Tactile Temporal Order Judgment with Tools: Questioning Past Literature and Exploring New Directions in Tool Use

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Abstract

We presented participants with a temporal order judgment (TOJ) task with vibratory stimuli presented to the ends of held tools. We manipulated whether the hands and tools were uncrossed or crossed, predicting that participants would respond more accurately if the responding body part and tool tip were in the same hemispace (see Yamamoto & Kitazawa, 2001). Participants were split into two groups (24 subjects in each group). One group responded manually with the stimulated tools, the other group responded with foot pedals. Contrasting previous findings, we found no significant effect of manipulating tool position when the hands were uncrossed, regardless of response type. Response type appeared to affect overall accuracy, as participants were significantly more accurate when responding with the stimulated tools compared to responding with foot pedals. Interactions were also found between response type and sex. Compared to males, females made a substantially greater number of confusion errors when responding with feet, but not when responding with tools. Additionally, compared to males, females made substantially more confusion errors with the arms crossed, reflecting previously reported results in tactile TOJ on the hands (Cadieux, Barnett-Cowan & Shore, 2010). These results suggest potential differences in spatial mapping and tactile processing in males and females. Subdividing subjects into groups based on accuracy on easy trials revealed that some subjects’ performance was not at all affected by tool position, while other subjects were. Applications of these results to our understanding of how humans use tools are discussed.
What makes humans special? Significantly larger brains and language quickly come to mind, but there is another distinct human phenomenon—complex tool use. Unlike monkeys, who need to train for weeks just to use rakes to get food, humans effortlessly use multiple tools every day. From deftly using pens to controlling enormous cranes, humans are undoubtedly the animal kingdom's expert tool users.

Yet, there exists dispute over how humans use tools. Some focus on the role of the body schema, a concept developed by Head and Holmes (1911) to explain how we represent our bodies. The body schema encompasses a number of representations, such as the representation of the size and shape of our bodies and the representation of the position of our bodies in relation to external space. Iriki et al. (1996) expanded on this theory by suggesting that tool use affects the neural correlates supporting these body representations; thus, when tools are used, they are incorporated into the body schema so that the tools are represented as extensions of the body and the representation of space directly around the body expands to include the area around the tool. Although this "body schema hypothesis" dominated the tool use field for years, it has been recently challenged by a new "attention hypothesis" developed by Holmes et al. (2004). The attention hypothesis states that humans do not incorporate tools into their body schemas at all; instead, when using a tool, attention is merely directed towards the functional tips of tools.

Evidence exists to support both hypotheses, creating a confusing and sometimes contradictory body of literature. This paper will serve as a guide through the tool incorporation debate. First, the definitions and neural correlates of the body schema—along with supporting evidence from
behavorial, lesion, TMS, and fMRI studies—will be reviewed. Then, the literature on Head and Holmes’ (1911) body schema hypothesis as well as the Holmes et al. (2004) attention hypothesis of tool use will be explored. Finally, this paper will propose two experiments—a behavioral study and a TMS study—designed to test the claims of both the body schema and attention hypotheses.

The Body Schema

Head and Holmes (1911) suggested that humans have body schemas—cognitive representations of the size, shape and posture of our bodies. Subsequent researchers have expanded on this idea, arguing that tools become incorporated into neural representations of the body schema. Thus, the body schema hypothesis of tool use is based on the idea that we have neural representations of the size and shape of our body (known as the body form representation), the position our body is in (known as the body postural representation), and the space around our bodies (known as the peripersonal space representation). Also critical to this hypothesis is that these representations can change in response to experience. Evidence exists to support both these claims, suggesting that the brain can indeed change its representations of the body, perhaps to incorporate tools. This section of the paper will examine evidence supporting the existence of the body form, body postural and peripersonal space representations, as well as their neural correlates and plasticity.

**Body form representation.** Critical to the body schema hypothesis is the existence of a plastic body form representation—a representation of the size and shape of our bodies that changes in response to experience. Without a plastic body form representation, there would be no mechanism to extend the representation of the body’s shape to include a tool. Support for a plastic body form representation comes from investigations of primary somatosensory
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representations—the neural representations of the skin surface (located in S1) that allow for the sensation and localization of touch (Penfield & Radmussen, 1950).

Studies on primary somatosensory representations have suggested there is not a perfect one-to-one mapping from tactile input to cortical maps to perceived sensation. Instead, it appears primary somatosensory representations can change in response to experience. For instance, primary somatosensory representations can be enlarged through extensive motor (Braun et al, 2001) and sensory (Schaefer et al, 2008) activity. Yet, after expansion of the fingertip representation due to constant usage, individuals can still accurately localize tactile stimuli, as if the enlargement of somatosensory representations in S1 did not affect their overall representation of their body size or shape. This implies there must be an additional representation that connects somatosensory maps in S1 to particular body parts which can be updated based on plastic changes in S1.

To investigate this, Taylor-Clarke, Jacobsen, and Haggard (2004) exploited the phenomenon demonstrated by Weber (1834/1996) that the ratio of a body part's size to the size of its cortical representation reflects how sensitive a body part is. For instance, the lips, though smaller than the calf, have a larger cortical representation since they are significantly more sensitive. Keeping this ratio in mind, Taylor-Clarke et al. (2004) blindfolded subjects and then touched different parts of their bodies with two tactile stimuli that were identical distances apart. Interestingly, subjects reported the two stimuli were further apart when stimuli were presented to body parts with greater sensitivity (e.g., the hand) than to body parts with lower sensitivity (e.g., the forearm). The authors argued that, just as the visual system has to rescale input from the fovea—to make the center of vision appear more detailed, not actually bigger—information from primary
somatosensory representations must be rescaled to be used by a second, higher order representation. This "size constancy" perspective explains that the overestimation biases in distance judgments found by Taylor-Clarke et al. (2004) were due to systematic errors in scaling from distorted primary somatosensory representations to a secondary body representation. In other words, it suggests there is a process that converts primary somatosensory representations to a secondary, higher order body representation which contains information on the size and shape of the body—i.e., the body form representation.

Tactile illusions studies also support the body form representation, particularly the plastic body form representation. Using tactile illusions, researchers can manipulate how people perceive the size of their bodies. These illusions can only work by affecting how people represent the size and shape of their bodies, in other words, the body form representation. One illusion that illustrates this is the Pinocchio illusion, which works by applying vibration to the biceps in order to produce the sensation of forearm movement and hand movement (Lackner, 1988). Because of this phenomenon, when a vibrating finger is put on the nose, it seems like the hand must be moving away from the face; since the hand is touching the nose while it "moves" the brain is confronted with the strange experience that the tip of the nose must be moving away from the face too. Thus, the Pinocchio illusion produces an illusory extension of the nose—hence the illusion's name. Such "extension" of the nose is a clear distortion of the body's perceived as opposed to actual size and shape. For such an illusion to work there must be a representation of the body's size and shape that is affected but not completely determined by the body's actual shape. Therefore, this supports the existence of the body form representation.
In a replication (and slight modification) of this experiment, de Vignemont, Ehrsson, and Haggard (2005) used the Pinocchio illusion to "elongate" a finger. During the illusion, stimuli on the "elongated" finger were perceived as farther apart than when the finger was not "elongated". Again, it appears researchers can change people's perception of the size and shape of their body parts without actually modifying their bodies, a phenomenon only made possible by the existence of a higher-order, plastic representation of the size and shape of body parts.

**Neural correlate.** Unfortunately, few studies have tried to find neural correlates for the body form representation. However, one fMRI experiment recorded neural activity during a modified Pinocchio illusion, in which the waist was shrunk instead of the nose (Ehrsson et al., 2005). The researchers found two distinct activation peaks: one near the junction of the intraparietal and postcentral sulcus (iPCS) and the other near the anterior intraparietal sulcus (aIPS; see Figure 1). Interestingly, these areas have been previously shown to be involved in tactile-proprioceptive integration (Iwamura, 1998). A TMS study by Medina et al. (unpublished) also supported the localization of body form to aIPS. They found that disrupting aIPS using TMS negatively affected subjects' performance on a tactile temporal order judgment task, a task which relied solely on using somatotopic information to localize tactile sensations. However, one cannot conclusively say body form has been localized to the iPCS or aIPS based on these few studies; more converging evidence is needed, as well as more investigation into whether other brain areas are involved in the representation of body form.
Figure 1. The Neural Correlates of Primary Somatosensory Representations (SI), Body Form Representations (aIPS and pVIP), and Body Posture (BA5) are illustrated. Image taken from Medina et al. (Unpublished).

**Body Postural Representation.** One key theoretical component of the body form representation is its somatotopic organization. This somatotopic organization represents body parts in their putative positions (e.g. the right hand is represented on the right side of the body and the left hand is represented on the left side of the body). Thus, one cannot localize a tactile sensation in external space with only the body form representation; it does not differentiate between being touched on the right hand versus being touched on the right side of space. Instead, while the body form represents the size and shape of body parts, another representation is needed to update the location of body parts—and tools, if the body schema theorists are correct—relative to external space. For instance, when trying to perceive the location of a tactile stimulus, this external representation must first determine what part of the body was touched relative to points on the skin surface (e.g., “My right hand was touched!”, or “My right tool was touched!”). Then, this representation must determine the location relative to external space (e.g., “My right hand was touched while it was on the left side of my body!”, or “My right tool was touched while it was
The necessity of representing the body in relation to external space has been discussed for a century. Head and Holmes (1911) as well as Schwoebel and Coslett (2005) noted that we need a real-time representation of the body's position relative to the external world to account for how effortlessly we interact with objects in our environment; because we do not have to consciously attend to the initial position of our body, it seems we have an automatically computed representation of our body position in space. This has been termed "the body postural representation" (Medina & Coslett, 2010).

Experiments examining tactile temporal order judgments (TOJ) support the notion of body postural representations. In TOJ tasks, subjects are usually blindfolded and then asked to determine which part of their body was touched first. Using this paradigm, Yamamoto and Kitazawa (2001) found that performance differed depending on whether subjects had crossed or uncrossed their arms. When arms were uncrossed (i.e. held straight out in front of the subject), subjects were able to determine which hand was touched first when stimuli were presented only 70ms apart (this is called "the just noticeable difference"). However, in trials where subjects' hands were crossed, just noticeable difference (JND) was much longer (~1 second), and some subjects consistently inverted the correct temporal order. Interestingly, this "crossed arm" effect has also been observed in tasks where participants crossed foot over foot and even foot over hand, suggesting that this phenomenon affects the whole body (Schicke & Roder, 2006).
To explain the "crossed arm" effect, Yamamoto and Kitazawa (2001) concluded that humans engage in two levels of processing to determine where their bodies are. The first level accesses the body form (e.g., "This is my right hand.") and assumes the body is in its typical position (e.g., the right hand is on the right side of space). The second level subsequently takes into account body posture (e.g., the right hand is on the left side of space at this moment). Only then do we realize where our bodies are in relation to external space. Confirming this hypothesis is an eye tracking study which examined saccades to tactile targets. When arms were crossed, the eyes initially moved towards the unstimulated hand—as if body position had not yet been taken into account and the brain was assuming the right hand was on the right side of space—before curving towards the actual target (Groh & Sparks, 1996).

Azanon and Soto-Faraco (2008) replicated these findings using a crossmodal cueing paradigm. In their experiment, subjects held their arms under an opaque screen and either crossed their arms over (so the right arm was on the left side of the body and the left arm was on the right side of the body) or held their arms straight out (so that the right arm was on the right side of the body and the left arm was on the left side of the body). Vibrators were placed on both of the subjects' ring fingers. In the cueing task, the vibrators served as non-predictive tactile-spatial cues. In congruent trials in the uncrossed arm condition, visual stimulus was presented on the same side as the tactile stimulus (e.g., when the right hand was stimulated and the visual stimulus appeared on the right side). In congruent trials for the crossed arm condition, visual stimuli were flashed on the same side of space as the vibrated finger (e.g., in a congruent trial there would be a visual stimulus on the right side of space after the left hand, which was occupying the right side of space, was stimulated). Visual stimuli were presented at two different elevations (either high or low); subjects were asked to respond to what elevation the visual stimuli were flashed, irrespective of
side of presentation and of the preceding tactile event, which was completely uninformative about
the location or elevation of the upcoming target. However, the measure of interest was actually
the spatial-cueing effect—the difference in response times to congruent and incongruent trials.

The researchers’ central question was how the body form representation—which represents the
body somatotopically—and the body postural representation—which represents the body in
relation to external space—interact to localize stimuli. Based on the conclusions of Yamamoto and
Kitazawa (2001), who argued that humans first access their body form representation before
accessing their body postural representation, Azanon and Soto-Faraco (2008) predicted that their
subjects would momentarily access their somatotopic body form representation before accessing
their body postural representation. If their predictions were correct, then subjects’ reaction times
would be faster when tactile cues were anatomically/somatotopically congruent with visual cues,
but only when the two cues were presented very close to each other in time. In contrast, if there is
a longer delay between the two cues, then subjects should respond faster when the tactile cue is
externally congruent with the visual cue.

Consistent with these predictions, the results showed that reaction times to the visual targets,
presented during the first hundred milliseconds after the tactile cue, were faster when the two
cues were presented on somatotopically congruent sides, even when the arms were crossed. In
other words, subjects would respond faster to a visual stimulus presented on their right side if
their right hand was stimulated, regardless of the right hand’s location in space. This is consistent
with a somatotopic organization, in which the hand’s actual position is not taken into account; it is
simply assumed to be in its prepotent location. However, “This pattern completely reversed after
about two hundred milliseconds, so that tactile cues produced a facilitation of targets presented at
If enough time passed between the two cues, it seemed that subjects no longer represented their hands somatotopically, without any regard to their actual position in space. Instead, cues that were externally congruent facilitated performance and cues that were externally incongruent (regardless of their somatotopic congruency) disrupted performance.

From these results, the researchers concluded that subjects first accessed the somatotopic body form representation before taking into account the external body posture representation. Such results are consistent with the findings of Yamamoto and Kitazawa (2001) as well as Groh and Sparks (1996), and further support the concept of the body postural representation.

Body schema theorists have applied findings from these body postural representation studies to the tool use debate. For instance, in the second part of the previously discussed TOJ study by Yamamoto and Kitazawa (2001), the researchers had subjects perform a TOJ task, this time while holding sticks with vibratory stimulators positioned at the end. Consistent with previous results, subjects performed well when the arms and sticks were uncrossed. However, when subjects maintained their hands on their respective sides (e.g., right hand on right side) but crossed the tips of their sticks, their just noticeable difference (JND)—defined as the smallest interval that produces 75% correct performance—was the same as if their hands were crossed. In other words, subjects' performance on the TOJ task suggested that they were behaving as if the tips of the sticks were part of their bodies, or as if stimuli are encoded the same way when applied to the body as when they are applied to tools. Body schema theorists claim this is clear evidence that tools become functional extensions of the body into space.
**Neural correlate.** Because the primary somatosensory cortex maps skin location independently of arm posture (Penfield & Ramussen, 1950; Sutherland, 2006), it seems like there must be a distinct neural process that uses sensory and body position information in order to locate the origin stimuli in external space. The neural substrate underlying this process appears to be the anterior portion of the superior parietal lobule (BA5). BA5 is implicated because of its structural connectivity as well as findings from single cell recording, lesion, and TMS studies. For instance, BA5 receives direct input from primary and secondary somatosensory cortices (Rizzolatti, et al, 1998). Further, primate studies have found neurons in BA5 that are preferentially active when limbs are in certain locations in space (Sakata et al., 1973). Additionally, neurons in BA5 encode location in a trunk-centered reference frame (Lacquianiti et al., 1995), suggesting BA5 is where the brain creates the external reference frame necessary to determine one's position in space. Lesion studies confirm this hypothesis; Wolpert et al. (1998) reported a subject with a large left superior parietal cyst (affecting BA5) who was unable to maintain a representation of limb location in space. In other words, without BA5, the subject appeared unable to create a body posture representation.

TMS studies have provided further proof for BA5’s role in postural representations. Using the TOJ paradigm developed by Yamamoto and Kitazawa (2001), Medina et al. (unpublished) had subjects determine which of their hands were touched first when their arms were either crossed or uncrossed. In a deviation from Yamamoto and Kitazawa (2001), Medina et al. (unpublished) also applied TMS to BA5 while subjects completed this task. The researchers predicted that if BA5 represented the body’s position in space, there would be no effect of applying TMS to BA5 when the subjects’ hands were uncrossed (as hands are in their typical position and body posture does not need to be taken into account. However, body posture would need to be taken into account if
the hands were crossed, so the researchers predicted that performance would be affected by TMS to BA5 during crossed hand conditions. Because subjects typically perform worse when their hands are crossed and they need to take into account body posture, the researchers predicted that applying TMS to BA5 would paradoxically improve performance on crossed hand trials. Indeed, this is exactly what they found; TMS to BA5 only affected trials where subjects had to determine the position of their hands, a finding that supports the localization of body posture to BA5.

**Peripersonal space.** In addition to the findings discussed earlier, Azanon and Soto-Faraco (2008) found that all cueing effects were neutralized when they moved the visual stimuli so that they were located higher above subjects' hands. In other words, it seemed that "...the cueing effects previously reported were spatially specific and not the result of a general orienting bias toward the whole hemispace." (p 1045) Thus, it appeared that space close to the hands was somehow being processed differently than space farther apart from the body. In fact, a number of studies have found visuotactile interactions are stronger when stimuli are presented in space close to the body compared to space further around the body (e.g. di Pellegrino et al., 1997; Lâdavas et al, 1998). Such differential processing has led to the distinction between area located near the body—typically the area within reaching distance of the arms—and area located outside reaching distance. The former is known as peripersonal space.

According to body schema theorists, the brain represents peripersonal space distinctly from far-space. Further, when people use tools, the area encoded as "peripersonal space" increases in order to include the area within reaching distance of the tool. Thus, the body schema hypothesis of tool use relies on two assumptions regarding peripersonal space: first, there is a peripersonal space representation; second, this representation is plastic and can enlarge in response to tool
This section will discuss studies that support both of these assumptions, as well as possible neural correlates of the peripersonal space representation.

Both human and non-human primate studies support the idea that space near the body is processed differently than space far away from the body. For instance, in monkeys, space around the hand (peri-hand space) is represented by visuo-tactile neurons, which display a gradient of firing dependent upon the distance of the visual stimulus from the hand (Duhamel et al., 1991, 1998; Fogassi et al., 1996, 1999; Graziano and Gross, 1995; Rizzolatti et al., 1981). Because the firing rates of these neurons increase when a stimulus approaches the hand, but decreases when the stimulus retreats away from the hand, it appears these neurons are coding space near the hand differently than space close to the hand. Interestingly, the neurons encoding this space are multimodal (as they respond to both visual and tactile stimuli), suggesting that peripersonal space is represented through integrated multisensory processing (e.g. Spence & Driver, 2004; Calvert et al., 2004; Maravita & Iriki 2004).

Studies of patients with neglect caused by brain damage, which is characterized by the tendency to ignore stimuli contralateral to the side of their brain damage—i.e. contralesional stimuli (Bisiach & Vallar, 2000)—also support the idea of peripersonal space. In a case study of patient P.P., who neglected space near her body, Berti and Frassinetti (2000) requested that P.P. mark the midpoint of a drawn line. As typically observed in neglect, P.P.’s mark was too far to the right because she failed to take into account the entire left side of the line. However, when the line was represented out of reach (i.e. in space far away from the body, outside of peripersonal space); P.P. was able to accurately bisect lines using a laser pointer. In contrast, when P.P. was given a stick—as opposed to a laser pointer—to bisect the far line, she again showed a rightward bias in her bisection. As
predicted by the body schema theory, it was as if using the stick made far-away space (outside peripersonal space) closer to her actual body (inside peripersonal space), causing her brain to expand the amount of area in peripersonal space, and suggesting that representations of peripersonal space can change in response to experience (in this case, tool use).

The idea that we have plastic representations of peripersonal space have also been supported by studies of cross-modal extinction in brain damaged humans. First, these studies suggest that peripersonal/near-space is encoded differently than far space (Bender, 1952; Mattingley et al., 1997). For these subjects, the presentation of an ipsilesional stimulus (i.e. presentation of the stimulus to the hemisphere not affected by their brain damage) can cause them to not perceive a stimulus simultaneously presented contralesionaly (i.e. presentation of the stimulus to the hemisphere that is affected by their brain damage). Interestingly, the effect of the ipsilesional stimulus on contralesional tactile perception can be modulated by the distance from the body at which ipsilesional visual stimuli are presented (di Pellegrino et al., 1997; Ladavas et al., 1998); stimuli presented closer to the body are more effective in extinguishing the perception of contralesional tactile stimuli than stimuli presented further away. Thus, both human and primate studies suggest that space is processed differently depending on how close it is to the body.

Evidence for body schema theorists’ second claim regarding peripersonal space representations—that the peripersonal space representation is plastic and can expand to include area within reaching distance of tools—has also been supported by studies on brain damaged patients. As just described, people with cross-modal extinction are less likely to be able to perceive contralesional stimuli when competing ipsilateral stimuli are presented close to their bodies. Typically, these patients’ perception of contralesional stimuli are less affected by ipsilesional stimuli presented
further away from the body. However, when given tools that extend their reachable space, the
same stimuli that were previously out of reaching distance and ineffective at producing extinction
become significantly more effective at producing extinction. As Farnè et al. (2007) explain,

Using tools to extend reachable space modifies the strength of visual-tactile
extinction, thus showing that tool-mediated actions modify the multisensory
coding of near peripersonal space. For example, following the use of a rake to
retrieve distant, otherwise nonreachable objects, the peri-hand multisensory area
has been documented to extend to include the distal part of a rake (Farnè and
Làdavas, 2000). (p 436)

Interestingly, the increased effectiveness of distant stimuli only occurred when the subjects were
able to use the tool. When researchers impeded tool-use, the severity of cross-modal extinction
decreased to levels found before subjects used the tools. Consistent with these findings, Maravita
et al. (2001) found visual-tactile extinction in area around the tip of a stick a subject was using.
Visual-tactile extinction in the exact same area was found to be significantly weaker when the
stick was not present, or even when the stick was there but the subject was not holding it.
Additionally, Farnè et al. (2005a) found that simply passively holding a tool did not evoke the
patterns of cross-modal extinction found when the same subject actively used the tool.

If it can be assumed that the increased effectiveness of stimuli at producing cross-modal extinction
reflects how these stimuli are being represented as in peripersonal space, while stimuli that fail to
produce effective cross-modal extinction are not being represented in peripersonal space, then it
appears peripersonal space representation is quite plastic; when subjects are not using tools, only
the area within reaching distance of their arms is represented as peripersonal space; directly after
they use a tool, space represented around the tool becomes encoded as peripersonal space; after they are no longer using a tool (regardless of whether the tool is still accessible), the area represented as peripersonal space decreases, shrinking back to the area within reaching distance of the arms.

Moreover, Farnè et al. (2005b) found that they could manipulate the size of subjects' peripersonal space (defined in this study as the area in which stimuli reduced the most effective cross-modal extinctions) by manipulating the length of the tool subjects were given. Farnè et al. (2005b) gave subjects 30 or 60 cm long rakes. They found that stimuli presented 60 cm away from the hand produced greater cross-modal extinction after subjects' used a 60 cm long rake compared to a 30 cm long rake (although these stimuli were more effective at producing cross-modal extinction following the 30 cm long rake use than following no tool use). These findings provide support for idea that peripersonal space representations are plastic, changing to represent the areas within reaching distance of tools—a fundamental aspect of the body schema hypothesis.

Studies of typical subjects and crossmodal interference also support the body schema hypothesis. For instance, Maravita et al. (2002) investigated whether the behavioral effects caused by crossmodal interference when subjects cross their arms also occur when subjects cross their tools (see Figure 2). The researchers used a paradigm in which visual distractors are flashed at subjects' fingertips while subjects have to localize tactile stimuli. The interference caused by visual distractors is stronger when the flashes are on the same side as the hand (ipsilateral) than when the flashes are presented on the opposite side of the hand (contralateral). Interestingly, this effect reverses when the hands are crossed; instead, the distractors interfere more with
localization of stimuli delivered to the anatomically contralateral hand (which is now ipsilateral in external space).

In a modification of this paradigm, Maravita et al. (2002) had subjects hold tools while their hands were stimulated and visual distractors flashed at their tool tips. They found a similar reversal of crossmodal interference—seen when just the hands are crossed—when just the tools were crossed. It appeared that stimuli presented to the left tool distracted from touches on the left hand, even though its functional tip was in the right side of space. Intriguingly, this reversal of visual interference based on tool posture increased with increased tool use. Consistent with Yamamoto and Kitazawa's (2001) as well as Ishibashi et al.'s (2000) findings, Maravita et al. (2002) provided support for the hypothesis that—after tool use—tools become treated like parts of the body.

**Neural correlate.** Because of the ethical considerations preventing researchers from conducting single cell recording studies in healthy humans, scientists have heavily relied on monkey models to inform us on the localization of tool use. Although some researchers question the applications of monkey models of tool use to human (e.g. Holmes et al., 2004), others maintain that humans and monkeys share similar multisensory systems that serve to represent peripersonal space (e.g. Bremmer et al., 2001; Rizzolatti et al., 1983).
Figure 2. Crossmodal effects of tool use in humans. (a–c) Normal observers were required to judge which of two computerized vibrotactile targets (denoted by yellow triangles throughout) placed under the thumb and finger of either hand was stimulated while wielding two toy-golf clubs. Subjects must respond as quickly as possible and also ignore simultaneous visual distractors (red star symbols throughout), arranged in a similar up/down orientation at the tools' tip. As in other experiments with the stimulated hands in direct contact with visual distractors [35], with uncrossed tools (a) the typical somatosensory–visual interference (a slower response for incongruent relative elevation of stimuli and distractors) was stronger from distractors on the same side of space as the stimulated hand (indicated by red arrows; red bars in (c)), than from those on the opposite-side (blue arrows, bars). The pattern of interference reverses with crossed tool-tips (b).

(d–h) Crossmodal extinction (percentages below each panel) of left touches in patient B.V., who has right-hemisphere damage (denoted by X) Extinction decreased when simultaneous flashes near the right hand (d) were moved further away (e). Extinction increased again if the far flash was reached by a long stick (f) but not if the stick was disconnected from the hand (g). (h) After ten minutes of rake-assisted reaching with the left hand, left tactile extinction from right flashes at the tool tip decreased (pink bar) compared with the pre-training baseline level (blue bar). The pink dotted oval represents the expansion of a putative hand-centered somatosensory–visual space representation (blue circle) up to the tool-tip following tool use. This expansion might underlie the reduced competitive extinction.

Assuming the monkey model of peripersonal space is in fact analogous to the human model, single cell recording studies of non-human primates have revealed that peri-hand space coding appears to be implemented by bimodal neurons within a circuit of cerebral structures including the putamen, parietal and ventral premotor areas (Bremmer, Shlack, Duhamel, Graf, & Fink, 2001; Duhamel, Colby, & Golberg, 1991, 1998; Graziano & Gross, 1995, 1998; Rizzolatti, Luppino, & Matelli, 1998; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981). Neurons in these structures have receptive fields around the hand; when visual or tactile stimuli approach the hand, the firing rate of these bimodal neurons increase; when visuo-tactile stimuli withdraw from their hand, the firing rate of these bimodal neurons decrease (Duhamel et al., 1991, 1998; Fogassi et al., 1996; Fogassi et al., 1999; Graziano & Gross, 1995; Rizzolatti et al., 1981).

Neurons in the parietal and intraparietal cortex seem to be especially involved in the representation of peripersonal space. Iriki et al. (1996) recorded from neurons in the parietal cortex in monkeys while they used tools and found that the visual receptive fields of these neurons expanded to include area around a tool (in this case, a rake) that the monkeys had to use to retrieve distant food pellets. The authors argued this expansion of receptive fields reflected the incorporation of the tool into the monkey's peri-hand space. Interestingly, the extension of these receptive fields contracted back to the pre-tool-use size after the monkeys stopped using the tools (regardless of whether or not they continued to simply hold the tool).

Maravita and Iriki (2004) reported similar findings after they recorded from neurons in the intraparietal cortex of Japanese macaques; the receptive field of neurons that coded for area within reaching distance of the macaque's body (pre-tool-use) were found to expand post-tool-use to include areas only accessible through reaching with a tool.
In fact, a number of studies have associated the intraparietal cortex with representations of peripersonal space. For instance, Ishibashi et al. (2000) conducted an experiment in which macaques were trained for two weeks to use a rake to pull food into reach. By using the tool, the macaques' reaching distance was increased, and thus they could interact with a larger amount of space in the environment. Before, during and after tool use training, the researchers recorded activity from neurons that responded to both somatosensory (Figure 3a, blue area) and visual stimulation (Figure 3b, pink area). Some of these neurons had visual receptive fields (vRFs) that responded to somatosensory stimuli at the hand and to visual stimuli near the hand (Distal-type neurons). The vRFs of these neurons changed as the hand moved in space, appearing to track the area near the hands, regardless of hand position. Similarly, they found neurons with vRFs covering the space the macaque could reach with its arm (Proximal-type neurons; Figure 3f). These proximal-type neurons appear to code for peripersonal space, the area around our bodies that we can interact with.

The crucial finding of this study is that tool use appeared to expand peripersonal space (space originally around the body) to include new space accessed by the tool, as seen by the expansion of receptive fields to include the new space made accessible by the rake (Figure 3g). The researchers suggested the expansion of the vRFs of distal-type neurons to include the entire length of the tool after tool use (Figure 3c) might demonstrate how tools become incorporated into the body.
Distal-type neurons
(a) (b) (c) (d)

Proximal-type neurons
(e) (f) (g)

Figure 3. Changes in bimodal receptive field properties following tool use. The somatosensory receptive fields (sRF) of cells in this region were identified by light touches, passive manipulation of joints or active hand-use. The visual RF (vRF) was defined as the area in which cellular responses were evoked by visual probes (the most effective ones being those moving towards the sRF). (a) sRF (blue area) of the ‘distal type’ bimodal neurons and their vRF (pink areas) (b) before tool use, (c) immediately after tool use, and (d) when just passively grabbing the rake. (e) sRF (blue area) of ‘proximal type’ bimodal neurons, and their vRF (pink areas) (f) before and (g) immediately after tool use.

Figure and text taken from Maravita and Iriki (2004).
schema theory as well as informs us regarding the role of intraparietal cortex in representing peripersonal space.

**Summary of the body schema literature.** The body schema literature suggests we represent our bodies through multiple, multisensory representations, the product of which has been termed the body schema. Critical to the body schema are the body form representation (neural correlates possibly including the iPCS and aIPS)—which somatotopically represents the size and shape of the body—as well as the body postural representation (neural correlate: BA5)—which represents the posture of the body in relation to external space.

The body schema hypothesis of tool use states that humans use tools by incorporating them into their body schemas. This hypothesis relies first on the existence of the body schema and second, on the ability of body schema representations to dynamically change in response to experience. As discussed in this section, both of these claims appear to be well supported; a number of studies suggest body schema representations enlarge following tool use in order to represent the tool as part of the body. Both behavioral and single cell recording studies of peripersonal space—the area around the body—strongly support the idea that tools become incorporated into representations of our bodies; after tools are used to extend one’s reach, area that was previously coded as far away from the body appears to be coded as close to the body. Hence, it appears that tools can become incorporated into a plastic neural representation of our body, as suggested by Head and Holmes (1911) and Iriki (1996).
Thus, it appears the theoretical foundation of the body schema hypothesis—interactions between the body form, body postural, and peripersonal space representations—are well supported. However, as discussed in the introduction, there are two competing explanations of the results of body schema studies in the context of tool use. The first hypothesis is the body schema hypothesis, developed in 1911 by Head and Holmes and extended by Iriki et al. (1996). The second is the attention hypothesis, proposed by Holmes et al. (2004), which questions the role of the body schema in tool use.

Holmes et al. (2004) argue that tools do not simply 'extend' peripersonal space; instead, they propose that tool use might be modulated by a remapping of extrapersonal visual space around the tips of tools as peripersonal space and/or a redirection of multisensory spatial attention to the functional tips of tools (Holmes et al., 2007). Consequently, according to this hypothesis, the shafts of tools—which do not interact with the environment—are not paid attention to or incorporated into peripersonal space.

The attention theory was developed less than a decade ago. Hence, attention theorists' claim that past literature has failed to control for the possibility that subjects were merely paying attention to the tips of tools is accurate. However, this does not imply that the attention theory must be true. Instead, it has become necessary to design experiments that explicitly test the attention theory of tool use versus the body schema theory. This section will cover a number of experiments supporting the attention theory as well as a few experiments that, when viewed through an attention theory lens, fail to continue supporting the body schema theory.
Problems with past studies. Holmes et al. (2004) claims that the 'extending peripersonal space' hypothesis (the body schema theory) has not yet been tested empirically in humans. This claim is partly based on the fact that single cell recording studies of visuotactile peripersonal space are commonly performed on animals, as opposed to humans, due to practical and ethical concerns. Hence, researchers have long assumed, but not tested, the idea that non-human-primate studies of tool use yield analogous results for humans. Holmes et al. (2004) flatly reject this assumption. While it is unclear whether primate tool use is homologous to human tool use, it is clear that the human tool use model relies heavily on support from primate studies.

Another methodological issue Holmes et al. point out is that most previous studies of peripersonal space applied visual stimuli to the tips of tools, but not to areas the hands or on tool shafts. In such a design, it is impossible to determine whether the effects seen at the tips of tools apply to the entire length of the tool. As predicted by the attentional hypothesis, the shafts of the tools are processed differentially than the handles or functional tips of tools; failing to measure the effects of stimuli applied to the shafts of tools masks any potential difference between processing of the shaft versus the tip.

Holmes et al. (2007) cites another common methodological issue with tool use studies: they often require subjects to only use one tool. Although there are exceptions (e.g., Holmes et al., 2004; Maravita et al., 2001; Yamamoto and Kitazawa, 2001; Yamamoto et al., 2005), most studies require subjects to use one tool, usually just with the right hand. In such a design, it is difficult to tell what is happening when subjects make comparisons between stimuli presented on both sides of space. In these situations, it is possible participants simply pay attention to the side of space containing
the tool, enhancing the salience of visual stimuli presented there. If so, the results of some “body
schema studies” are attributable to paying attention, not incorporating area into peripersonal
space.

Holmes et al. (2004; 2007) argues that without the controls listed above, it is quite possible past
researchers have been misled; instead of observing VRFs of neurons expand to include whole
tools, researchers may have been observing VRFs of neurons center on the hands as well as shift
their centers to the tips of tools, ignoring tool shafts. In other words, Holmes et al. theorizes that
we use tools by shifting our attention to the functional tips of tools and/or by treating the region
of space specifically around the tips of the tools the same as peripersonal space near the hands.

In order to test their hypothesis, Holmes et al. (2004) made the following predictions:

(1) The same-tool versus opposite-tools difference in visuotactile interactions will be
stronger near the hands and at the tips of the tools, than in the middles of the shafts
of the tools [since the middles of tools are not incorporated into the body schema];
and (2) The magnitude of visuotactile interactions will be largest at the hands,
smallest in the middle of the tools, and larger again at the tips of the tools, perhaps
even as large as for visual stimuli presented near the hands. (p. 63)

Thus, Holmes et al. predicts that the previous effects of tool use on performance actually only
apply to the functional tips of tools and hand area, not to the entire tool.

**Crossmodal congruency task.** To test these predictions, Holmes et al. used a crossmodal
congruency task to measure the interaction between visual and tactile stimuli presented on tools
(Spence et al., 2004; see Figure 4).
Subjects were given a long rod to hold in each hand, which they used to discriminate the elevation of vibrotactile stimuli presented to their thumb (upper) or forefinger (lower) of either hand.

Visual distractors were presented in either an “upper” or “lower” location on the same or opposite side of the vibrotactile target. Subjects responded to where they thought the tactile stimuli were
coming from by pushing different foot pedals, one of which was located under the toes (upper),
and the other under the heel (lower). Congruent trials in this task were when visual and
vibrotactile stimuli were presented at the same elevation, regardless of side of space or distance of
the visual distractors (which were placed near the hands, middle of tools, and ends of tools). In
incongruent trials, the different stimuli were presented at different elevations. Between blocks of
trials, subjects had to press buttons with their tools; thus, subjects unquestionably had practice
using the tools.

The researchers found visuotactile interactions depended on which part of a tool was being used.

As Holmes et al. (2004) predicted,

When the tips of the tools were used to perform the tool use task, visual distractors
near the handles and near the tips resulted in a larger crossmodal congruency effect
when presented with same-tool vibrotactile targets than with opposite-tool targets
in interleaved trials of the crossmodal congruency task. (p. 65)

This seems to support the attention hypothesis, as it appears the subjects were paying more
attention to distractors by the hands and the tips of the tools than the tool shafts.

However, the researchers also found that when the shafts of the tools were used, visual distractors
on the shafts did not show any preferential effect of one tool with respect to the other, while the
distractors at the tips showed a strong effect. This defies Holmes et al.’s predictions, as they would
say that when the shafts of the tools were used to perform the intervening tool use tasks, the shaft
of the tool would become the “functional” part of the tool that requires attention and relocation of
VRFs. Thus, using the shafts of tools should produce increased same-tool versus opposite-tools
crossmodal congruency effects. Yet, this was not the case. Unfortunately for attention theorists,
this finding is quite troublesome for the attention theory; instead of unequivocally proving that attention is always redirected to the functional parts of tools, it suggests the task was designed in such a way that attention was directed towards the tips of tools. Perhaps the sheer complexity of the task (multiple distractors, multiple tactile stimulations, multiple ways to respond, multiple trials, and different ways of using the tools) affected subjects in an unmeasured but systematic way.

Further, Holmes et al.'s (2004) findings are inconsistent with a number of subsequent studies. In response to the findings of Holmes et al. (2004), Farné et al. (2007) conducted a single case study on a subject with crossmodal visual-tactile extinction was given a 60 cm long rake to use to retrieve distant objects. The researchers assessed visual-tactile extinction near the ipsilesional hand (holding the rake handle), near the functional tip of the rake, and near the middle (i.e. shaft) of the tool. Contrary to Holmes et al.'s (2004) findings—stimuli near the hands and tips of tools result in a larger crossmodal congruency effect—Farné et al. (2007) found that tool use produced a significant difference in crossmodal extinction between areas both near the shaft and the tip of tool. Further, there was no statistically significant difference between the crossmodal extinction seen at the shaft and the tip of the tool. Also, there was no change in the severity of cross-modal extinction in the area around the hand following tool use. These findings are consistent with the body schema hypothesis, that representations of peripersonal space do not shift towards the functional tips of tools, but rather elongate to include the entirety of tools. However, it is inconsistent with the attention hypothesis’ predictions that the shafts of tools are not incorporated into the body schema.
Although the findings of Fame et al. (2007) are intriguing, it is important to keep in mind the study was based on a single patient with fairly extensive brain damage (affecting areas BA 39, 40, 5, 7, 37 and 22). In order to provide more support for Fame et al.'s (2007) findings, Bonfiazi et al. (2007) replicated their study with 5 patients with crossmodal extinction. Again, it was found that crossmodal extinction effects following tool use were not statistically different in areas around the middle of the tool compared to areas around the tip of the tool. Such findings pose a large problem for the attention hypothesis of tool use, as it appears the shafts of the tools are not being attended to or processed differently than the functional tips of tools.

Still, both Fame et al. (2007) as well as Bonfiazi et al. (2007) only tested brain damaged patients, so it is unclear whether their results are applicable to the general population. For instance, it is possible subjects had brain damage that interfered with their attentional processes, causing their performance on tool use tasks to become qualitatively different than typical subjects. This explanation is actually quite possible, considering how Fame et al.'s (2007) subject showed moderate left visuospatial neglect, which is considered to be a problem associated with attention. Additionally, even after combining the subjects from both studies, these experiments reflect data from less than 7 different people. Clearly, further research is needed before any conclusions are made regarding relationships between crossmodal extinction, tool use, and the processing of tool shafts versus tool tips.

**FMRI study.** To provide further support for the attentional hypothesis of tool use, Holmes et al. (2008) conducted another test of whether tool use is mediated by shifting attention towards the functional tips of tools (see Figure 5). The researchers scanned healthy subjects using fMRI while subjects used a tool to find the location of vibrations. During the task, congruent (presented
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on the same side of space to the tool) or incongruent (presented on the opposite side of space) visual stimuli distracted subjects. Increased activation was found in the right lingual gyrus when visual stimuli were presented contralaterally, but decreased activity was found when distractors were presented ipsilaterally to the tool. Crucially, the effect of interactions on behavioral performance and BOLD response in the occipital cortex were modulated by both visual stimulus location and tool position. The researchers concluded these results show how using a tool causes a shift of spatial attention to the area around the functional tip of the tool. According to the researchers,

The consequence of this shift in spatial attention was that activity in occipital cortex was modulated in a manner consistent with previous studies of the voluntary orienting of spatial attention, enhancing activity contralateral, and suppressing activity ipsilateral to the visual distractors. (p. 12)

However, it is unclear how these results refute the body schema theory. The authors failed to have a condition where subjects did not use tools, so it is impossible to compare their performance with tools (namely, the effects of having ipsilateral vs. contralateral distractors) against their performance without tools. Instead, this study examined attention. Body schema theorists undoubtedly concede that attention is involved in tool use tasks (it would be quite difficult to use a tool without paying attention to it), so proving that attention is involved does not seem to affect the body schema theory. Additionally, this study failed to address any past
Figure 5.

A. Four of the eight experimental conditions are depicted (i.e., for the right hand tool use experiment only). The participants held a simple tool in their hand, with the tip held on the left or the right side. Filled circles: active visual distractors in each condition. Open circles: inactive visual distractors in each condition. Filled rectangles: active vibrotactile targets in each condition. Open rectangles: inactive vibrotactile targets in each condition.  

B. Main effect of visual distractor position (left/right illustrated). Grey columns: left hemifield visual stimuli. White columns: right hemifield visual stimuli.  

C. Main effect of tool tip and vibrotactile target position (left/right illustrated).  

D. Interaction between visual distractor and tool tip positions (same sides/different sides illustrated).  

E. Experimental apparatus. The participant lay supine in the scanner, viewing the apparatus via a head-coil-mounted mirror system. A tool (96750 mm wooden dowel) was held in either the participant’s left or right hand, and a response box was held in their other hand. The tool was oriented towards the participant’s legs. The tip of the tool was positioned on either the left or right vibrotactile target stimulator, depending on the condition, and guided by a semicircular rubber guide. The visual distractors were presented with two 10 mm red LEDs, positioned immediately above and behind each vibrotactile stimulator. The vibrotactile and visual stimulators were supported on an acrylic table, resting over the participant’s legs.  

literature regarding possible neural correlates of tool use, including BA5 and the pVIP. Instead, the researchers focused on how they found activation in the occipital cortex, which is hardly surprising considering they were presenting subjects with a visual task. In the end, this study demonstrates visual attention is probably involved in visual tool use tasks, but it fails to significantly contribute to the tool use debate.

**Crossmodal interference.** In a better test of attention, body schema and tool use, Holmes et al. (2007) investigated how tool position and body posture affect crossmodal interference. Over the course of 5 experiments, the researchers had subjects sit at a table and hold either one or two tools (one tool per hand) either straight out in front of them, or crossed so that the left tool was on the right side of space. In each trial the subjects had to use their tools to discriminate between single or double vibrotactile stimuli presented via their tools to either their right or left hands. During this task, subjects had to ignore visual distractors presented immediately above the left or right vibrotactile stimulators. Foot pedals were used to respond to the stimuli. The researchers’ main question was whether patterns of crossmodal interference—caused by the visual distractors—would change based on whether the subject was holding one or two tools.

When subjects only had one tool, visual-tactile interactions were strongest when the distractors were presented at the distal end of the tool held in the uncrossed posture. Interactions were also seen when the distractors were presented on the distal end of the tool when the tool was crossed to the opposite side of space. These results appear to support the body schema hypothesis; the area around the tool, regardless of where the tool was, was treated as if it was incorporated into peripersonal space.
Holmes et al. proposed an alternative explanation; perhaps participants were merely paying attention to the side of space occupied by the active tool. By directing attention to the “active” side of space, they became more vulnerable to being distracted by visual stimuli occupying the active space around the tool. A simple way to test this was to give participants two tools; with two tools, both sides of space are “active”, so differences in performance due to paying attention to the active side of space (the “tool-dependent spatial effect”) should disappear.

As predicted by the alternative explanation, the tool-dependent spatial effect was reduced when subjects held two tools. This suggests that some tool use studies might have accidently been measuring spatial attention, not incorporation of the tool into peripersonal space.

**Summary of the attention hypothesis.** Holmes et al. (2004; 2007) challenge the view that we use tools by incorporating them into our body schema. Instead of incorporating the entire tool into the body schema, they argue that the brain simply focuses on the functional tips of the tools, either by allocating attention to the functional tips of tools or by incorporating just the tips of tools into peripersonal space.

Holmes and colleagues conducted three experiments to test this alternative hypothesis. The first experiment, a crossmodal congruency task, seemed to show that subjects pay more attention to visual distractors presented by the handles and tips of tools, regardless of whether the tip of the tool or the shaft of the tool was used to complete a task. This finding is problematic for attention theorists, as it appears attention is not directed towards the functional part of the tool; instead, attention appears to be directed towards the tip and handle of the tool, regardless of their function.
In a second experiment, Holmes et al. (2008) scanned subjects using fMRI while subjects used tools to locate vibro-tactile stimuli. Activation in the occipital cortex was found. However, it is unclear how this finding contributes to the tool use debate; while it makes sense to find activation in the occipital cortex during a visual task, it does not at all test whether subjects were incorporating the whole tool into their body schemas.

In another experiment, Holmes et al. (2007) compared subjects' performance on a crossmodal interference task when they were given only one tool compared to when they were given two tools. Consistent with previous research, it was found that visual-tactile interactions were strongest when distractors were presented near the tip of the tool, regardless of which side of space the tool occupied. Although this could have been interpreted as evidence for the tool being incorporated into peripersonal space, Holmes et al. (2007) argued that the subjects' attention was merely being drawn to the side of space occupied by the tool. To test this, they gave subjects a tool to hold with the other hand, so that attention would be equally distributed between the two sides of space. As Holmes et al. (2007) predicted, the effectiveness of distractors presented at the tips of tools decreased.

Together, these studies suggest that people pay attention to the tips of tools they are using (perhaps even when the tips are not the part of the tool being used). If this is the case, it is possible that the results of some tool use studies might have accidently been measuring spatial attention as opposed to the incorporation of the entire tool into peripersonal space. Despite this possibility, the results of Holmes and colleagues' three experiments are not sufficient to entirely reject the body schema hypothesis. In fact, because the body schema hypothesis does not deny the
involvement of attention in tool use, the results of these three studies do not seem to strongly contradict the body schema hypothesis.

**Theoretical Basis for the Present Study**

With the findings from Holmes et al. (2004; 2007; 2008) in mind, we have designed four TOJ experiments to test the two tool use theories. As Holmes et al. (2004) point out, many previous studies that appear to support the body schema theory failed to measure the effect of two tools. Additionally, many tool use experiments do not take into account the possibility that tool shafts might be processed differently than tool tips. Complicating matters is the extraordinary difficulty in experimentally teasing the body schema and attention theories apart. After all, you cannot "see" someone incorporating a tool into their body schema any more than you can "see" someone paying attention to the functional tips of tools. However, there are a few clever paradigms that can be manipulated to reveal hidden cognitive processes. One such research paradigm is the tactile Temporal Order Judgment (TOJ) tasks. For our thesis, we will use this design to test the predictions of the body schema theory and attention theory.

**The TOJ Literature**

In typical TOJ tasks (see Yamamoto & Kitazawa, 2001), subjects close their eyes and are then asked to put their arms out in front of them. Vibrotactile stimuli are applied to each hand, although one hand is stimulated before the other. The subject is then asked to judge which hand was touched first.
In a variation on this paradigm, Yamamoto and Kitazawa (2001b) had eight subjects perform a TOJ task while they held sticks with vibratory stimulators positioned at the end. This modification allowed the researchers to investigate whether crossing the sticks (i.e., tools) led to the same performance as crossing the hands. The researchers found that subjects performed very well when the arms and sticks were uncrossed and could accurately determine which of their sticks were touched first, even if there was only a 70ms difference between stimulation times. Interestingly, when subjects kept their hands on their respective sides (e.g., right hand on right side) but crossed the tips of their sticks, they needed much more time between stimulations to determine which hand was touched first. In fact, they needed the same amount of time between stimulations as when only their hands—but not their tools—were crossed. In other words, consistent with the body schema theory, subjects' performance on the TOJ task suggested that they were behaving as if the tips of the sticks were part of their bodies. However, attention theorists argue that the subjects were merely paying attention to the position of the tips of the tools; when the tool tips were on the opposite sides of space as the responding body part (when just the hands or just the tools were crossed), subjects needed more time between stimuli to determine which tool was vibrated first. When the tool tips were on the same side of space as the responding body part (when hands and tools were both uncrossed or crossed), subjects needed less time between stimuli to determine which tool was vibrated first.

**Performance with L-shaped tools.** Yamamoto and Kitazawa (2001b) found significant, consistent patterns of behavior, despite their exceedingly small sample size (n=8). However, no independent authors have yet published a replication of their results. The only published replication thus far (to this author's knowledge) was conducted by Yamamoto, Moizumi, and Kitazawa (2005). In this follow up study, 17 subjects were originally recruited, but data from 2
subjects were excluded from analysis because they performed below chance in at least one condition. In the end, 10 subjects completed a TOJ task using "L" shaped tools, while 5 subjects completed a TOJ task with straight tools. Of the 10 subjects who used L shape sticks, 6 participated in the first series of experiments, where they had their arms crossed or uncrossed but always held the L shaped sticks crossed twice. Only 4 subjects participated in conditions where there arms were always crossed and their L shaped sticks were crossed once or twice.

The procedure used by Yamamoto, Moizumi and Kitazawa (2005) had a number of similarities and important deviations from Yamamoto and Kitazawa (2001b). First, like the previous study, subjects were not given any practice with the tools before the experiments. Also similar to the previous study, audio interference was minimized by plugging the subjects' ears and giving them headphones which played white noise at 80 dB. Unlike the previous study, participants kept eyes open for all trials and were told to visually fixate on a central target. Also unlike the previous study, subjects were required to judge the order of stimulus presentation and respond by pressing the foot pedal below the tool tip that was judged to be stimulated last. In the 2001 study, subjects used their hands to respond with tools.

**The importance of tool configuration.** Although the small sample size (a problem compounded by the researchers' subdivision of subjects into 5 subject, 6 subject, and 4 subject groups) is a major limitation of this study, its results inform the tool use debate because performance depended on whether the tool tips were on the same side of space as the side of the body making the response. As seen in Yamamoto and Kitazawa (2001b), data from the straight tool condition (with 5 subjects) showed performance was better when the tool tips were on the same side of space as the responding body part (i.e. when hands and tools were both uncrossed or
when hands and tools were both crossed), and performance was worse when the tool tips were on
the opposite side of space as the responding body part (i.e. when just the tools or just the hands
were crossed). Interestingly, the results from the L shaped tool conditions confirmed these
results, suggesting that there is a strong performance difference between when subjects have to
cross their hands or tools an even number of times (putting the tool tips in ipsilateral space to the
responding body part; see Psychometric Curves 1 and 2, part A) versus an odd number of times
(which puts the tool tips in contralateral space to the responding body part; see Psychometric
Curves 1 and 2, part B). For instance, when hands are crossed and tools are crossed twice (an
odd number of crossings; Psychometric Curves 1 B) performance was similar to when hands were
uncrossed and tools were crossed (also an odd number of crossings). Meanwhile, performance
when hands and tools were crossed once each (an even number of crossings; Psychometric Curves
2 A) was similar to performance when hands were uncrossed, but tools were crossed twice (again,
an even number of crossings; Psychometric Curves 1 A).

One way to interpret this data is that the position of the tool tip relative to the responding body
part mattered while the configuration of the rest of the tool was irrelevant. In this interpretation,
what matters is whether the stimulated tool was on the same side of space (ipsilateral) or
different side of space (contralateral) as the responding foot, with ipsilateral performance being
better than contralateral performance. This interpretation is consistent with the results from
Yamamoto and Kitazawa (2001b), who also found the tool tip position predicted performance.

In support of the idea that the actual configuration of the tool was irrelevant and that only the
position of the tool tips mattered, the authors also looked at reaction times by each hand/tool
configuration. It was found reaction time did not directly correlate with the number of crossings,
suggesting that the complexity of the physical configuration actually does not matter, only
whether the tool tip is contralateral or ipsilateral to its “responding foot”. Although it is difficult to
draw any conclusions from this study due to its extremely small sample size, these results seem to
support the claims of the attention theorists, that tool shafts are ignored while tool tips are
attended to.

**Psychometric Curves 1**

Psychometric Curves 1: Temporal order judgment with L-shaped sticks crossed twice. Open
circles and black curves show data from the control condition for comparison. A and B illustrate
order judgment probability. C and D show mean reaction time. Each circle represents an average
performance over 50 judgments from 5 subjects. For A and B, the Y axis represents whether the
subject responded with their right foot pedal (signifying right tool was stimulated first). The x
axis on all graphs represents the stimulation interval (time between the two stimulations), with
positive numbers signifying the right tool was stimulated first and negative numbers signifying
the left tool was stimulated first. For A and B, perfect performance on positive stimulation
intervals is 1, perfect performance on negative stimulation intervals is 0. Figure taken from

In A and C, arms were uncrossed (even number of crossings, tool tips ipsilateral to responding
body part, good performance). In B and D, arms were crossed as well as the tools (odd number of
crossings, tool tips contralateral to responding body part, poor performance).
Psychometric Curves 2: Temporal order judgment with L-shaped with hands crossed. Each data point represents 24 judgments from 4 subjects. Other graph conventions follow the figure above. Figure taken from Yamamoto, Moizumi and Kitazawa (2005). A and C reflect performance when tools were crossed once as well (even number of crossings, tool tip ipsilateral to responding body part, good performance. B and D reflect performance when tools were crossed twice (odd number of crossings, tool tip contralateral to responding body part, bad performance.

Still, body schema theorists could argue that the entire tool was being incorporated into the body schema as an abnormally bent arm. Following this reasoning, although the “arm” bent and crossed a number of times, the “hand” eventually ended up on one side of space, which is what mattered during the TOJ performance. Clearly, further research is needed to test these possibilities.

The importance of different kinds of crossings. Another interesting finding from Yamamoto, Moizumi and Kitazawa (2005) came from a direct comparison to Yamamoto and
Kitazawa (2001a; 2001b). As can be seen in figure 6, between these three experiments, a number of different crossings were examined: (A) a physical hand crossing; (B) not a physical crossing of the hands, but a placing of the hands in the contralateral side of space; (C) a physical crossing of straight tools; (D) placing the tips of L shaped tools in contralateral space without crossing the tools, a “non-physical” crossing.

**Figure 6**

**Figure 6: Diagrams of different TOJ paradigms.** Part A illustrates the physical hand crossing seen in Yamamoto and Kitazawa (2001a). Part B illustrates crossing the hands into opposite sides of space without physically crossing the hands, as also seen in Yamamoto and Kitazawa (2001a). Part C illustrates the physical tool crossing seen in Yamamoto and Kitazawa (2001b). Part D illustrates the non-physical tool crossing made possible with L-shaped tools, where the tool tips are on different sides of space with a physical hand or tool crossing (Yamamoto, Moizumi & Kitazawa, 2005).

Figure taken from Yamamoto, Moizumi and Kitazawa (2005).

While performance when hands are physically crossed (see Psychometric Curves 3, e and f) was less accurate in comparison to hands uncrossed performance (see Psychometric Curves 3, a),
performance when hands are non-physically crossed (see Psychometric Curves 3, c and d) was very similar to hands uncrossed performance. This suggests that physical crossings have a stronger effect on performance than simply putting body parts in contralateral sides of space.

**Psychometric Curves 3.** Temporal order judgment in six arm arrangements. Each data point represents 128 judgments from 16 subjects. Figure taken from Yamamoto and Kitazawa (2001a).

However, that is not to say there is no effect of non-physical crossings. As illustrated in Psychometric Curves 4 A, non-physically crossing the tools (Psychometric Curves 4 A) significantly decreases performance accuracy compared to crossing the hands to keep the tool tips in ipsilateral space (Psychometric Curves 4 B).
Psychometric Curves 4: Temporal order judgment with L shaped sticks without physically crossing the sticks. Arms were uncrossed in A and C, but crossed in B and D. Each circle represents 50 judgments from 5 subjects. Figure taken from Yamamoto, Moizumi and Kitazawa (2005).

Together, the results from these experiments suggest there are two different types of position that affect performance: physically crossing the hands/tools or non-physically crossing the hands/tools. Although physically crossing the hands produces similar performance to physically crossing the tools, it appears non-physical crossings affect TOJ performance with tools but not TOJ performance with hands. This difference appears to undermine the body schema hypothesis, as tools are not being processed the same way as hands. Body schema theorists counter this claim by suggesting tools are not necessarily *automatically* incorporated into the body schema. Instead, one needs time and practice with the tool before it becomes represented as part of the body. Since
none of Yamamoto and Kitazawa's experiments included tool practice, this claim has yet to be tested in humans.

**Summary of the TOJ literature.** The combined findings of Yamamoto and Kitazawa (2001a; 2001b) and Yamamoto, Moizumi and Kitazawa (2005) suggest that the positions of tool tips influence performance (as opposed to the configuration of the tool shafts), and that only physical crossings of the hands (as opposed to physical crossings of the tools or non-physical crossings of any type) affect performance. This suggests there are two separate factors (position of tool tips and position of hands) that simultaneously affect performance.

In terms of specific patterns of performance, it appears response accuracy when tool tips are ipsilateral to the responding body part is quite high, even on difficult trials. In contrast, performance is less accurate when tool tips are contralateral to the responding body part. In non-tool TOJ tasks, it appears physical crossings of the hands affect performance while non-physical crossings do not.

### 4 TOJ Experiments to Test Theories of Tool Use

Although the experiments conducted by Yamamoto and Kitazawa are often cited, together, their 2001b and 2005 studies draw conclusions based on 13 subjects who used straight tools and 10 subjects who used L shaped tools. Moreover, to the extent of this author's knowledge, their results have not been replicated by independent authors in any published studies. Clearly, further
evidence is needed to support the robustness of Yamamoto and Kitazawa's claims by testing how well their results characterize performance on TOJ tasks with tools under different conditions.

To address this gap in the literature, we decided to replicate Yamamoto and Kitazawa's (2001b) results using a variety of paradigms and an increased number of subjects. We designed 4 experiments: a pure replication of Yamamoto and Kitazawa (2001b), a test of the effects of tool practice, a test of the effects of having one's eyes open or closed, and a test of the effects of using foot pedals versus tools to respond to stimuli. Unlike Yamamoto and Kitazawa (2001b), who did not even report the number of female subjects in their study, we also investigated the effect of sex on TOJ task performance.

**Theoretical Basis for the Different Conditions**

We decided to investigate the effects of tool practice for a number of reasons. First, Maravita and Iriki (2004) demonstrated that bimodal neurons in macaques that originally encoded area near the hand could come to encode area around a macaque's tool. However, this only happened after weeks of tool practice. Additionally, Yamamoto, Moizumi and Kitazawa (2005) proposed they might have obtained different results from their TOJ task if they had given subjects practice using tools.

We did not originally mean to test different response types. However, when we attempted to replicate Yamamoto and Kitazawa (2001b) using foot pedals, we found unexpected patterns in performance, despite the fact Yamamoto, Moizumi and Kitazawa (2005) used foot pedals and eye saccades and found similar patterns of performance to Yamamoto and Kitazawa (2001b). Thus, we decided to directly compare foot pedal response to tool response.
Sex differences have been seen in a TOJ task involving auditory stimuli as opposed to tools. Wittmann and Szelag (2003) found females needed longer interstimulus intervals than males to determine which auditory stimulus came first. However, sex differences in tactile TOJ tasks using tools have not been found, largely because they have not been investigated. In a non-tool tactile TOJ task, Cadieux et al. (2010) stimulated subjects hands while subjects used foot pedals to respond to which side of space was stimulated first, regardless of which “side hand” (i.e., the left hand or right hand) were stimulated first. It was found females were significantly worse than males at this task when they had to cross their hands. Based on this, the authors concluded females had more “right-left confusion” because they relied more on visual, external reference frames while males relied more on egocentric, internal reference frames. To the extent of this author’s knowledge, Cadieux et al.’s claims have not since been replicated, let alone further investigated. Still, findings that males outperform females in auditory TOJ tasks combined with the claim females make more right-left confusion errors in tactile TOJ tasks suggested males would outperform females in our tactile TOJ task with tools. While sex differences were not intended to be the focus of this study, they were still examined because of the dearth of research in this field.

The decision to test eyes open or closed was based largely on our repeated failures to replicate Yamamoto and Kitazawa’s results. Yet, this decision also had a theoretical basis. Azanon and Soto-Faraco (2007) conducted a TOJ experiment without tools and found that subjects’ performance decreased after they crossed their hands, consistent with Yamamoto and Kitazawa (2001a). Then, Azanon and Soto-Faraco had subjects look at uncrossed rubber hands while their actual hands were crossed, which caused subjects to actually perform better. Thus, it seems visual
information can affect spatial and tactile processing. Although we were unsure how visual information might affect performance on a TOJ experiment with tools, we were curious to see its effects.

Predictions

For all experiments we expected to replicate the results of Yamamoto and Kitazawa (2001b) in that the position of the tool tips would predict performance (i.e. hands crossed tools uncrossed performance would be equivalent to hands uncrossed tools crossed performance while hands uncrossed tools uncrossed performance would be similar to hands crossed tools crossed performance).

Experiment 1: Replication of Yamamoto and Kitazawa (2001b) with Foot Pedals

Participants. Twelve right handed participants were recruited from Haverford’s Introduction to Psychology pool. There were 10 females with an average age of 18.5 years (age range 18-20). Participants received Introduction to Psychology credit as compensation for their participation in the experiment. All participants were right handed, as reported on a handedness questionnaire, and all provided written informed consent prior to their participation. All participants were naïve to the purpose of the experiment.

Apparatus. In all experiments, subjects were seated at a table and were given two tools to hold. The tools in all experiments in this study were backscratchers (19” long, by Earth Therapeutics, Plainview, NY). The backscratchers hand a handle, shaft, and a tip that was slightly curved at the end. Tactaid VBW32 Skin Transducer (Audiological Engineering Corporation,
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Somerville, MA) were attached to the dorsal surface of the tool tips. Subjects held these tools (13” from tip to handle) and judged which of the tools were vibrated first.

**Stimuli.** In all experiments, each TOJ trial involved two successive tactile stimuli (7 ms supra-threshold intensity) delivered to the tips of the tools at a series of inter-stimulus intervals ranging from 10 to 750 ms. The vibrations were faint enough to not produce any audible noise (experimenters’ observations). It seems unlikely subjects used noise—as opposed to tactile stimuli—from the vibrations to detect which tool was vibrated first; no subjects reported doing so.

There were 168 trials per block. Each trial presented vibrations at one of 12 interstimulus intervals (750, 450, 300, 200, 150, 100, 75, 50, 40, 30, 15, or 5 ms). 14 trials of each interstimulus interval were presented in a randomized order. On half the trials, the right tool was stimulated first. On the other half, the left tool was stimulated first. Additionally, time between trials was randomized (between 750-1250 ms) so that subjects could not anticipate the onset of the next trial.

**Procedure.** In experiments 1 and 2 subjects responded with foot pedals placed under their feet: if they felt their right tool vibrated first, they responded by lifting their right foot off the right foot pedal; if they felt their left tool vibrated first, they responded by lifting their left foot off the left foot pedal.

In all experiments in this study, subjects adopted the 4 different positions seen in Yamamoto and Kitazawa (2001). In position 1, hands and tools were both uncrossed (HUTU). In position 2, hands were uncrossed, tools crossed (HUTX). In position 3, hands were crossed and tools were
uncrossed (HXTU). In position 4, both hands and tools were crossed (HXTX). On tool crossed conditions (positions 2 and 4), foam pads were placed between the tools to disrupt any possible vibration transfer between the tools.

The order subjects adopted these positions was semi-counterbalanced in all experiments. Because there were four different blocks (HUTU, HUTX, HXTU, HXTX), there were 24 possible permutations. It was intended to have 12 subjects per experiment, so only 12 of the 24 possible permutations were used. The same set of permutations was used for all experiments. The position of the hands in the crossed conditions (i.e. which hand was on top) was not counterbalanced. Instead, subjects adopted whatever position was most comfortable.

At the beginning of each experiment subjects were given a practice session to become acquainted with the tools, stimuli, and pedals. In this practice session, subjects were shown a central fixation point. Then only one of their tools was vibrated. The subject had to judge which tool had been vibrated. Accuracy and response time was presented to ensure the subjects understood how to accurately respond to the stimuli. The practice session had 10 trials. If the subjects performed at chance during the practice session, or reported being unable to feel the vibrations, the practice session was repeated to ensure the subject understood how the experiment worked.

Data collection began after the practice session. Subjects were instructed to respond as accurately as possible without paying attention to their response times. Subjects were also reminded how to appropriately respond to stimuli. These instructions were repeated before each block. Subjects were given the option of taking a short break between blocks.
In experiments 1-3, subjects completed each block with their eyes closed in a quiet room, using only their sense of touch to determine which tool was vibrated first. The vibrators attached to the tool did not produce any audible noise (researchers' observations), nor did they move in a visually detectable way when they vibrated (researchers' observations).

**Analysis.** In cases where subjects performed at chance for the tools and hands uncrossed condition, it was assumed the subject either did not understand the task or was not motivated to complete the experiment to the best of his or her ability. The data for these subjects were excluded from analysis and additional subjects were recruited and run under the block permutation assigned to the excluded subjects.

**Results.** One subject consistently performed at chance, even on the hand and sticks uncrossed condition. This subject's data was excluded from analysis.

The Graph of TOJ Performance 1 illustrates our results. As can be seen, hands crossed, tools crossed (HXTX) and hands crossed tools uncrossed (HXTU) conditions were very similar. Hands uncrossed tools uncrossed (HUTU) and hands uncrossed tools crossed (HUTX) were also very similar, suggesting there was not a very big effect of crossing tools. This contradicts the findings of Yamamoto and Kitazawa (2001b), who found similar performance between HXTU and HUTX conditions.
Graph of grand average performance for experiment 1: foot pedal response, eyes closed, no practice.

The x axis represents different ISIs. Negative values represent trials when the left tool was stimulated first. Positive values represent trials when the right tool was stimulated first. The y axis represents percent of right first responses. For negative ISI, when the left tool is stimulated first, 0 is perfect performance. For positive ISI, when the right tool is stimulated first, 1 is perfect performance.

Experiment 2: Foot Pedals and Tool Practice

Participants. Fourteen new participants were either recruited from the Haverford College Introduction to Psychology pool and compensated for their participation with Introduction to Psychology credit, or recruited by word of mouth and compensated with $10 for their participation. There were 9 females with an average age of 19.1 years (age range 18-20). All but 3 participants were right handed, as reported on a handedness questionnaire, and all provided written informed consent prior to their participation. All participants were naïve to the purpose of the experiment.

Procedure. The procedure for experiment 2 was exactly the same as experiment 1 but with one modification. Before each block, the subject would “practice” with the tools in the
position he or she would be adopting for the upcoming TOJ task. This practice included repeatedly picking up a small ball with the tools and moving it to a target location. Subjects were given one minute to move the ball to the target location (where it was then picked up by the experimenter and moved to a random location) as many times as possible. The practice session was designed to give subjects more experience with the tools, possibly allowing subjects to incorporate the tools into their body schemas.

**Prediction.** It was also predicted that more practice would result in a stronger effect of tool crossing. Hand crossing has repeatedly shown to affect TOJ task performance; according to the body schema theory of tool use, tools are incorporated into the body schema and “processed” as part of the body. It was thought practice with the tools would facilitate this incorporation, so that crossing the tools would result in effects similar to crossing the arms.

**Results.** Two participants did not appear to understand the directions of the experiment so their data were excluded from analysis. Other subjects were run on their block permutations. Additionally, three subjects (all female) performed at chance on the hand and tool uncrossed condition (HUTU). Because previous research has demonstrated subjects are very accurate in the HUTU condition (Yamamoto and Kitazawa, 2001b), it was decided these subjects also did not understand the experiment. Their data was excluded for analysis and no additional subjects were recruited or run under their block permutations.

Despite the lower number of subjects included in the analysis of experiment 2, as well as the introduction of tool practice, a similar pattern of performance to that seen in experiment 1
emerges, see the Graph of TOJ Performance 2. Again, there is a clustering of performance between the hands crossed conditions at lower accuracy than conditions with hands uncrossed.

**Graph of TOJ Performance 2**

Graph of grand averages for experiment 2: foot pedal response, eyes closed, tool practice. Overall performance patterns appear quite similar to those seen in Experiment 1, with HCTC and HCTU performance less accurate than HUTC and HUTU performance.

**Experiment 3: Responding with the Tools**

**Participants.** 12 new right handed participants (6 female, age range 18-33 years, average age 20.91 years) who had not participated in this study's previous experiments were recruited from Haverford and Bryn Mawr Colleges. Participants were either recruited from the Haverford College Introduction to Psychology pool and compensated for their participation with Introduction to Psychology credit, or recruited by word of mouth and compensated with $10 for their participation.
**Procedure.** For Experiments 3 and 4, subjects responded with their tools instead of their feet. In order to achieve this, the foot pedals were mounted in a metal and wood frame on top of the table. The pedals were placed perpendicular to the table so that subjects could reach out with their tools and push the pedals. The pedal mounts were designed so that they could be swung inwards, making it easier for subjects to push the pedals in the tool crossed conditions. Subjects could put the tips of their tools (which formed small hooks) into plastic bands on the fronts of the pedals. This helped hold the tools in place next to the pedals when subjects had to close their eyes for the task. Subjects also had the option to invert the “top” pedal (based on which hand was on top in the crossed hand conditions) to make the pedals easier to push.

Subjects were instructed to adopt the same four positions adopted in Experiment 1. However, instead of responding with their right feet if their right tool was stimulated first, subjects were instructed to respond with their right tool if their right tool was stimulated first. In addition to the bands keeping the tools in place next to the appropriate pedals, the pedals were positioned in such a manner that each tool was only within easy reaching distance of one pedal. Thus, there was little risk subjects would get confused and use the correct tool to press the incorrect pedal.

**Predictions.** Yamamoto, Moizumi and Kitazawa (2005) claimed that responding with foot pedals (and even eye saccades) results in similar performance on TOJ tasks compared to responding with tools (Yamamoto and Kitazawa, 2001b). Based on these claims, we did not predict an effect of response type on performance.

**Results.** Despite the change in response type, a similar pattern of performance emerges (compared to experiments 1 and 2), see the Graph of TOJ Performance 3. Yet again, hands crossed
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Performance clustered around lower rates of accuracy than hands uncrossed performance, regardless of tool crossing.

Graph of TOJ Performance 3

Graph of grand averages for experiment 3: tool response, eyes closed, no tool practice. Overall performance patterns appear quite similar to those seen in Experiment 1, with HCTC and HCTU performance less accurate than HUTC and HUTU performance.

Experiment 4: Responding with the Tools, Eyes Open

Participants. 11 new right-handed participants and 1 new left-handed participant (4 female, age range 18-20 years, average age 19.2 years) who had not participated in this study's previous experiments were recruited from Haverford and Bryn Mawr Colleges. Participants were either recruited from the Haverford College Introduction to Psychology pool and compensated for their participation with Introduction to Psychology credit, or recruited by word of mouth and compensated with $10 for their participation.

Procedure. Experiment 4 was much like experiment 3 except subjects had their eyes open during the task instead of closed. Two small adjustments were also made: an amplifier (Logitech, Fremont, CA) was used to slightly increase the intensity of the tactile stimuli and the springs in the pedals were replaced with lighter springs that made pushing the pedals easier. These small adjustments helped subjects perceive and respond to stimuli.
Predictions. We were unsure how having one’s eyes open would affect performance on a TOJ task with tools, but Azanon and Soto-Faraco’s (2007) results suggested visual information can affect TOJ performance. If Cadieux et al.’s (2010) conclusions are correct—that females rely more on visual cues during spatial processing—perhaps females might perform better with their eyes open, or they might become more confused during crossed conditions. With so little previous research the effect of visual cues on TOJ performance, we did not know what to predict.

Results. For experiment 4, less clustering was found for performance on hands crossed or hands uncrossed conditions than was found for previous experiments (see the Graph of TOJ Performance 4). However, HXTU performance was still below HUTX, in contrast to the findings of Yamamoto and Kitazawa (2001b).

Graph of TOJ Performance 4

Graph of grand averages for experiment 4: tool response, eyes open, no tool practice. Overall performance patterns appear quite similar to those seen in Experiment 1, with HCTC and HCTU performance less accurate than HUTC and HUTU performance.

Results across Experiments

In order to get a better grasp of large scale patterns of performance, analyses were conducted across experiments to both look at performance of all subjects as well as to compare and contrast
performance across experiments. This allowed us to investigate differences between experiments, as well as look at the effects of posture, sex and response type across a greater number of subjects.

We conducted a number of ANOVAs. For all analyses, the dependent variable was response accuracy. Additionally, Greenhouse-Geisser corrections were done when assumptions of sphericity were violated. There were only four levels of interstimulus interval (ISI) in our analyses because for all the experiments, the different ISIs were grouped together (i.e. binned) into 4 different categories. Bin 1 included trials with ISIs of 5-30ms, Bin 2 had trials with ISIs of 40-75ms, Bin 3 included trials with ISIs of 100-200ms, and Bin 4 had trials with ISIs of 300-750ms.

**Tool practice, eyes open or closed.** First, to determine whether there were any effects of tool practice or having eyes open, we conducted two mixed 2 (experiment) X 2 (sex) X 2 (side of space stimulated first) * 4 (ISI) * 2 (hand position) * 2 (tool position) ANOVAs. If there were no effects of tool practice or having eyes open, data from experiments 1 and 2 could be combined and experiments 3 and 4 could be combined, allowing for further investigation of the other factors that differed between and within experiments (e.g., response type, sex, etc.).

The first ANOVA was run to investigate the effects of experiment in experiments 1 and 2. No main effect of experiment was found, $F(1, 17) = .047, p = .83$, nor were any significant interactions involving experiment found. The lack of any significant effects or interactions of experiment suggest that tool practice did not significantly affect performance. Thus, we combined subject data from experiments 1 and 2 to better investigate the effects of responding with foot pedals.
The second ANOVA was conducted on subjects from experiments 3 and 4 to determine whether having eyes open significantly affected performance. Again, no main effect of experiment, $F(1, 20) = .005, p = .942$, was found. Thus it was determined that having eyes open did not have a large effect on performance. Subject data from experiments 3 and 4 were combined for further analyses of the effects of responding with tools.

**Hand and tool positions.** Although it appeared there was no effect of tool practice or having eyes open, grand average performance across experiments reflects a clear effect of posture (see the Graph of TOJ Performance 5).

![Graph of TOJ Performance 5](image)

**Graph of performance over all 4 experiments by posture**
As seen in the individual experiments, HUTU and HUTX performance is very similar and very accurate. In contrast, HCTC and HCTU are less accurate. This is inconsistent with the results from Yamamoto and Kitazawa (2001b), who found HXTU and HUTX to be equivalent and significantly different from HXTX and HUTU, which were found to be equivalent to each other.

Yamamoto and Kitazawa (2001b) also found differences in performance based on posture, however the patterns they found were quite different from ours. While we found hands
uncrossed performance to be similar and hands crossed performance to be similar (regardless of tool position), Yamamoto and Kitazawa found it was the position of the tool tip that mattered, not the position of the hands (so HXTU was similar to HUTX while HUTU was similar to HXTX).

To further investigate the effect of posture, analyses were conducted on the effects of hand position and tool position. The effects of hand crossing and tool crossing were individually investigated using a 2 (hand position) X 2 (tool position) X 4 (ISI) X 2 (side) X 2 (sex) mixed factor ANOVA. A main effect of hand position (crossed or uncrossed) was found, F(1, 41) = 43.62, p < .001. This was consistent with our predictions, as well as past literature. There was no main effect of tool position, F(1, 41) = 1.45, p = .235, which was inconsistent with our predictions and past literature. Additionally, a significant interaction was found between hand position and tool position, F(1, 41) = 8.47, p = .006. This interaction confirms the statistical significance of the patterns of behavior in the graph of overall performance; tool position did not seem to have a big effect when hands were uncrossed, but did seem to have a big position when hands were crossed.

Summary of tool position * hand position analyses. Analyses on data from all 4 experiments revealed a main effect of hand position, but no main effect of tool position. Instead, an interaction was observed between hand and tool position, suggesting tool position only has an effect when hands are crossed.

Post-hoc testing: Paired t-tests. Because previous research has consistently found an effect of tool crossing, post-hoc testing was necessary to understand the differences in performance patterns we observed.
Paired t-tests on overall accuracy by hand and tool position (i.e. HXTX vs. HXTU vs. HUTX vs. HUTU) were conducted to further investigate the tool position * hand position interaction. It was found performance on hands uncrossed tools uncrossed (HUTU) was significantly better than hands crossed tools uncrossed (HXTU), \( t(44) = -9.69, p < .001 \), as well as hands crossed tools crossed (HXTX), \( t(44) = -4.828, p < .001 \). This is consistent with previous findings that HUTU produces the most accurate performance and hand crossing leads to a decrement in performance (Yamamoto & Kitazawa, 2001b). Consistent with the idea hands crossing affects performance, HXTX performance was significantly different from hands uncrossed tools crossed (HUTX), \( t(44) = -3.76, p < .001 \).

Inconsistent with previous findings, HUTU performance was not significantly different from HUTX, \( t(44) = -1.92, p = .06 \), although it did approach significance. This suggested there was at most a slight effect of tool crossing. It was also found that HXTU performance was significantly different from HUTX performance, \( t(44) = -7.448, p < .001 \), in contrast to Yamamoto and Kitazawa's (2001b) findings that HUTX and HXTU performances were similar. Still, some evidence was found for a tool crossing effect, with HXTU performance actually being significantly worse than HXTX performance, \( t(44) = 2.578, p = .01 \).

**Summary of t-test results.** It appeared there was only an effect of tool crossing when the hands were crossed. When the hands were uncrossed, HUTU and HUTX performance was not significantly different. However, when the hands were crossed, HXTX performance was significantly better than HXTU performance. This seems inconsistent with past literature, which found HUTU and HXTU performance to be similar, and HUTU and HUTX performance to be different.
Psychometric Curve Fitting and Monte Carlo Analyses

The effects of posture (i.e. tool position and hand position) by response type were further investigated using psychometric curve fitting and Monte Carlo analyses. These analyses are more fine grained ways of analyzing data because they are more sensitive about capturing data; all time points are looked at—as opposed to being binned, which was done for the ANOVAs—and the data is fitted to a curve, which is more representative of the data. With curved shaped data it is important to analyze the slope, intercept, and ends of the curve. ANOVAs are not very sensitive to capturing the slope of the curve, which is unfortunate, as the curve’s slope is the primary measure of a subject’s skill at the TOJ task.

In contrast, psychometric curve fitting takes the slope, intercept and ends of curves (also known as the lambda and gamma) into account, allowing us to examine at what ISIs the participants were no longer to determine which stimulus came first (as measured by the slope) as well as how well they were able to respond to the task after perceiving the stimuli (as measured by the end performance, i.e. the easy trials where stimuli were separated by more than half a second). Monte Carlo analyses focus on two aspects of the psychometric curves: slope—which in our analyses is equivalent to accuracy during difficult trials, and threshold—which represents the amount of side bias (i.e. how much accuracy differed by the right side vs. left side). Monte Carlo analyses ignore end performance (performance on easy trials), so follow up t-tests on performance on large ISI trials were also conducted.

We used Psignifit software (http://bootstrap-software.org/psignifit/toolbox.php) to fit psychometric functions to our data sets using MATLAB. Psignifit can fit two data sets to
psychometric functions, and then uses Monte Carlo simulations to examine if the slope and/or thresholds of the two curves are statistically different.

In Monte Carlo analyses, a comparison is conducted between the psychometric functions of two data sets. A Monte Carlo analysis combines all the data from the two conditions (per time point), and then randomly selects from the combined data set to create two curves. The difference in slope and threshold in these randomly generated curves is noted, and this process is repeated 5000 random permutations of the data. The difference in the slope and threshold of the actual data sets are compared to the differences in slope and threshold in the 5000 randomly generated curves. The p value is generated by comparing the size of the difference in slope/threshold in the two curves from the data set to the slope/threshold differences in the 5000 permutations. If the difference in slope/threshold was greater than 95% of the randomly generated slope/threshold differences, then the analysis deems the results significant.

**Hand position * tool position * response type.** We first used the Monte Carlo analyses to explore the effect of crossing tools. Contrary to past literature, we failed to find a main effect of tool position but did find an interaction between hand and tool position. To understand when this interaction was taking place, we compared conditions where the tools were being crossed to conditions to where tools were not being crossed. These analyses were further broken down by response type to examine how response modality influenced performance.

Monte Carlo analyses revealed that in experiments where subjects responded with tools (Experiment 3 & 4), there was no significant difference between performance on HUTX and HUTU conditions, p = .323 (see Monte Carlo Analysis 1). The same was found for experiments 1 and 2,
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when subjects responded with foot pedals; HUTU and HUTX performance was not significantly different, \( p = .171 \) (Monte Carlo Analysis 2).

These findings from the HUTU and HUTX conditions, combined with the failure to find a main effect of tool position suggest that tool position does not have a significant effect on performance at least when hands are uncrossed.

However, as mentioned earlier, there was a significant interaction found between hand position and tool position. Monte Carlo analyses revealed this interaction manifested itself in the HXTU vs. HXTX conditions, which were found to produce significantly different patterns of behavior in experiments 3 and 4, \( p < .001 \) (see Monte Carlo Analysis 3). While this finding seemed to reveal some effect of tool position (or possibly some effect of just the tool tip position) when the hands were crossed, the Monte Carlo analysis found no significant difference between HXTX and HXTU conditions in experiments 1 and 2, \( p = .105 \) (see Monte Carlo Analysis 4). This suggests response type has an effect on performance during hands crossed trials.
Monte Carlo Analysis 1

Psychometric curve and Monte Carlo Analysis of Experiments 3 and 4: HUTU vs. HUTX
Performance on the HUTX condition are red dots on psychometric curve, HUTU performance are blue. Monte Carlo analyses focus on the middle of the curve (the slope). The top of the figure plots performance while the bottom of the figure checks for significance. The x axis checks for "threshold" differences, or a right/left bias in response patterns. The y axis checks for slope (i.e. accuracy on hard trials) differences. The crosshairs represent where our data falls relative to the "data" randomly generated by the Monte Carlo analysis.
For this analysis, the crosshairs fall within the range of the random data's threshold and slope, so our curves are not judged to be statistically significant.
Psychometric curve and Monte Carlo Analysis of Experiments 1 and 2: HUTU vs. HUTX
Performance on the HUTX condition are red dots on psychometric curve, HUTU performance are blue. Both threshold and slope were not significantly different.
Psychometric curve and Monte Carlo Analysis of Experiments 3 and 4: HXTU vs. HXTX
Performance on the HXTX condition are red dots on psychometric curve, HXTU performance are blue. Slope was significantly different. Although the end performance of the curves appear similar, the middle performance is clearly different, highlighting the advantages of using psychometric curve fitting for analyzing this kind of performance data.
Psychometric curve and Monte Carlo Analysis of Experiments 1 and 2: HXTX vs. HXTU

Performance on the HXTX condition are red dots on psychometric curve, HXTU performance are blue. Both threshold and slope were not significantly different. However, upon closer inspection, it appears the blue “curve” is actually a line while the red performance is more reminiscent of a curve. This highlights the disadvantages of psychometric curve fitting; linear data and data with high variance are difficult to fit to a representative curve, making it difficult to find significance.
Summary of Monte Carlo analyses of hand position * tool position * ISI * response type. We found tool position only appeared to affect performance when hands were crossed and subjects were responding with tools instead of foot pedals. When hands were not crossed (HUTU and HUTX conditions) tool position did not appear to affect performance, regardless of response modality. These findings are inconsistent with previous research that has consistently found an effect of tool tip position.

Sex Differences

The mixed factor 2 (sex) X 2 (side) X 2 (response type) X 4 (posture) X 4 (ISI) ANOVA did not reveal a large effect of sex. In fact, the main effect of sex only approached significance, F(1, 43) = 3.21, p = .08), but there were significant interactions between posture, sex and response type, F (3, 123) = 2.80, p = .04. Additionally, the sex by response type interaction, F(1, 41) = 3.779, p = .059, approached significance. Although the ANOVA only hinted at significant sex differences, graphs of our data suggested there might be major differences in performance between the sexes, thus revealing the relative weakness of ANOVAs when analyzing data better represented by curves than group averages.

Overall sex differences. Using Monte Carlo analyses, we found general sex differences across all experiments. The results of these analyses are reported below. The graphs of the results are located in Appendix A: Supplementary Monte Carlo Analyses.

First, it was found males generally performed better than females. Significant differences (p = .011) exist between males and females on HUTU conditions, with females performing slightly worse than males (see Supplementary Monte Carlo Analysis 1). Additionally there was a significant
difference in performance between males and females on the HUTX condition, \( p = .001 \) (see Supplementary Monte Carlo Analysis 2). Although the difference was slight, it appeared males slightly outperformed females again.

Although the psychometric curves in the males versus females HXTU condition look significantly different, the Monte Carlo analysis focused on performance on the difficult trials (middle of the curves), performance which was not significantly different, \( p = .316 \), between males and females (see Supplementary Monte Carlo Analysis 3). Examining the curves reveals large differences in the end performance (easy trials). A follow up t-test was conducted on end performance (trials with large ISIs) to confirm whether these apparent differences were statistically significant, which they were, \( t(43) = -2.481 \ p = .017 \), with males again outperforming females.

For the final condition, HXTX, a significant difference was found between males and females, \( p = .007 \), with males performing significantly better than females (see Supplementary Monte Carlo Analysis 4). Again, it appears end performance was significantly different between males and females. However, a follow up t-test, \( t(43) = -1.27 \ p = .211 \), reveals this difference in end performance is deceptive; instead of reflecting a statistically significant difference, the differences in the curves reflects the huge variance in the data sets.

**Summary of sex * hand position * tool position.** The results from these overall analyses of sex * hand position * tool position are summarized in Table 1 below. It was found male performance on hard trials was significantly better than female performance on HXTX, HUTX, and HUTU conditions. Male performance on easy trials was significantly better than female performance on the HXTU condition.
Table 1: Summary of Sex * Hand Position * Tool Position

<table>
<thead>
<tr>
<th>Condition</th>
<th>Sex</th>
<th>Hand</th>
<th>Tool</th>
<th>t(43)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>HXTX</td>
<td>Female</td>
<td>HX</td>
<td>TX</td>
<td>-1.270</td>
<td>.211</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>HX</td>
<td>TX</td>
<td>-2.481</td>
<td>.017*</td>
</tr>
<tr>
<td>HUTX</td>
<td>Female</td>
<td>HU</td>
<td>TX</td>
<td>.201</td>
<td>.842</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>HU</td>
<td>TX</td>
<td>-.560</td>
<td>.578</td>
</tr>
<tr>
<td>HXTU</td>
<td>Female</td>
<td>HX</td>
<td>TU</td>
<td>-2.481</td>
<td>.017*</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>HX</td>
<td>TU</td>
<td>-.560</td>
<td>.578</td>
</tr>
<tr>
<td>HUTU</td>
<td>Female</td>
<td>HU</td>
<td>TU</td>
<td>.201</td>
<td>.842</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>HU</td>
<td>TU</td>
<td>-.560</td>
<td>.578</td>
</tr>
</tbody>
</table>

Table 1: Summary of Monte Carlo and t-test analyses of sex*hand position*tool position

Monte Carlo analyses focus on slope, or the performance on hard trials in the center of the psychometric curve. Because these analyses do not examine performance on easy trials (on the tails of curves) follow up t-tests were conducted to see if there were significant differences in performance on easy trials. Significant values are noted with an *.

Sex differences by response type: Males vs. females. Although it appears males clearly outperformed females, analyzing sex by posture by response type reveals a completely different story. To further investigate the differences in performance by sex, we graphed performance by sex in different conditions by the different possible response types (see Graphs of TOJ Performance 6-9).

The graphs reveal that in experiments 1 and 2, where foot pedals were used to respond, males performed significantly better, especially on HXTU and HXTX conditions. Females performed barely above chance in experiments 1 and 2 during the HXTX and HXTU conditions. This is in sharp contrast to their performance on HXTX and HXTU conditions during tool response experiments, in which they performed so accurately, they outperformed males. Additionally, males performed consistently worse on tool response trials (relative to foot response trials). Females only performed better on tool response trials in HXTX and HUTU conditions.
Graph of male performance on experiments 1 and 2: Foot Pedal Response
The x axis represents the interstimulus intervals (ISIs), with negative numbers reflecting trials where the left tool was stimulated first and positive numbers reflecting trials where the right tool was stimulated first. The y axis represents right-first responses. Chance performance was at .5. For the left hand of the graph, when the left tool was stimulated first, perfect performance is 0. For the right hand of the graph, when the right tool was stimulated first, perfect performance is 1. Male performance with foot pedals seems to reflect the grand average performance across all experiments.

Graph of female performance on experiments 1 and 2: Foot Pedal Response
In contrast to male performance, female performance on HXTX and HXTU was almost at chance. Because performance on HUTU and HUTC conditions was more accurate, it does not appear the females misunderstood the directions of the task. Note that the HXTU and HUTC conditions show very different patterns of performance, as opposed to the similarity between HUTX and HXTU conditions seen in Yamamoto and Kitazawa (2001b).
Graph of male performance on experiments 3 and 4: Tool Response
Male performance on experiments 3 and 4 looks very much like performance on experiments 1 and 2, although it is slightly worse.

Graph of female performance on Experiments 3 and 4: Tool Response
While subjects used foot pedals to respond in experiments 1 and 2, subjects used tools to respond in experiments 3 and 4. Females exhibit significantly better patterns of performance in these experiments, and even outperform the males.

**Sex * response type * hand position * tool position: Monte Carlo analyses:** To confirm the patterns seen in the performance graphs, additional Monte Carlo analyses were conducted based on sex differences by position and response type. The results from these analyses are
reported below. The graphs from these analyses are located in Appendix A: Supplementary Monte Carlo Analyses.

In experiments one and two, where foot pedals were used, there was a significant (though slight) difference in performance between males and females on the HUTU condition, $p < .001$ with males performing slightly better (see Supplementary Monte Carlo Analysis 5). Males also performed significantly better on the foot pedal response experiments in the HUTX condition, $p < .001$ (see Supplementary Monte Carlo Analysis 6).

Slight, though significant differences were found in performance between males and females in the hands uncrossed (with tools crossed or uncrossed) conditions. In the hands crossed conditions, female performance dramatically decreased, to the point that it was barely above chance. Males very significantly outperformed females in the HXTU condition, $p < .001$ (see Supplementary Monte Carlo Analysis 7). As would be expected by the significantly different psychometric curves (female performance was basically linear, while male performance actually curved), a follow up t-test revealed that males also performed significantly better than females on easy trials, $t(19) = -2.814, p = .011$.

Interestingly, when hands and tools are crossed (HXTX), females still perform worse than males, but not significantly according to the Monte Carlo analyses, $p = .087$ (see Supplementary Monte Carlo Analysis 8). Although tool crossing does not appear to affect performance very much when hands are uncrossed (as seen by the similar performance in HUTX and HUTU conditions), when hands are crossed, the tool crossing somehow has an effect.
Intriguingly, completely different patterns of performance were seen in the tool response condition. First, in contrast to their significantly different performance on HUTU in the foot pedal condition, when responding with tools in the HUTU condition, males and females did not perform significantly differently, \( p = .802 \) (see Supplementary Monte Carlo Analysis 9). Further, in contrast to how males performed better than females in the HUTX condition with foot pedal response, a significant difference between male and female performance in the HUTX condition with tool response was observed, \( p = .047 \), with females outperforming males (see Supplementary Monte Carlo Analysis 10).

Again, in contrast with findings from the foot pedal experiments, females appeared to significantly outperform the males in the HXTU condition when responding with tools, \( p = .004 \) (see Supplementary Monte Carlo Analysis 11). However, like the HXTX condition with foot pedals, no significant difference in performance between males and females was found on the HXTX condition when responding with tools, \( p = .974 \) (see Supplementary Monte Carlo Analysis 12).

**Summary of sex * response type * hand position * tool position results:** Differences in performance between the sexes by posture and response type are summarized in Table 2. When responding with feet, males performed significantly better than females in HUTU, HUTX, and HXTU positions. When responding with tools, females outperformed males in HXTU and HUTX positions—positions where the tips of the tools were in the contralateral side of space as the responding hands. However, male and female performance when responding with tools was not significantly different when the tips of the tools were on the same sides of space as the responding hand. The importance of this distinction is explored in the discussion section.
Table 2: Summary of sex * response type * hand position * tool position results

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Condition 2</th>
<th>T-Test of End Effects</th>
<th>Monte Carlo p Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male Foot HXTX</td>
<td>Female Foot HXTX</td>
<td>$t(19) = -1.377$, $p = .184$</td>
<td>$p = .081$</td>
</tr>
<tr>
<td>Male Foot HXTU</td>
<td>Female Foot HXTU</td>
<td>$t(19) = -2.814$, $p = .011^*$</td>
<td>$p &lt; .001^*$</td>
</tr>
<tr>
<td>Male Foot HUTX</td>
<td>Female Foot HUTX</td>
<td>$t(19) = .238$, $p = .815$</td>
<td>$p &lt; .001^*$</td>
</tr>
<tr>
<td>Male Tool HXTX</td>
<td>Female Tool HXTX</td>
<td>$t(21) = .004$, $p = .996$</td>
<td>$p = .974$</td>
</tr>
<tr>
<td>Male Tool HXTU</td>
<td>Female Tool HXTU</td>
<td>$t(21) = -.0261$, $p = .796$</td>
<td>$p = .004^*$</td>
</tr>
<tr>
<td>Male Tool HUTX</td>
<td>Female Tool HUTX</td>
<td>$t(21) = .845$, $p = .408$</td>
<td>$p = .047^*$</td>
</tr>
<tr>
<td>Male Tool HUTU</td>
<td>Female Tool HUTU</td>
<td>$t(21) = .889$, $p = .384$</td>
<td>$p = .802$</td>
</tr>
</tbody>
</table>

Table of differences in performance between the sexes by posture and response type
Significant values are noted with an asterisk (*)

**Different Response Types by Posture within Each Sex**

Our analyses revealed clear performance differences between the sexes depending on response modality. To further explore these interactions, Monte Carlo analyses were used to directly compare the interactions between sex, response type, tool position and hand position.

**Females.** It was found female performance was significantly better when responding with tools than with foot pedals, but only in the HXTX condition, $p = .021$, and HUTU condition, $p = .031$ (see Supplementary Monte Carlo Analysis 13). Although Monte Carlo analyses did not find the female performance on HXTU conditions significantly different between tool response and foot response trials, an examination of the post hoc tests reveals this is only because the Monte Carlo does not examine high ISI behavior (i.e. the tails of the curves/performance on easy trials). As discussed earlier, Monte Carlo analyses ignore tail performance (also called gamma and lambda differences), which measure the amount of error on the very large ISI trials. Because of this, follow up t-tests were conducted to further examine behavior on large ISI trials. It was found that
for these large ISIs, female performance was significantly better when responding with tools compared to foot pedals on HXTU trials, $t(22) = -3.53, p = .002$.

The t-test revealed that female performance was better when responding with tools on the HXTU trials, in addition to the HXTX and HUTU trials (as mentioned above). The only condition in which responding with tools did not improve performance was on HUTX trials. Neither the Monte Carlo analysis on central behavior, $p = .305$ (see Supplementary Monte Carlo Analysis 15), nor a follow up t-test on end behavior, $t(22) = -1.22, p = .24$, revealed any significant differences between female HUTX performance when responding with tools or foot pedals.

**Males.** Males consistently performed better with foot pedals than they did with tools. This was seen in the HUTU condition, $p = .018$ (see Supplementary Monte Carlo Analysis 16), HUTX condition, $p = .008$ (see Supplementary Monte Carlo Analysis 17), HXTU condition, $p <.001$ (see Supplementary Monte Carlo Analysis 18), and HXTX condition, $p = .003$ (see Supplementary Monte Carlo Analysis 19). Male foot pedal response performance was significantly better than male tool response performance for all hand and tool positions. Further, a follow up t-test on the HUTU condition found that even male tail performance was better for foot pedal responses. However, follow up t-tests for the other conditions did not find significantly different performance on tail performance.

**Summary for females and males: Within sex response type differences.** These within sex performance differences by response type are summarized in Table 3, which compares Monte Carlo p values for central effects (performance on small ISI trials) to the t-tests of end effects (performance on large ISI trials). Male central performance with foot pedals was significantly
better than male central performance with tools. Female performance was less consistent, with central HXTX and HUTU performance and tail HXTU performance better with tools than with foot pedals.

Table 3: Summary for females and males: Within sex response type differences

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Condition 2</th>
<th>T-Test of End Effects</th>
<th>Monte Carlo p Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female Foot HXTX</td>
<td>Female Tool HXTX</td>
<td>t(21) = x, p = .105</td>
<td>p = .021*</td>
</tr>
<tr>
<td>Female Foot HXTU</td>
<td>Female Tool HXTU</td>
<td>t(21) = x, p = .008*</td>
<td>p = .495</td>
</tr>
<tr>
<td>Female Foot HUTX</td>
<td>Female Tool HUTX</td>
<td>t(21) = x, p = .241</td>
<td>p = .305</td>
</tr>
<tr>
<td>Female Foot HUTU</td>
<td>Female Tool HUTU</td>
<td>t(21) = x, p = .454</td>
<td>p = .031*</td>
</tr>
<tr>
<td>Male Foot HXTX</td>
<td>Male Tool HXTX</td>
<td>t(20) = x, p = .684</td>
<td>p = .003*</td>
</tr>
<tr>
<td>Male Foot HXTU</td>
<td>Male Tool HXTU</td>
<td>t(20) = x, p = .817</td>
<td>p &lt; .001*</td>
</tr>
<tr>
<td>Male Foot HUTX</td>
<td>Male Tool HUTX</td>
<td>t(20) = x, p = .284</td>
<td>p &lt; .001*</td>
</tr>
<tr>
<td>Male Foot HUTU</td>
<td>Male Tool HUTU</td>
<td>t(20) = x, p = .028</td>
<td>p = .018*</td>
</tr>
</tbody>
</table>

Within sex differences by response type
Significant values are noted with an asterisk (*)

“Good” versus “Bad” Performers

In another attempt to explain why our results differed so much from the literature, we decided to see whether dividing subjects into “good” versus “bad” performers would reveal patterns of performance more similar to Yamamoto and Kitazawa (2001b). The theoretical basis for this division came from Yamamoto, Moizumi and Kitazawa (2005), who chose to exclude subjects from analysis if they performed at chance in at least one condition. We originally excluded subjects from analysis only if they performed at chance in the HUTU condition, as that has been consistently been shown to produce very accurate performance (suggesting that poor performance in this condition demonstrates a misunderstanding of the directions). However, we did not exclude participants who performed at chance in other conditions.
As seen in the Graph of TOJ Performance 10, if we had excluded data from subjects who performed at chance in any condition, we would have had to exclude a large number of female subjects who performed at chance on the HXTX and HXTU conditions.

Graph of TOJ Performance 10

Graph of female performance on experiments 1 and 2: Foot Pedal Response

Performance was at chance for hands crossed trials, but not on hands uncrossed trials, suggesting subjects understood the task directions but had trouble processing stimuli during hands crossed conditions.

However, as also seen in the Graph of TOJ Performance 10, these subjects performed well on hands uncrossed conditions, demonstrating that they understood the task directions and could accurately respond to stimuli. Their chance performance in certain conditions is actually a fascinating behavioral phenomenon that we decided to examine instead of exclude from analyses.

Thus, instead of excluding subjects’ data, we decided to split subjects up into two groups based on their performance on the high ISI, “easy” trials. We decided that subjects who scored above 88% (median performance) on high ISI trials would be classified as good performers (n = 24, 11 females) who made few left/right confusion errors. Subjects who scored below 88% on high ISI
trials were classified as bad performers (n = 20, 12 females) who made many left/right confusion errors on easy trials.

The differences in performance patterns between the two groups are striking. Good performers appear to have equivalent performance on HUTU, HUTX and HXTX trials (see the Graph of TOJ Performance 11). In contrast, HXTU performance is significantly worse than performance on all other conditions. This pattern of behavior is inconsistent with previous literature, as well as the behavior observed in “bad” performers. Follow up Monte Carlo analyses confirmed HUTU and HUTX were not significantly different, p = .369 (Supplementary Monte Carlo Analysis 21), and that HUTU and HXTX were not significantly different, p = .277 (Supplementary Monte Carlo Analysis 22). Monte Carlo analyses also confirmed HXTU performance was significantly worse than HUTU performance, p < .001 (Supplementary Monte Carlo Analysis 23), as well was HUTX performance, p < .001 (Supplementary Monte Carlo Analysis 24).

Graph of TOJ Performance 11

Graph of Overall Performance of Good Performers
Graph reflects data from 25 subjects.
The bad performers showed similar performance between HUTU and HUTX conditions, as seen in the Graph of TOJ Performance 12. However, in a huge deviation from the good performers, the bad performers performed at around chance on the HXTX and HXTU conditions. Follow up Monte Carlo analyses confirmed that like the good performers, HUTU and HUTX performance were the same, $p = .123$ (Supplementary Monte Carlo Analysis 25), while HUTU and HXTU performance were different, $p < .001$ (Supplementary Monte Carlo Analysis 26). Unlike the good performers, HXTX performance was significantly worse than HUTU performance (Supplementary Monte Carlo Analysis 27). Further, hands crossed performance (i.e. HXTU and HXTX conditions) was the same, $p = .144$ (Supplementary Monte Carlo Analysis 28).

These differences in behavior were fascinating. Yet, we wanted to ensure we were not simply seeing sex differences, as males tended to perform better than females, as mentioned earlier. A breakdown in the group demographics confirmed we were seeing more than sex differences; about 50% of females (11/23) were in the “bad” group, while about 60% of males (14/22) were in
the “good” group, reflecting a roughly even distribution of males and females between the two
groups.

**Good vs. bad performers by sex.** We also graphed performance type by sex to compare
female good and bad performers to male good and bad performers (see Graphs of TOJ
Performance 13-16).

Subdividing the bad performance group by sex reveals a fundamental difference in performance
between males and females. Female bad performers experience an N-shaped flip in performance
on hands crossed trials, reflecting left-right confusion when hands are crossed (see Graph of TOJ
Performance 13). While male bad performance also decreases during hands crossed trials, no N-
shaped flip is observed, suggesting males experience less left-right confusion (See Graph of TOJ
Performance 14).

Interestingly, no N-shaped flips were observed for male or female good performers (see Graphs of
TOJ Performance 15 and 16). Instead, performance on all conditions, except for the HXTU
condition, was nearly perfect.
Graph of TOJ Performance 13

Graph of Female Bad Performers
Female bad performers, n = 12

Graph of TOJ Performance 14

Graph of Male Bad Performers
Male bad performers, n = 8
Good vs. bad performers by sex and response type. We also subdivided subjects into 8 groups based on performance type, sex and response type. Subdividing the sample population into this many groups meant that some groups had as few as 3 subjects, while others had as many as 10 subjects. Although it was not thought these groups were big enough to produce and statistically significant, or even representative results, we made graphs of their performance as a rough preliminary analysis in order to help develop ideas for future research (see Graphs of TOJ Performance 17-24). These graphs with their sample sizes can be seen below.
First, we investigated what conditions produced N-shaped flips. Female bad performers using foot pedals clearly demonstrated the flip (Graph of TOJ Performance 17), but performance patterns were less clear for female bad performers using tools (Graph of TOJ Performance 18). Since the latter group contained only 3 subjects, it is quite possible further testing would reveal clearer results.

Graph of TOJ Performance 17

Graph of Female Bad Performers: Foot Response
N = 9

Graph of TOJ Performance 18

Graph of Female Bad Performers: Tool Response
N = 3
Although the female good performer groups had similarly few subjects, there were no clear differences between female good performers who responded with feet (Graph of TOJ Performance 19) and female good performers who responded with tools (Graph of TOJ Performance 20). This distinction between the female good responder and female bad responders suggests female bad responders might be processing tactile stimuli in a way that is highly affected by response modality, while female good performers process tactile stimuli in a qualitatively different way.

Graph of TOJ Performance 19

Graph of Female Good Performers: Foot Response
N = 4

Graph of TOJ Performance 20

Graph of Female Good Performers: Tool Response
N = 7
The performance graphs did not reveal any clear qualitative distinctions between male bad performers who used foot pedals compared to those who used tools to respond. The foot pedal responders (Graph of TOJ Performance 21) seemed slightly more accurate than the tool responders (Graph of TOJ Performance 22), but with only 4 subjects per condition, it is difficult to say how significant this overall accuracy difference is.

**Graph of TOJ Performance 21**

**Graph of Male Bad Performers: Foot Response**

\[ N = 4 \]

**Graph of TOJ Performance 22**

**Graph of Male Bad Performers: Tool Response**

\[ N = 4 \]
One clear difference was found between male good performers using foot pedals (Graph of TOJ Performance 23) and male good performers using tools (Graph of TOJ Performance 24). While the former had nearly perfect performance across all positions, the latter had markedly worse performance only on the hands crossed, tools uncrossed position.

Graph of Male Good Performers: Foot Response
N = 4

Graph of Male Good Performers: Tool Response
N = 10
Summary of good vs. bad performer analyses. There were clear differences between subjects who made few errors on easy trials (classified as good performers) and subjects who made many errors on easy trials (classified as bad performers). While good performers had high accuracy on all positions, with the exception of HXTU, bad performers had relatively high accuracy on HUTU and HUTX positions and strikingly low accuracy on HXTX and HXTU positions. Subdividing these groups by sex revealed female bad performers experienced an N-shaped flip in performance on hands crossed trials, which typically demonstrates left-right confusion. Neither female good performers nor male subjects showed this confusion. Subdividing the groups further to examine the effect of response type revealed female bad performers clearly showed the N-shaped flip for foot pedal response trials, but less clearly for tool response trials. Interestingly, female good performers showed no clear changes in performance between foot pedal response trials and tool response trials. This could suggest that female bad responders might be processing tactile stimuli in a way that is highly affected by response modality, while female good performers process tactile stimuli in a qualitatively different way. This clear distinction between foot and tool responses was not seen in male responders.

Discussion

Our results do not appear to conform to the predictions of either the body schema hypothesis or attention hypothesis. Both hypotheses would predict HUTU and HXTX performance to be good and HUTX and HXTU to be equivalently bad, as for both the position of the tool tip matters (although the hypotheses disagree regarding the importance of the rest of the tool). Instead, we found overall HUTX behavior to be almost as good as HUTU behavior, suggesting tool tip position
TACTILE TEMPORAL ORDER JUDGMENT WITH TOOLS

did not strongly affect performance when hands were uncrossed (see Table 4). However, because HXTX performance was significantly more accurate than HXTU performance, tool position appeared to have a bigger effect on performance when hands were crossed.

Table 4: Predicted Behavior vs. Observed Behavior

<table>
<thead>
<tr>
<th>Predicted Behavior</th>
<th>HUTU</th>
<th>HUTX</th>
<th>HXTU</th>
<th>HXTX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Bad</td>
<td>Bad</td>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Observed Behavior</td>
<td>Good</td>
<td>Good</td>
<td>Bad</td>
<td>Better than HXTU, Worse than HUTU</td>
</tr>
</tbody>
</table>

Our results were inconsistent with the predictions of the body schema and attention hypotheses. The inconsistencies between the body schema and attention hypotheses' predictions of consistently strong tool position effects and our results made us consider alternative factors and theoretical frameworks to interpret our findings. First, we examined whether there were any effects of tool practice or having eyes open on TOJ performance. Analyses revealed no effects of these factors, so we decided to examine the effects of response type (foot pedal vs. tool).

Although there was no main effect of response type, there did appear to be an interaction between sex, response type, tool position and hand position, with males generally outperforming females when responding with foot pedals, but not when responding with tools. Females were also seen to make significantly more left-right confusion errors than males when just the hands were crossed.

To examine the relationship between left-right confusion errors and overall performance, we divided subjects into two groups, good performers who made few left-right confusion errors (as measured by their performance on easy trials) and bad performers who made many left-right
confusion errors. Differences between the two groups suggested bad performers were neither paying attention to nor incorporating the tools into the body schema. However, it was unclear what mechanisms good performers were employing, as tool position only affected their performance when their hands were crossed. A further subdivision of the good and bad performer groups revealed female bad performers experienced massive amounts of left-right confusion, much more than male bad performers.

Our findings from different hand and tool positions, different response types, different sexes, and different performance type groups defy the predictions of the previously discussed theoretical frameworks. This section will describe in depth how our results relate to the tool use debate, as well as how we could use our results to build new theoretical frameworks to describe how different people use tools.

Our Findings and the Tool Use Debate

Yamamoto and Kitazawa (2001b) found crossing the hands results in similar performance to crossing the tools; their subjects performed similarly on HUTX and HXTU conditions. Body schema theorists interpreted these results as clearly showing the tools were incorporated into the body schema—as hands and tools appeared to be processed similarly—and attention theorists interpreted these results as clearly showing the importance of the position of the tool tips—as it was the tool tip position that appeared to best predict performance.

However, inconsistent with Yamamoto and Kitazawa (2001b), we did not find similar performance on HUTX and HXTU conditions in any of our experiments. Instead, we found HUTX and HUTU conditions resulted in similar performance. Meanwhile, HXTU and HXTX conditions
resulted in similar, significantly worse performance. In other words, it appeared the important factor was whether or not the hands were crossed. There was a slight effect of tool crossing (as seen by how HUTX performance was slightly, but not significantly worse than HUTU, and how HXTX performance was slightly better than HXTU in experiments 3 and 4), yet our results clearly show that hand position predicts performance better than tool tip position.

These results contradict the predictions of the body schema hypothesis of tool use. Instead of having similar effects, it appears hand position dramatically affects performance while tool position does not. Such findings seriously undermine the claims of the body schema theory, as it appears hands and tools are being processed significantly differently. Body schema theorists would argue this is only the case if we assume tools are automatically incorporated into the body schema; if not, then experience and practice with the tools is necessary before a clear effect of tool position will emerge. However, our results indicate that even tool practice does not enhance the effect of tool position, although it is possible that we did not give subjects enough practice with the tools.

Our results also contradict the predictions of the attention theory of tool use. Attention theorists argue that the functional tips of tools are attended to, which causes their position to affect TOJ performance. As discussed earlier, the positions of tool tips did not consistently affect performance. Attention theorists could explain these results by saying our experiments were designed in such a way that subjects did not attend to the tips of the tools. Yet, this explanation fails to predict why tool tip position did slightly affect performance only when hands were crossed.
While our results do not conclusively disprove the attention or body schema hypotheses of tool use, they do suggest that we neither observed tools being incorporated into the body schema (perhaps because subjects needed more practice with tools) nor observed subjects consistently attending to the tips of tools. The failure of the attention and body schema hypotheses to explain our results led us to use other theoretical frameworks to explain our findings.

Sex Differences and Response Type

Our results revealed evidence for sex differences in TOJ performance. Overall experiments, it appeared males outperformed females. However, closer analysis revealed males only outperformed females when they were responding with foot pedals. In tool response conditions, females tended to outperform males. Further, male performance was worse on all tool response conditions relative to male performance on foot response conditions. Conversely, female performance was worse on many foot response conditions, relative to female performance on tool response conditions. Overall, females also made more right-left confusion errors, especially when responding with foot pedals.

Hand-foot coordination explanation. One way to describe these sex differences is that the foot pedal condition required hand-foot coordination that engaged additional cognitive mechanisms, some of which affect spatial and/or tactile processing. Meanwhile, the tool mapping was less complicated, as the part of the body vibrated (the hands) was the same as the part of the body that responded to the stimuli (also the hands). It is quite possible females and males differ in their use of these hand-foot coordination mechanisms. Although hand-foot coordination was not
the focus of this paper and was not explicitly measured by our experiments, its mechanisms and applications to TOJ tasks could be the focus of future research.

**Internal vs. external reference frames explanation.** Another way to explain our response type by sex interactions is through the idea of internal and external reference frames. An internal reference frame is when stimuli are coded in their location relative to the body; if a stimulus is presented on or near the right hand, it is coded as being in the “right” side of space, regardless of where the right hand happens to be. In contrast, in an external reference frame, stimuli are only coded as being on the right side of space if they are on the right side of a line projected from the body’s midline.

Cadieux et al. (2010) found females rely more on external reference frames while men rely more on internal, somatotopic reference frames. Perhaps one could interpret the foot response condition as relying on internal reference frames, as the right foot has to respond to stimuli applied to the right hand, regardless of the location of the right hand. The tool response condition, on the other hand, could be interpreted as relying on external reference frames in the crossed conditions; in the HXTU and HUTX conditions, the right hand has to use the tool to push the left pedal. As Cadieux et al. (2010) would predict, females did better on conditions that relied on external reference frames (tool response conditions) and performed poorly on conditions that relied on internal reference frames (foot pedal response conditions). Meanwhile, men performed worse on conditions that relied on an external reference frame.

This reference frame hypothesis largely explains our results, with some exceptions. First, one would predict that on HUTU trials, where one could equally rely on internal or external reference
frames, there would not be a difference in performance, regardless of the response method. This was not what was found. Instead, it seemed females still performed significantly worse than males on the HUTU condition during foot pedal response trials. Yet, males and females performed about the same on the HUTU condition during tool response trials. These results suggest there might also be a sex difference in mapping tactile stimuli from hands to feet, or more generally, there might be sex differences in hand-foot coordination mechanisms.

The reference frame hypothesis also predicts that accuracy would be worst on HXTU and HUTX conditions, as these are the conditions with the most internal vs. external conflict. Instead it was found that HUTX and HUTU performance was most accurate for both sexes across all conditions, while HXTU and HXTX performance was least accurate. The reference frame hypothesis struggles to explain why HUTX performance would be so accurate.

Taking into account these exceptions, it still seems as if the reference frame hypothesis gives a reasonable account for the sex differences observed in relation to posture and response type.

**Good vs. Bad Performers**

Another important aspect of our results concerns differences found between "good" and "bad" performer groups. As discussed earlier, we divided our subjects into two groups: a good performer group that made few right-left confusion errors and a bad-performer group that made many left-right confusion errors.

The results from the good performers versus bad performers violate predictions from both the body schema and attention theories. The finding that HUTX performance is relatively good for
both groups violates both body schema (tools being treated differently than hands) and attention predictions (no change in performance even though tool tips are in contralateral sides of space). Additionally, the finding that HXTX performance is relatively bad for poor performers also violates the predictions of both theories; body schema and attention theorists would say the double crossing (hands crossed and tools crossed) puts the stimulated tool tip on ipsilateral side of space, which should produce good performance. The observed violations of both theories’ predictions suggest some subjects might not have incorporated the tools into the body schema or paid attention to tools.

This requires another category, people who “ignore” tools by neither paying attention to them nor incorporating them into the body schema. Poor performers seem to fall into this category, as their hands crossed performance (HXTX and HXTU) is the same and their hands uncrossed performance (HUTU and HUTX) is the same, regardless of tool position. In other words, it appears they simply ignore tools.

In contrast, good performers do not fall into this “ignore” tools category; their HXTX performance differs from their HXTU performance, suggesting that tool position is taken into account. Because the body schema theory and attention theory make similar predictions regarding performance on all conditions, people who either pay attention to tools or incorporate tools into the body schema can be put into a different category—people who “process” tools.

These two different categories neatly explain all our results, except for how “good” performers did not show a performance difference between HUTU and HUTX performance. If good performers truly processed tools, their performance on the HUTX condition should be less accurate. This was
not observed. Further, if they completely ignored the location of the tool tips, HXTU and HXTX should be the same. Instead, HXTX performance significantly differed from HXTU performance. One explanation for this strange pattern comes from differences in performance seen by Yamamoto and Kitazawa (2001a) between when hands were physically crossed or when they were simply in different sides of space than usual. As seen in the Psychometric Curves 5 below, physically crossing the hands negatively affects performance (see e and f). However, simply putting the hands in opposite sides of space (see c and d) does not negatively affect performance. This suggests physical crossings are what negatively affect performance.

Psychometric functions of performance by different hand position. This figure focuses on the “center” of the psychometric functions we have been discussing. Center performance reflects performance on difficult trials with short interstimulus intervals. The interstimulus intervals in these graphs range from 0-300ms. Red lines indicate significantly worse performance compared to condition a, hands uncrossed. Figure taken from Yamamoto and Kitazawa (2001a).

Applying these results to what we observed in good performers during HUTX trials requires a combination of the body schema and attention theorist hypotheses. Perhaps good performers
only incorporate the tips of the tools into their body schema. If only the tool tips are processed as part of the hands, during the HUTX condition, the brain would process the hands as being physically uncrossed, but also as being on the opposite side of space as usual (see part B of Figure 7). This would lead to performance as seen in part d of Psychometric Curves 5 above.

Figure 7

A represents the positions our subjects actually adopted. If only the tool tips are incorporated into the body schema, the brain might ignore the physical crossing of the tools; instead, the brain might code the tool tips as if they were hands on opposite sides of space without being physically crossed (see B). This results in the same performance as seen in C.

Combining these two theories also accurately predicts the other patterns of performance exhibited by the good performers. In the HXTU condition, there is a physical crossing of the hands with the tool tips on contralateral sides of space, which would predict poor performance. In the HXTX condition, there is a physical crossing of the hands, with the tool tips on ipsilateral sides of space, which would predict good performance. Table 5 below illustrates predictions for behavior for subjects who processed the tool tips and hand crossings compared to subjects who ignored the tools and only processed hand crossings. "Good" performers' results are consistent with the top row while "bad" performers' results are consistent with the bottom row.
Table 5: Performance predictions for posture by whether subjects process or ignore tools

<table>
<thead>
<tr>
<th>HXTX</th>
<th>Good Performance: A crossing is processed but the tool tips are in ipsilateral space</th>
<th>Poor Performance: A physical crossing is taken into account</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subjects Who Only Good</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance:</td>
<td>A physical crossing is taken into account</td>
<td></td>
</tr>
</tbody>
</table>

Summary of good vs. bad performers. The patterns of performance exhibited by good vs. bad performers seem to strongly support the idea that people do not incorporate entire tools into their body schemas. Instead, they either selectively incorporate the functional tips of tools into their body schemas or they do not incorporate any parts of the tool into the body schema.

Combining Performance Type and Reference Frames

Thus far we have discussed two different frameworks to explain our results. The first concerns external vs. internal/somatotopic reference frames, the second concerns "ignoring" the tool vs. processing the tool (perhaps by selectively incorporating the tool tips into the body schema). It seems everyone must either process or ignore tools while simultaneously relying on either an
external or internal reference frame. Let us assume males use internal reference frames while females use external frames. Additionally, let us assume our good performers processed tools while bad performers ignored tools. Table 6 illustrates how these factors apply to our subject groups.

Table 6: An illustration of how reference frame and tool processing factors apply to our subject groups

<table>
<thead>
<tr>
<th></th>
<th>Internal Reference Frame</th>
<th>External Reference Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Tools</td>
<td>Male Good Performers</td>
<td>Female Good Performers</td>
</tr>
<tr>
<td>Ignore Tools</td>
<td>Male Bad Performers</td>
<td>Female Bad Performers</td>
</tr>
</tbody>
</table>

Combining performance predictions concerning whether or not people process tools with performance predictions concerning what reference frame people use predicts that these four groups will exhibit different patterns of behavior. To a certain extent, this was what we found.

**Bad performers and right-left confusion.** Female bad performers had so much trouble during hands crossed conditions, that they actually produced an N-shaped pattern of performance. In other words, they performed so far below chance on easy, large ISI trials that they were clearly not responding randomly; instead, they were responding as if their right tool was their left tool. This is called left-right confusion. While male bad performers also made a large number of left-right confusion errors, their performance never went below chance.

This performance difference between the two bad performer groups can be interpreted through the reference frames lens. Crossing the hands puts them in the opposite side of external space. If one relies on an internal reference frame, this crossing is not very important. However, if one
relied on an external reference frame, crossing the hands in external space can be very confusing; suddenly, stimuli that are coded as being in the left side of external space require making a response with the right foot pedal or—when responding with tools—the right pedal on the table, but only when the tools are also crossed.

In other words, people who rely on external reference frames and do not process tools would make many left-right confusion errors on hand crossed trials when responding with feet, but slightly fewer when responding with tools. Assuming the female bad performers relied on external reference frames, this is exactly what we found, with foot pedal responses producing more left-right confusion errors than tool responses. Neither good nor bad male performers exhibited N-shaped performance patterns, suggesting males do not rely on external reference frames.

**Lack of Sex differences between good performers.** Interestingly, female good performers and male good performers exhibited almost exactly the same patterns of performance, suggesting both groups relied on the same frame of reference. This finding suggests not all females rely on the same reference frame.

**Summary of performance type by reference frame results.** Our results suggest good performers all process tools and use the same reference frame. Meanwhile, bad performers ignore tools. It appears female bad performers rely on an external reference frame, as evidenced by the number of right-left confusion errors they commit when their hands are crossed.
However, it is unclear what reference frames male bad performers use. As a group they exhibit fewer right-left confusion errors than the female group, but it is possible that a few of the individual males were also relying on external reference frames. Which reference frames subjects used were not explicitly measured in our study, and it is quite possible (if not probable) that sex is not a perfect predictor of reference frame. Thus, it is unclear whether male bad performers underperformed only because they ignored tools and were generally bad at the task or whether they underperformed because they were relying on an external reference frame.

Limitations

Problems across all experiments

This study had a number of limitations. First, there were only 12 subjects per experiment and some subjects’ data had to be excluded from analysis, leaving experiment 2 with only 9 subjects and experiment 1 with only 11 subjects. Further, because sex differences were not expected to be the focus of this study, subjects were not explicitly recruited based on their sex. Consequently, there were not equal numbers of males and females in this study. Additionally, of the 45 subjects whose data was analyzed, only 4 were left handed. Again, since handedness was not the focus of this study, subjects were not recruited based on handedness. Consequently, it was impossible to find any effect of handedness.

Another problem that affected all experiments was that in our attempt to perfectly replicate Yamamoto and Kitazawa (2001b), the practice session presented to subjects before the experiment involved stimulating only one tool and having the subject judge which tool was
stimulated first. This is what Yamamoto and Kitazawa had subjects do, but it might have been confusing, as both tools were vibrated in the actual experiment. It seems a practice session more similar to the actual TOJ task might have been more helpful to subjects.

As discussed earlier, it is difficult to understand the relationship between TOJ task performance and relying on internal or external reference frames when one does not directly measure subjects’ reference frames. Although using sex as a measure of reference frame is supported by the literature, it is quite possible some females rely on internal reference frames while some males rely on external reference frames. By sorting subjects by sex, we could have easily introduced noise into our reference frame analyses.

Analysis Problems

At the level of each individual participant, some females performed very well while some performed very poorly. The combination of the two created a group performance with huge variance, which does not reflect actual participant performance and could have hindered our attempts to find significant differences between male and female group performance as well as within female group performance. In the future, these individual differences need to be carefully considered when examining group differences.

Stimuli Problems

Another possible problem with this study was that subjects did not wear ear plugs, headphones, or blindfolds. Although the experimenters could not determine when the vibrators were vibrating based on consciously perceived audio or visual cues, it is possible that subjects could pick up on audio or visual cues from the vibrators subconsciously. In response to this potential issue, we
should have had subjects explicitly blindfolded for Experiments 1-3. For all experiments, subjects' ears should have been plugged and/or subjects should have worn headphones playing white noise.

We also had a slight problem with our stimuli. For experiments 1-3, the vibrations delivered to the tools were suprathreshold, but still very faint. The experimenters judged them to be suprathreshold, but some subjects reported having trouble feeling the vibrations. These same subjects often started to feel the vibrations by the end of the practice session, and sometimes the first practice session was run twice so that the subjects could get a better feel for the vibrations. However, at the end of the experiment, subjects often mentioned that they merely guessed which tool was stimulated first on some trials. While this was expected on small ISI trials, it is possible they were also guessing because they had trouble feeling the vibrations. It seems that for the large part, it can be assumed the vibrations were felt, as most participants performed above chance. Still, the weak vibrations could have introduced noise into our data, possibly obscuring some significant interactions.

**Experiment Specific Problems**

For experiment 2 (tool practice experiment), subjects were only given 4 minutes of practice manipulating objects with the tools. These 4 minutes were broken up into one minute sections before each block. Perhaps more tool practice would have produced a change in performance.

Also, since we only had 9 subjects with usable data for the tool practice condition, we might not have had enough subjects to observe a significant effect of tool practice. Further, since we had so few subjects in the tool practice condition, there could have been a sex * tool practice effect, but not enough subjects to observe it.
To address the weak vibration issue discussed earlier, we varied multiple parameters for experiment 4, including amplitude of vibrations, springs in pedals, and eyes open vs. closed. It is unclear whether amplifying the vibrations and making the pedals easier to press affected our analysis of the effect of having one’s eyes open or closed. However, it would have been better to not change multiple parameters and instead have run experiment 4 with eyes open and weak vibrations.

Conclusions

Our results conform to neither the predictions of either the body schema hypothesis nor the attention hypothesis. Instead, a number of other theoretical frameworks can be used to interpret our findings; it appears some subjects used external reference frames during the task, which caused them to commit a massive number of right-left confusion errors. Additionally, it appears some subjects processed tools (as evidenced by how tool position influenced their performance), while some subjects completely ignored tools (as evidenced by how tool position did not affect their performance).

One of our hardest findings to explain is how HUTX performance was relatively good compared to HXTU performance. However, we can interpret this finding by combining the body schema and attention hypotheses; if subjects only incorporated the tips of the tools into their body schemas, they might not process the physical crossing of the tools, causing them to process the stimuli as if their hands had made a non-physical crossing.
It is unclear why our results are inconsistent with past research on TOJ tasks with tools. Even after subdividing subject performance by tool practice, visual information, response type, performance type and/or sex, we failed to replicate the results of Yamamoto and Kitazawa (2001b), suggesting there might be other unmeasured, systematic differences between our experiments. Cultural differences might be at play; Yamamoto and Kitazawa's subjects were all recruited and tested in Japan, while our subjects were recruited and tested in the United States. However it is unclear how such cultural factors or any of the other differences between our experiments we did not control for could have caused the significant differences in our results. These unanswered questions demonstrate the need for further research into tactile processing and spatial mapping before we can fully understand how humans use tools.

**Future Research**

**Replications of our Experiments**

To address some of the issues addressed in the limitation section, future research could try to replicate experiment 2 with more tool practice time and more subjects with an equal number of male and female subjects. This will allow for the further investigation of the effects of tool practice on TOJ performance, and possibly the interaction between sex and tool practice.

In another variation of experiment 2, investigators could have subjects respond with tools instead of foot pedals. The reasoning behind this is that our tool practice caused subjects to pay attention to the tips of tools. However, during the TOJ task, they could have attended to just the vibrations...
in their hands, not the tips of the tools, because they responded with their feet. Perhaps interesting interactions could be observed by having subjects respond with the parts of the tools they use during the practice session.

In a variation of experiment 4, future research could further investigate sex differences in the effects of visual information on TOJ experiments with tools. Females might rely more on visual information than males, so having eyes open or closed during a TOJ task might affect females more. Because of the small number of females in experiment 4 (n=4), we were unable to investigate these effects ourselves.

For all experiments, it could be of interest to compare right handed participant performance to left handed performance. This was not the focus of this study, so we did not explicitly recruit left-handed subjects, leaving us with only a small number of left handed subjects. Rerunning experiments with more left handed subjects could allow for the investigation of the effects of right vs. left hemispheric dominance on spatial processing.

It could be interesting to examine the interactions between reference frames and response modalities. Instead of using sex as a predictor of reference frame, future investigators could use a more direct measure of reference frame use, such as the rod-and-frame test (RFT; Witkin & Asch, 1948). The RFT consist of aligning a visual rod to the subjective vertical. A tilted frame is put or drawn around the rod and subjects have to compensate for the tilt. Subjects who set the rod closer to the direction of the tilt are said to rely more on external reference frames than subjects who are not affected by the tilt. The latter group is said to rely more on internal reference frames.
Correlated RFT performance to TOJ performance could help explain why some subjects experience more right-left confusion errors than others.

**TMS Experiment**

In a variation of the present study, future research could try to replicate Yamamoto and Kitazawa’s (2001) TOJ experiment using transcranial magnetic stimulation (TMS). TMS induces weak electric currents to temporarily inhibit cortical areas by causing neurons to depolarize and discharge an action potential, temporarily inhibiting the neuron. These effects are temporary, usually lasting no more than a few minutes. There are multiple kinds of TMS, including single, paired and repetitive TMS (rTMS). Future research could use rTMS to inhibit an area of the brain involved in body postural representations (BA5; Graziano, Cooke & Taylor, 2000) as well as a region involved in allocating attention to peripersonal space (posterior ventral intraparietal region; Bolognini & Maravita, 2007; Azanon et al, 2010), while subjects perform TOJ tasks.

Previous research has shown that combining TMS and TOJ can provide insights into the body schema and tool use. Medina et al., (unpublished) used the same paradigm as Yamamoto and Kitazawa (2001), except they also applied TMS to BA5 while subjects performed the TOJ task. Medina et al. found the TMS had no effect on performance when subjects did not have to cross their hands or tools. However, they found a change in performance when the hands or tools were crossed; when hands were crossed, application of TMS to BA5 actually improved performance. The researchers explained these results by proposing that inhibiting BA5 caused subjects to rely on their primary somatotopic representation to localize sensations, a representation that is processed faster (Azanon & Soto-Faraco, 2008) than the body postural representation.
Future research could extend the study by Medina et al. by using a similar paradigm, by also applying TMS to an attention area in the brain in order to explicitly test the attention hypothesis. If the body schema hypothesis is correct, tools are incorporated into the body schema. If tools are incorporated into the body schema TMS to the neural correlates of body posture (BA5) will affect performance on trials where hands or sticks are crossed; because limbs/tools are not in their prepotent positions in these trials, the body postural representation must be accessed to determine their location in space. However, when subjects do not have to cross sticks or hands, body posture does not have to be taken into account, so the inhibition of body posture on these trials will not affect performance. In contrast, if the attention theory is correct, TMS to BA 5 will not affect performance when subjects cross their tools, as the tools are not incorporated into the body schema. Instead, according to the attention hypothesis, TMS to the pVIP, which has been seen to allocate attention to peripersonal space (Bolognini & Maravita, 2007; Azanon et al, 2010), would disrupt TOJ performance in all conditions.

**Simon Effect Experiment**

The Simon effect (Simon, 1969) is a phenomenon in which subjects respond more slowly on a non-spatial task when they are presented with a stimulus on one side of space and have to respond using a body part on a different side of space (incongruent) compared to when the stimulus and response are on the same side of space (congruent). For example, subjects will respond quickly on trials where they see a red flash on their right side which means they need to respond with their right hand. However, if the red flash means they have to respond with their right hand, subjects will respond slower if the red flash appears on the left side (see Figure 8).
Figure 8. This figure illustrates the Simon effect. Red flashes require a response from the right hand. Green flashes require a response from the left hand. When subjects see a red flash on the right side of space, they are faster to respond compared to when they see a red flash on the left side of space. Similarly, subjects are fast to respond when they see a green flash on the left side of space compared to when they see a green flash on the right side of space.
Figure taken from Medina, Kliot and Coslett (2010).

Medina, Rapp and Coslett (submitted) used this effect to examine tactile processing while subjects crossed and uncrossed their arms. When arms were uncrossed, the researchers found the classic Simon effect (e.g., subjects responded faster when stimuli were presented to right hand and they had to respond with their right foot). However, their results were different when subjects crossed their hands. With hands crossed, there was a significant Simon effect based on somatotopic, but not external representation (see Figure 9). In a somatotopic representation, limbs are represented as always in their putative position (e.g. the right hand is always on the right side, regardless of its actual location in space). In an external representation, "left" and "right" stay constant, regardless of which limbs are on which side of space (e.g. even if arms are crossed,
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whichever hand is on the right side of space is the “right” hand). Thus, in an external representation, subjects would always respond quickly if they had to respond with their left foot to a stimulus presented on the left and would respond slower with their left foot to a stimulus presented on the right.

However, this is not what was found. Instead, subjects were slow to respond if they had to respond to a stimulus on the left side of space with their left foot if their hands were crossed (so that the right hand was on the left side of space). In contrast, if subjects had to respond to a stimulus on the right side of space (while their left hand was on the right side of space), they were faster to respond with their left foot. This is consistent with a somatotopic organization, where “left” and “right” are determined by where parts of the body are.

Future research could extend Medina et al.’s (submitted) study by investigating whether researchers can elicit a visual Simon effect similar to the tactile Simon effect Medina et al. In this experiment, subjects would hold a stick shaped tool in each of their hands. Subjects would cross their arms so that the tip of the tool held in the right hand (“right tool”) is in the left side of space and the tip of the tool held in the left hand (“left tool”) is on the left side of space. Lights would appear on the hands, and well as the shafts and tips of the tools (see Figure 10).
Figure 9. This figure represents the findings of Medina, Kliot and Coslett (2010), in which the Simon effect was studied using subjects with crossed arms. It was found that subjects were slow to respond if they had to respond to a stimulus on the left side of space (occupied by their right hand) if they had to respond with their left foot. In contrast, if subjects had to respond to a stimulus on the right side of space (occupied by their left hand), they were faster to respond with their left foot.

Subjects would have to respond which side of space they see visual stimuli. In order to compare responses when subjects have their hands crossed to when they have their hands uncrossed, as well as to compare performance with tools versus without tools, subjects would have to adopt different positions: not holding tools with arms uncrossed, not holding tools with arms crossed, holding tools with arms uncrossed, or holding tools with arms crossed. This paradigm would allow researchers to tell whether the shafts and/or tips of tools are coded somatopically (the way hands are coded), or externally (the way external space is coded).

If the body schema theory is right, then the entire tool will be coded the way hands are coded (somatopically). However, if the attention theory is right, then only the hands and tips of tools will be coded like the hands while the tool shafts are coded as external space (externally). Thus, the body schema theory would predict that subjects will respond faster whenever the stimulus is hand (now hand and tool) congruent (see Figure 11). According to the body schema theory, this
will be caused by how the entire tool is incorporated into the body schema. In contrast, the attention theory predicts subjects will only respond faster when lights on the tool tip or hand are "hand" congruent; subjects will respond faster to lights on the shafts of tools when they are externally congruent, as only the tips and handles of tools are treated as if they are part of the hand. The shaft is not paid attention to, so it is represented as more similar to external space than peripersonal space.

Figure 11

Figure 10. Predictions of the body schema theory vs. predictions of the attention theory. According to the body schema theory, subjects will respond fastest when the stimulus is congruent with a somatotopic map of their hand/tool their hand is holding. In contrast, the attention theory predicts that subjects will be faster only when the stimulus is congruent with their hand and tips of the tools their hands are holding. When it comes to the shafts of the tools, subjects will respond faster when the stimulus is externally congruent (e.g., have to respond with the left foot when the stimulus is presented to the tool shaft of the left side of space).
Put in more concrete terms, according to the body schema hypothesis, if we shine a red light on the right tool shaft (which when crossed is in the left side of space) we will see faster performance than if we shine a green light on the right tool shaft. According to the attention hypothesis, we will see the opposite; reactions will be faster when we shine a green light on the right tool shaft when it is in the left side of space than when we shine a red light.

This possible experiment addresses concerns raised by Holmes et al. (2007) that many previous studies on tool use failed to measure the effect of two tools or the possibility that tool shafts are processed differently than tool tips; by only examining the area around the tip of a single tool, many studies did not control for the possibility subjects were merely paying attention to the tips of their tools, not incorporating the entire tool into their body schemas. In order to address this concern subjects in this paradigm will use two tools (one per hand). In order to address another other concern, that tool use studies do not compare processing of area around the shaft of the tool to area around the tip of the tool, this paradigm will also measure three points along the tool in all experiments: the handle, shaft and tool tip.
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Appendix A: Supplementary Monte Carlo Analyses

Supplementary Monte Carlo Analysis 1

Psychometric Curves and Monte Carlo Analyses: Males vs. Females HUTU

Females are red dots on psychometric curve, males are blue. Although threshold was not significantly different, there was a significant difference in slope. Males appeared to have significantly better accuracy in the HUTU condition.
Supplementary Monte Carlo Analysis 2

Psychometric Curves and Monte Carlo Analyses: Males vs. Females HUTX
Females are red dots on psychometric curve, males are blue. There was a significant difference in slope. Males appeared to have significantly better accuracy in the HUTX condition.
Psychometric Curves and Monte Carlo Analyses: Males vs. Females HXTU

Females are red dots on psychometric curve, males are blue. There was no significant difference in performance on hard trials, but a follow up t-test confirmed significant differences in performance on the easy trials.
Supplementary Monte Carlo Analysis 4

Psychometric Curves and Monte Carlo Analyses: Males vs. Females HXTX

Females are red dots on psychometric curve, males are blue. Although threshold was not significantly different, there was a significant difference in slope. Males appeared to have significantly better accuracy in the HXTX condition.
Experiments 1 and 2 (Foot pedal response): Males vs. Females: HUTU
Although threshold was not significantly different, there was a significant difference in slope.
Males perform significantly better than females.
Experiments 1 and 2 (Foot pedal response): Males Vs. Females: HUTX
Although threshold was not significantly different, there was a significant difference in slope. Males perform significantly better than females.
Supplementary Monte Carlo Analysis 7

Experiments 1 and 2 (Foot pedal response): Males Vs. Females: HXTU
Although threshold was not significantly different, there was a significant difference in slope. Males significantly outperform the females.
Supplementary Monte Carlo Analysis 8

Experiments 1 and 2 (Foot pedal response): Males Vs. Females: HXTX
Males perform better than females, but not significantly.
Experiments 3 and 4 (tool response): Males Vs. Females: HUTU
Neither threshold nor slope was significantly different between males or females.
Experiments 3 and 4 (tool response): Males Vs. Females: HUTX
There was a significant difference in performance, with females slightly outperforming males.
Experiments 3 and 4 (tool response): Males Vs. Females: HXTU
There was a significant difference in performance, with females slightly outperforming males.
Experiments 3 and 4 (tool response): Males Vs. Females: HXTX

There was no significant difference in performance.
Female Tool Response Performance vs. Female Foot Pedal Response Performance: HXTX

Although threshold was not significantly different, there was a significant difference in slope. Female tool response performance on HXTX is significantly better than female foot pedal response.
Female Tool Response Performance vs. Female Foot Pedal Response Performance: HXTU
Neither threshold nor slope were significantly different, suggesting response modality does not affect female performance on HXTU conditions.
Female Tool Response Performance vs. Female Foot Pedal Response Performance: HUTX
Neither threshold nor slope were significantly different, suggesting response modality does not affect female performance on HUTX conditions.
Female Tool Response Performance vs. Female Foot Pedal Response Performance: HUTU
Slope was significantly different, with females responding better with tools in the HUTU condition.
Male Tool Response Performance vs. Male Foot Pedal Response Performance: HUTU
Slope was significantly different, suggesting males perform better when responding with foot pedals in HUTU conditions.
Male Tool Response Performance vs. Male Foot Pedal Response Performance: HUTX
Slope was significantly different, suggesting males perform better when responding with foot pedals in HUTX conditions.
Male Tool Response Performance vs. Male Foot Pedal Response Performance: HXTU
Slope was significantly different, suggesting males perform better when responding with foot pedals in HXTU conditions.
Male Tool Response Performance vs. Male Foot Pedal Response Performance: HXTX
Slope was significantly different, suggesting males perform better when responding with foot pedals in HXTX conditions.
Supplementary Monte Carlo Analysis 21

There were no significant changes between slope and threshold in the two conditions. This suggests good performers do not take tool position into account when hands are uncrossed.
Supplementary Monte Carlo Analysis 22

There were no significant changes between slope and threshold in the two conditions. This suggests good performers do take tool position into account when hands are crossed.
Supplementary Monte Carlo Analysis 23

Good Performers HUTU vs. Good Performers HXTU
There was a significant difference in slope, with good performers responding less accurately in the HXTU condition than the HUTU condition.
Good Performers HUTX vs. Good Performers HXTU
There was a significant difference in slope, with good performers responding less accurately in the HXTU condition than the HUTX condition.
Supplementary Monte Carlo Analysis 25

Bad Performers HUTU vs. Bad Performers HUTX
There were no significant differences between slope or threshold, suggesting bad performers do not take tool position into account when hands are uncrossed.
Bad Performers HUTU vs. Bad Performers HXTU
There was a significant difference between slope, suggesting bad performers perform worse when hands are crossed.
Bad Performers HUTU vs. Bad Performers HXTX

There were significant differences between slope and threshold, suggesting bad performers perform relatively worse when their hands are crossed.
Supplementary Monte Carlo Analysis 28

There were no significant differences between slope or threshold, suggesting bad performers do not take tool position into account when hands are uncrossed. Instead, they just perform worse when their arms are crossed.