise when trying to match the center of the dot to the perceived judgment of center. Already this added variance was making it difficult to specify the outcome, much less whether it aligned with the predictions. Further complication arises from statistical difficulties obtaining a second *p*-value less than 0.05 is a difficult task (e.g., Killeen, 2005; Rossi, 1997); obtaining significant effects upon replication is less likely than intuition might predict. Failing to find significance at the 0.05 level is not necessarily reflective of whether an effect was present or absent. Though this was not a direct replication of previous studies, it is similar enough that the patterns in the data are indicative of what effect is represented. Taking these considerations into account, the *p*-values of interest, though larger than traditional standards, look promising; a *p*-value of.19 for the interaction provides somewhat weak evidence still, but the *p*-value of .10 for the contrast between arm far and dot far is noteworthy.

Given that the pattern of results for peripersonal and extrapersonal encoding align with previous findings (i.e., Gamberini et al., 2008; Longo & Lourenco, 2006; Longo & Lourenco, 2007), the somewhat weak statistics are interpreted as confirming differences between the conditions. Of the two conditions in question (hand far and dot far), the dot elicited performance like the laser pointer with a rightward shift compared to the arm. However, the hand showed no difference compared to the arm for far lines. Based on previous studies looking directly at the neural processes, the rightward shift suggests that only the far lines bisected with the dot were encoded extrapersonally. All other lines, failing to elicit a rightward shift, were encoded peripersonally.

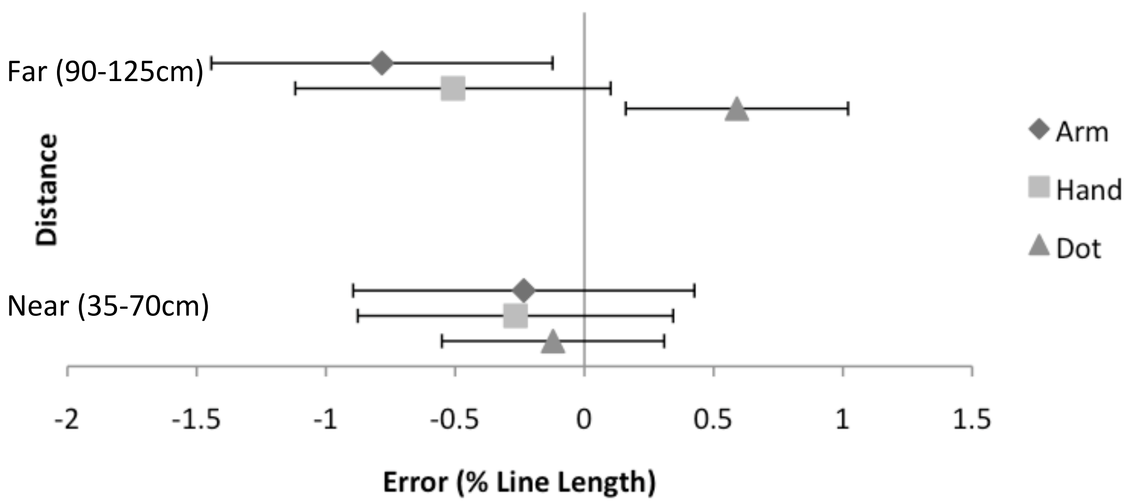

Figure 3. Bisection performance separated by mode (arm, hand dot) and distance (near, far). Leftward judgments indicate peripersonal encoding and rightward judgments indicate extrapersonal encoding. Bars indicate standard error of the mean.

Experiment 2

To check whether participants controlling the dot were truly exhibiting a peripersonal-extrapersonal shift to the right, a second experiment tested only this condition for near and far lines. A different method of control was also implemented, where participants used a joystick rather than the glove. Based on the findings of Gamberini et al. (2008), where a joystick was also used for the virtual replication of the laser pointer condition, the same rightward bias was expected for far lines. Finding a similar result, where a different action continues to show a rightward response, would indicate that the effects are more closely linked to the perceptual processing rather than the motor response. Failure to see a rightward shift for far lines could indicate that the rightward bias is linked to specific ways of acting in extrapersonal space (e.g. reaching out with a specific movement pattern).

Method

Participants. Twenty-three undergraduates (15 male and 8 female; ages 18-24) from the University of Waterloo participated for course credit. The same selection criteria from Experiment 1 were in effect.

Design. Only the dot condition was tested, with distance as a within-subjects variable. Measurements were the same as Experiment 1.

Apparatus and Stimuli. Apart from two changes, the apparatus and stimuli were the same as Experiment 1. First, participants controlled the dot with a cordless joystick instead of the glove (Allowing only left and right movement, the dot would automatically update to the proper height before each trial to match the random placement of the line). Second, an extra 90 cm were added to the visual distance for the far condition, instead of the original 60 cm. This was done to maximize the chances of finding a difference, based on the results of Longo & Lourenco (2007) where rightward bias continued to increase with distance.

Procedure. Because of the limitations with joystick control, there was no two-minute practice session with the bricks. Likewise, there was no tactile feedback provided by the lectern, making it more directly comparable to previous laser-pointer conditions. After performing just the two blocks of line bisections (near and far), participants completed the ITQ and PQ. Otherwise procedure was the same as Experiment 1.

Results and Discussion

Each participant had two means calculated, one from the 20 lines bisected in near space and the other from the 20 lines bisected in far space. Again, error in centimeters was translated to percent of line length after removing any values outside of the 3 cm strip in the middle. A paired-samples t-test confirmed differences when controlling the dot near instead of far away, $t(21) = 2.35$, $p = .028$. Bisecting the far lines demonstrated a rightward bias (M = .48%) compared to near lines (M = 0.08%), as seen in Figure 4.

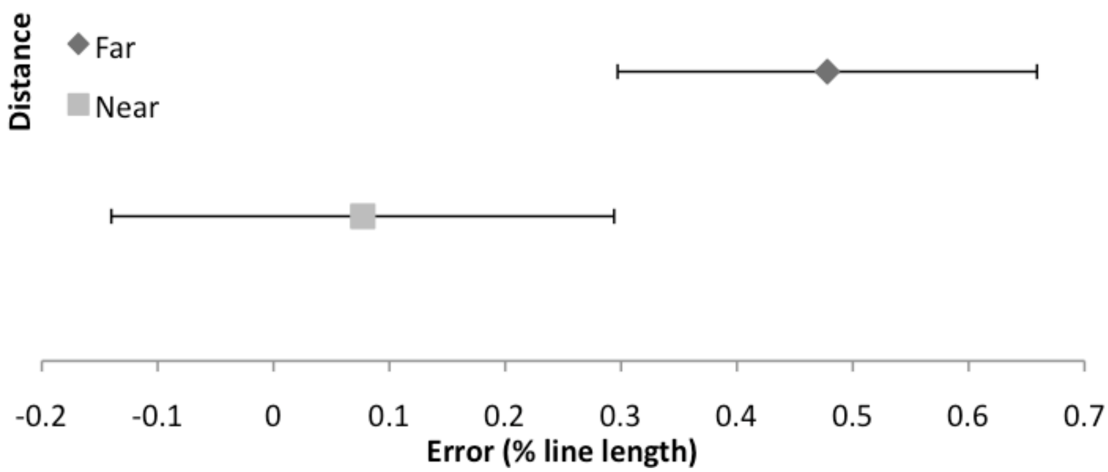

Figure 4. Bisection performance using a joystick to control the dot. Leftward judgments indicate peripersonal encoding and rightward judgments indicate extrapersonal encoding. Bars indicate standard error of the mean.

General Discussion

Using the arm or hand maintained a leftward bias for lines bisected in far space, whereas controlling the dot brought out a rightward shift in bisection performance. These findings mimic the results of Gamberini et al. (2008) and Longo and Lourenco (2006; 2007) who tested with sticks and laser pointers. Given that the IPS is active during peripersonal encoding and the leftward bias of line bisection has been linked to peripersonal encoding, there is good evidence that the IPS was active during all conditions except dot far. Like a laser pointer, the dot is an insufficient stimulus to evoke peripersonal encoding in the IPS. It is unclear if neural activity decreases throughout the brain, or just in this one network, because extrapersonal encoding may simply flow through different pathways. For example, Weiss et al. (2000) propose that extrapersonal visual information proceeds ventrally instead of dorsally with the peripersonal information.

Across the studies assessing peripersonal space with line bisection, the specific mode of control has changed. Traditionally studies have had participants use sticks and laser pointers, whereas Gamberini et al. (2008) and Experiment 2 showed typical results in virtual environments when participants used a joystick for control. With the unique control mechanism employed in Experiment 1, where participants were reaching naturally across all conditions, there is evidence that the pattern of results are independent of the specific control mechanisms used. Matching judgments across these various control mechanisms suggest that the biases in bisection performance are most closely linked to perceptual processing that occurs before the actions are performed. Considering the broader scope of action and perception, it is interesting to note that for this instance action seems to alter perception rather than merely altering cognitive appraisals. That is, participants are experiencing different perceptions rather than merely giving altered verbal reports.

Regarding the literature of peripersonal space, countless studies stress the importance of being able to manipulate the environment with a tool (e.g., Farne et al., 2005; Farne & Ladavas, 2000; Iriki et al., 1996; Witt et al., 2005). The current findings indicate that visual aspects of the tool are also relevant. While both the hand and the dot included a visual gap between the functional aspect and its user, only the dot elicited the rightward shift. Something about the hand allowed it to extend peripersonal representation into far space. More research is necessary to single out whether visual or other conceptual aspects are primarily responsible. Was it merely that it looked like a hand? Would this effect hold if an equally-sized block of wood took the hand's place? From the other side of the question, a dot could be made to look increasingly more like the hand, or a complete arm (or stick), until the rightward shift disappears.

It may also be worthwhile to see how IPS activity correlated with these stages between clear-cut peripersonal and extrapersonal boundaries. Assuming the gradual shift proposed by Longo and Lourenco (2007), it might be expected that activity steadily increased with stronger peripersonal representations. If it were more of a threshold effect seen by Gamberini et al. (2008), then the IPS might be relatively inactive before jumping into a flurry of activity when a sufficiently hand-like or stick-like object serves to extend peripersonal space.

It is interesting to note that Maravita, Husain, Clarke and Driver (2001) included a gap condition when testing a patient with extinction. In these trials, the sticks lay a short distance in front of the patient's hands without eliciting much of the expected extinction. However, this might be more comparable to the previous findings that active use is necessary. Once the sticks were no longer in-hand, they became ineffective for manipulating and interacting the surroundings. The visual gap created by the current experiment still allowed participants to continually interact with the virtual environment. With this continued interaction, peripersonal space could be extended in the absence of a gap, but only for the hand.

Conclusion.

The rightward bias in line bisection, found when controlling a dot in far space, indicates that the line was encoded as lying in extrapersonal space for this condition. Leftward estimates, maintained in far space for the hand and the arm, indicate that these stimuli were sufficient to extend peripersonal space where the dot failed. Based on macaque studies, there is evidence that levels of activity in the IPS may be linked to these biases. Both the hand and dot had no visual connection, suggesting that it is not merely visual appearance of a tool or hand that drives peripersonal space extension. However, with Experiment 1 using the same control mechanisms across all three conditions, the ability to manipulate the environment is not alone sufficient to extend peripersonal space. More work is needed to piece apart how these two variables interact and when accuracy will become subject to the biases. How much visual information must be added to a dot before it acts like a hand? Further study of these phenomena can inform the design of mechanical or computer systems like those used in telescopic and laparoscopic surgery.

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