

Somatotopic Representation of Location: Evidence From the Simon Effect

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Representing the locations of tactile stimulation can involve somatotopic reference frames in which locations are defined relative to a position on the skin surface, and also external reference frames that take into account stimulus position in external space. Locations in somatotopic and external reference frames can conflict in terms of left/right assignment when the hands are crossed or positioned outside of their typical hemispace. To investigate the spatial codes of the representation of both tactile stimuli and responses to touch, a Simon effect task, often used in the visual modality to examine issues of spatial reference frames, was deployed in the tactile modality. Participants performed the task with stimuli delivered to the hands with arms in crossed or uncrossed postures and responses were produced with foot pedals. Across all 4 experiments, participants were faster on somatotopically congruent trials (e.g., left hand stimulus, left foot response) than on somatotopically incongruent trials (left hand stimulus, right foot response), regardless of arm or leg position. However, some evidence of an externally based Simon effect also appeared in 1 experiment in which arm (stimulus) and leg (response) position were both manipulated. Overall, the results demonstrate that tactile stimulus and response codes are primarily generated based on their somatotopic identity. However, stimulus and response coding based on an external reference frame can become more salient when both hands and feet can be crossed, creating a situation in which somatotopic and external representations can differ for both stimulus and response codes.

Keywords: Simon effect, frames of reference, tactile localization, somatosensory

The location of tactile stimuli can be represented in either *somatotopic* or *external* frames of reference. In a somatotopic frame, a tactile stimulus has the same location representation regardless of how the stimulated body part is positioned in space. In an external frame, on the other hand, the represented stimulus location is determined by the location of the touched body part in external space. Consider a case in which a person's arms are crossed in front of her body, with the left hand on the right and the right hand on the left. If a tactile stimulus were presented to

the person's left hand, the left-right location of the stimulus would be left in a somatotopic frame of reference (because the left hand was touched), but right in an external frame based on the body midline (because the touched hand was to the right of the body midline in external space).

Studies manipulating hand position have provided evidence for both somatotopic and external tactile representations. One set of results concerns individuals showing tactile extinction after brain damage. These individuals accurately detect unilateral left- or right-sided tactile stimuli, but are impaired at detecting contralesional stimuli when left and right stimuli are presented simultaneously. Testing for tactile extinction with arms crossed and uncrossed has revealed evidence for both somatotopic and external tactile representations. Bartolomeo, Perri, and Gainotti (2004) described six individuals who demonstrated tactile extinction on the contralesional hand in both uncrossed and crossed postures, consistent with a somatotopic impairment. However, three participants with right-hemisphere brain damage were substantially better at detecting stimuli on the left hand when it was in right space (crossed condition) versus left space (uncrossed condition), consistent with impairment in an external reference frame (see also Aglioti, Smania, & Peru, 1999; Berti et al., 1999; Moro, Zampini, & Aglioti, 2004; Peru, Moro, Sattibaldi, Morgant, & Aglioti, 2006; Smania & Aglioti, 1995; Valenza, Seghier, Schwartz, Lazeyras, & Vuilleumier, 2004).

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Further evidence for somatotopic and external tactile representations comes from studies of neurologically intact individuals. Groh and Sparks (1996) examined saccadic eye movements to the locations of tactile targets. Participants saccaded directly to tactile targets on their hands when their arms were uncrossed. However, when their arms were crossed, participants often saccaded first toward the somatotopic side of the stimulus (e.g., left for a stimulus on the left hand positioned in right external space), before correcting about 250 ms after stimulus presentation (see also Buchholz, Jensen, & Medendorp, 2011, 2013; Heed & Roder, 2010; Overvliet, Azañón, & Soto-Faraco, 2011). Tactile temporal order judgments (TOJs) have been used in several studies to examine processing in somatotopic and external reference frames (Shore, Spry, & Spence, 2002; Yamamoto & Kitazawa, 2001). Stimuli are presented to both hands at different interstimulus intervals (ISIs), with the participant indicating which hand was stimulated first. With the arms uncrossed, individuals typically can differentiate temporal order at ISIs up to 70 ms. However, with the arms crossed, performance is significantly impaired compared with arms uncrossed, with some participants consistently responding based on the somatotopic, not external, side of the stimulus for relatively short ISIs (peaking at approximately 300 ms). There are a number of different theoretical accounts to explain performance changes in the different hand postures (for a review, see Heed & Azañón, 2014). Regardless, all of these accounts propose some transformation of tactile spatial information between somatotopic and external reference frames.

Stimulus-response compatibility effects have been used extensively to probe representations of spatial location, although relatively few studies have explored the representation of tactile stimuli. In the Simon effect, participants respond more quickly when a stimulus is located on the same side of space as the response, even when stimulus position is task-irrelevant (Simon, 1969; Simon & Small, 1969). For example, in a typical visual Simon effect task, a participant might be asked to respond to green visual stimuli by pressing a left-sided button, and red visual stimuli by pressing a right-sided button. The robust finding is that green stimuli elicit faster responses when presented on the left than when presented on the right, with the opposite being true for red stimuli. Accounts of the Simon effect propose that representations of both stimulus and response location influence performance, even though stimulus location is irrelevant to the task. The representations that mediate processing of stimuli and responses are often referred to as stimulus and response codes. When the stimulus code (e.g., green stimulus on the right) conflicts with the response code (e.g., press left button for green), the consequence is a longer reaction time (RT) than when the stimulus and response codes correspond.

Simon effect studies with visual stimuli have examined reference frames for encoding of both stimulus and response location. To examine coding of response location, arm crossing manipulations have been used in several studies. In Wallace (1971), a circle or square was presented to the left or right of fixation, and participants responded by pressing a key (left key for circle, right key for square) with their arms crossed or uncrossed. Under these circumstances, response position could be coded in a somatotopic (left hand, right hand) and/or external (left key, right key) frame of reference. Wallace found that in the crossed condition, participants demonstrated a Simon effect based on congruency between stimulus and external, but not somatotopic, response location. For

example, left-key responses were faster for left- than for right-side stimuli, even though these responses were made with the right hand. Furthermore, the magnitude of the external Simon effect did not differ with the arms uncrossed versus crossed, suggesting no influence of somatotopic representations on performance (Simon, Hinrichs, & Craft, 1970). Other studies have used crossing with tools to dissociate the effects of effector position from response goal position. Riggio, Gawryszewski, and Umilta (1986) presented participants with a visual Simon effect task in which key press responses were made with tools that were crossed or uncrossed, while keeping the hands uncrossed. They found a Simon effect based on the position of the response goal (keys), not the hands (see also Hommel 1993a). Overall, these studies indicated that response codes to visual and auditory stimuli in a Simon effect task were determined not by the somatotopic laterality (right or left) of the effector, but instead by the location of the response goal in an external reference frame.

Studies examining visual stimulus codes have found evidence for multiple representations with different reference frames. For example, Nicoletti and Umilta (1989) found stimulus-response compatibility effects based on visual stimulus position relative to the focus of attention. Other studies have shown that, within the same experiment, stimulus codes from multiple reference frames can be active. Lamberts, Tavernier, & d'Ydewalle (1992) presented participants with a visual Simon paradigm in which a fixation point was presented to the left or right of the participant's body midline, and the target stimulus was presented within one of two boxes positioned to the left or right of the fixation point. Lamberts et al. found significant stimulus-response compatibility effects that were modulated by body midline, visual hemifield, and the relative left/right position of the two boxes, and concluded that multiple spatial representations of a stimulus may be generated in a Simon paradigm (see also Roswarski & Proctor, 1996). There is also evidence that visual stimulus codes can be generated based on stimulus location on the receptor surface. For example, Valle-Inclán, Hackley, and de Labra (2003) tested participants with color patches presented monocularly in a Simon effect task. Regardless of whether participants were aware or unaware of the monocular presentation, there was a significant Simon effect based on the laterality of the stimulated eye, providing evidence that visual stimulus codes can be generated based on the laterality of a receptor surface relative to the stimulus location (see also Schankin, Valle-Inclán, & Hackley, 2010).

In contrast to the large body of Simon-effect research with visual stimuli, only a few studies have used the Simon paradigm to examine stimulus and response coding in tasks with *tactile* stimuli. Hasbroucq and Guiard (1992) presented participants with a tactile Simon task in which a stimulus was presented to one of two fingers. Responses were made with the same two fingers (e.g., strong stimulus, left thumb response; weak stimulus, right index finger response). Participants were significantly faster when the stimulus and response were on the same finger (congruent trials) as opposed to different fingers (incongruent trials). Because the stimulus is on the same side of space as the response on congruent trials (with the opposite on incongruent trials), these results might reflect a tactile Simon effect. However, the stimulus and response are also not just on the same side of space, but are also in the same spatial location on congruent trials. Therefore, another possibility is that individuals were simply responding more rapidly when the

stimulus and response were at the same location versus different locations. If so, there is no need to characterize these results as deriving from a conflict between stimulus and response codes. In a more recent study, Salzer, Aisenberg, Oron-Gilad, and Henik (2014) placed tactile stimulators on participants' backs located either left or right of the spine, and asked them to respond (via horizontally defined key presses) to either continuous or pulsed 500-ms tactile stimuli. They found a significant Simon effect, such that responses were faster when the key press was on the same side as the tactile stimulus. However, neither study examined whether stimulus codes in a tactile Simon paradigm were based on external or somatotopic reference frames.

The present study uses the Simon effect to further our understanding of the frames of reference implicated in making spatially defined motor responses to tactile stimuli. In such situations multiple spatial representations corresponding to both the *stimulus* and the *response* may be active. Furthermore, stimuli and responses may conceivably be encoded within different reference frames, and complex reference frame transformations may be required for the stimulus to drive the response in an appropriate manner. We first ask whether Simon effects can be observed for tactile stimuli presented to the hands when—unlike in the Hasbroucq and Guiard (1992) study—stimulus and response locations are separated. This question is critical for establishing whether or not the Simon paradigm can be applied to issues concerning frames of reference implicated in processing of tactile stimuli. In Experiment 1, we report a tactile Simon effect in a task that distinguished stimulus and response locations by means of stimuli presented to the hands and responses executed with foot pedals. We then examine whether the tactile stimulus and response codes used to drive spatially defined responses are generated within somatotopic or external reference frames. Experiments 2 and 3 examine the nature of the stimulus codes by manipulating external stimulus location through changing arm position. Finally, in Experiment 4, we examine the interaction between stimulus and response codes by manipulating both arm and leg position.

Experiment 1: Tactile Simon Effect

Experiment 1 examined whether a tactile Simon effect can be observed when stimulus locations (hands) are differentiated from response locations (feet).

Method

Eight naïve participants tested at Johns Hopkins University (two men, six women, research approved by Johns Hopkins University Institutional Review Board) were seated at a counter in front of a flat-screen monitor with each hand resting palm-down on its own piece of foam rubber with a hole for the middle finger. The middle finger of each hand was approximately 12 cm to the left or right of the screen midline. The experimenter strapped a Tactaid VBW32 Skin Transducer (Audiological Engineering Corporation, Somerville, MA) connected to a PC running E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA) to the palmar side of the distal segment of each middle finger. To mask any potential noise emitted from the stimulators, participants listened to gray noise on headphones. Two foot pedals were positioned underneath the counter, 30 cm to each side of the screen midline. At the start of

each trial the participant depressed both foot pedals; responses were made by releasing one of the pedals.

In all reported experiments, each participant first received a pre-experiment training screener to ensure that they could differentiate between high- and low-intensity tactile stimuli. The participant was first given examples of high- and low-intensity tactile stimuli, set at the same durations and thresholds as the stimuli presented in the experiment. Next, 20 screening trials were administered in which the participant verbally indicated whether the stimulus was high or low intensity; no feedback was provided. Across all experiments, all but one participant achieved the screening criterion (19/20 correct) on the first or second attempt; one participant in Experiment 3 failed both attempts, and was replaced with another participant.

For the experiment, a fixation point was displayed at the center of the screen before each trial. To encourage fixation, the experimenter monitored eye movements via a camera focused on the participant's eyes. No participant made more than three visible eye movements away from the fixation point in any of the reported experiments. On each trial, participants were presented with a 250-ms high-intensity (.25 s, 250-Hz pulse presented 40 dB above typical sensory threshold) or low-intensity (.25 s, 250-Hz pulse presented 25 dB above typical sensory threshold) tactile stimulus. After stimulus presentation, participants responded by releasing a foot pedal as quickly and as accurately as possible. Half of the participants responded with the left foot pedal for a high-intensity stimulus and the right pedal for a low-intensity stimulus, and the other half of the participants used the opposite stimulus-response mapping. Immediately after each trial, participants were given feedback as to whether they were correct or incorrect. To encourage rapid responding, participants were instructed to respond more quickly on correct trials with RTs greater than 750 ms. A trial ended if no response was recorded 1,500 ms after stimulus onset.

In Experiment 1, participants were seated with hands uncrossed and completed two blocks of trials. Each block consisted of 32 practice trials, followed by 120 test trials, which were balanced for stimulated hand, response foot, intensity, and congruency.

Results

Participants failed to respond within 1,500 ms on 0.1% of trials, and 2.6% of trials were excluded from analyses as outliers (defined as RTs >2.5 SDs above or below the participant's mean RT for the block).

Reaction times were analyzed in a 2 (Intensity) \times 2 (Stimulus Hand) \times 2 (Response Foot) analysis of variance (ANOVA). Mean RT was 40 ms faster for high-intensity stimuli (504 ms) than for low-intensity stimuli (544 ms), $F(1, 7) = 25.7, p < .001$. No main effect was observed for stimulus hand, $F(1, 7) = 1.32, p = .288$, or response foot, $F(1, 7) = .01, p = .923$. However, a Simon effect was observed, as indicated by a significant stimulus hand by response foot interaction, $F(1, 7) = 68.0, p < .001$ (Figure 1). Participants were 33 ms faster on spatially congruent trials (when the stimulus and response were on the same side) than on incongruent trials (when the stimulus and response were on different sides). Finally, the analysis revealed a three-way interaction among intensity, stimulus hand, and response foot, $F(1, 7) = 21.2, p = .020$, because the difference between congruent and incon-

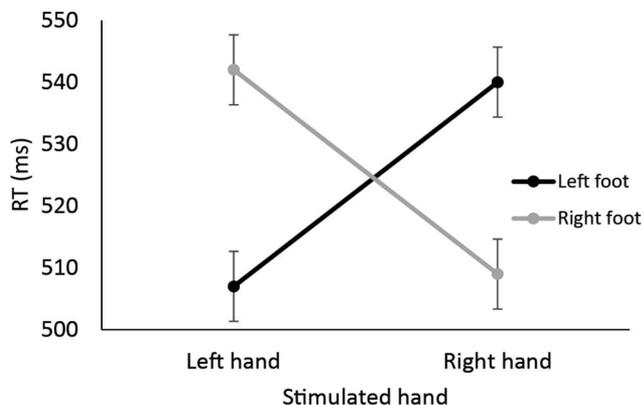


Figure 1. Mean reaction times (RTs) by stimulus hand and response foot for Experiment 1. All error bars (here and elsewhere) show 95% within-subject confidence intervals (Loftus & Masson, 1994).

gruent trials was more pronounced on high-intensity trials (49 ms) than on low-intensity trials (17 ms).

Analysis of error rates revealed only a significant stimulus hand by response foot interaction, $F(1, 7) = 7.11, p = .032$, because participants made more errors on incongruent trials (4.9%) than on congruent trials (2.3%).

Discussion

The results of Experiment 1 show a clear tactile Simon effect: Participants were significantly faster and more accurate on spatially congruent trials than on spatially incongruent trials, despite the fact that stimulus location was task-irrelevant. However, this experiment was not designed to evaluate whether the tactile stimulus codes were represented in somatotopic or external frames of reference. In the next experiment, we address this question.

Experiment 2: Somatotopic Versus External Tactile Representations

Participants were tested with their arms crossed (over the trunk midline) to dissociate somatotopic and external stimulus representations. If tactile stimulus codes are generated within a somatotopic reference frame, responses should be facilitated when the stimulus hand and response foot are congruent (e.g., left foot response to a left hand stimulus), even when the hand is in the opposite external hemifield (i.e., across the trunk midline). If, however, tactile stimulus codes are generated within an external reference frame, responses should be affected by the position of the hand in external space. In that case, responses should be facilitated when the stimulus and response are on the same side of external space (e.g., left foot response to a stimulus on the hand positioned on the left side of the trunk midline).

Method

Twelve new participants (3 men, 9 women, undergraduates at Johns Hopkins University) were tested. Each participant completed three blocks of trials, one in each of the following conditions: arms uncrossed (as in Experiment 1), left hand crossed over

right hand, and right hand crossed over left hand. The hands were the same distance from the screen midline as in Experiment 1. Each block of 100 trials was preceded by 36 practice trials. Block order and stimulus-response mapping were balanced across participants. Procedures were otherwise the same as in Experiment 1.

Results

It is important to note that in the arms crossed condition, every trial that is congruent in a somatotopic frame of reference (e.g., left hand stimulus, left foot response) is incongruent in an external reference frame, and vice versa. In the present and subsequent experiments, we report results according to their congruency in a somatotopic reference frame—for example, left hand stimulus-left foot response trials are classified as congruent in both hands-uncrossed and hands-crossed conditions. Accordingly, longer and/or more error-prone responses to incongruent trials would be consistent with a somatotopic code for the tactile stimulus, while the reverse pattern in the hands-crossed condition would imply an external reference frame.

Participants failed to respond within the 1,500-ms deadline on 0.31% of trials, and 1.44% of trials were outliers. Because there was no difference in overall RT, $t(11) = .94, p = .366$, or Simon effect magnitude, $t(11) = .50, p = .624$, between the two crossed conditions (left hand over right vs. right hand over left), RTs and error rates were collapsed across these conditions. Reaction time and error data were analyzed in separate 2 (Stimulus Hand) \times 2 (Response Foot) \times 2 (Crossed vs. Uncrossed) ANOVAs (Figure 2). As in Experiment 1, there was a significant stimulus hand by response foot interaction, $F(1, 11) = 21.0, p < .001$, over all postures (Figure 2). When the hands were uncrossed, participants were 35 ms faster on somatotopically congruent trials (e.g., left hand stimulus, left foot response) than on somatotopically incongruent trials (e.g., left hand stimulus, right foot response), $t(11) = 3.77, p = .003$. It is important that there was also a 38-ms effect of *somatotopic* congruency when the hands were crossed, providing clear evidence for somatotopic encoding of tactile stimulus location, $t(11) = 4.42, p < .001$. The fact that the congruency

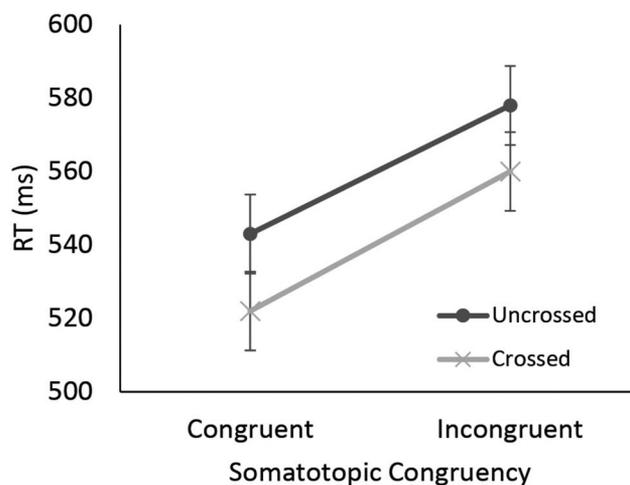


Figure 2. Mean reaction times (RTs) for *somatotopically* congruent and incongruent trials with the arms uncrossed and crossed in Experiment 2.

effect was as large in the crossed as in the uncrossed condition suggests that external encoding of stimulus location made no noticeable contribution to performance on the task. Unexpectedly, participants were also significantly faster overall on crossed trials (538 ms) than on uncrossed trials (560 ms), $F(1, 11) = 7.03, p = .023$. No other effects were significant.

The analysis of error rates revealed that participants made significantly fewer errors in the crossed (3.5%) than in the uncrossed (5.7%) condition, $F(1, 11) = 6.46, p = .027$. There was also a main effect of stimulus hand, $F(1, 11) = 12.9, p = .004$, because participants made fewer errors on right- than left-hand stimuli (3.7% vs. 5.5%, respectively). Participants also made fewer errors on somatotopically congruent trials (3.2%) than on somatotopically incongruent trials (6.0%), though this difference was not statistically significant ($p = .142$).

Discussion

The results of Experiment 2 provide evidence of tactile stimulus codes based on a somatotopic representation. The absence of an external Simon effect could suggest that external stimulus codes play no significant role in the tactile Simon task. However, in a study by Yamamoto and Kitazawa (2001) participants made tactile temporal order judgments with their hands in the opposite hemisphere (i.e., left hand in right hemisphere, right hand in left hemisphere), with their arms either crossed or uncrossed (see Figure 3 for an example of this posture with the arms uncrossed). Even though the hands were located in the opposite hemisphere in both conditions, participants were significantly less accurate in the arms-crossed versus arms-uncrossed condition. This result raises the possibility that crossing the hands itself may have an effect on tactile performance that is distinct from the effects of changing the spatial location of the hands. Therefore, another possible interpretation for the failure to observe an external Simon effect is that

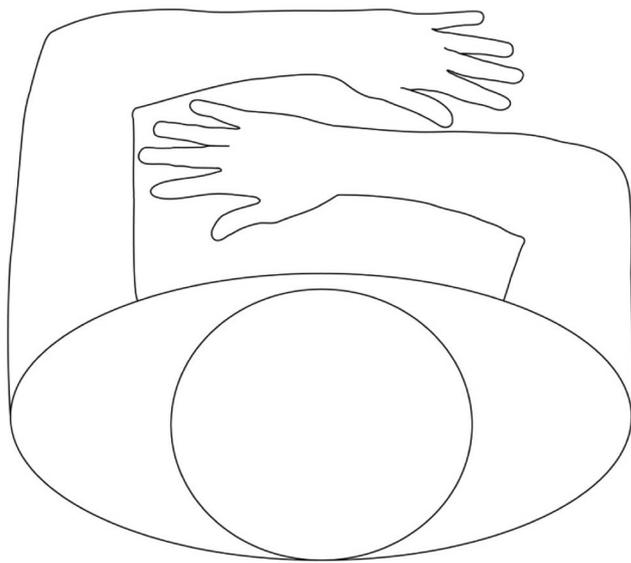


Figure 3. Diagram illustrating body position in the “opposite hemisphere” condition in Experiment 3.

something specific about *crossing* the hands interferes with external stimulus coding. This issue is examined in Experiment 3.

Experiment 3: Examining the Effects of Crossing

Experiment 3 examined whether the results observed with hand crossing in Experiment 2—a somatotopic Simon effect with no evidence of an external Simon effect—would also be observed when the hands are uncrossed yet still positioned in the opposite external hemisphere (Figure 3). In this *opposite hemisphere* condition, we dissociate somatotopic and external reference frames *without* hand crossing. One possibility is that the act of hand crossing itself somehow interferes with external stimulus coding, thus resulting in a failure to find an effect of external reference frames in Experiment 2. If so, presenting the hands in opposite hemispaces without crossing should remove this potential source of interference, and we should see evidence of external stimulus codes in this posture. In particular we should observe an attenuation or reversal of the somatotopic Simon effect, indicating an effect of external stimulus codes. However, if only somatotopic stimulus codes are generated, regardless of hand crossing, then the somatotopic Simon effect should be as large in the opposite hemisphere condition as when each hand is in its own hemisphere (i.e., left hand in left hemisphere, right hand in right hemisphere).

Method

Thirteen undergraduates at the University of Pennsylvania (4 men, 9 women, research approved by the University of Pennsylvania Institutional Review Board) were tested. Data from one participant who failed the screener were not analyzed. Each participant was presented with three blocked conditions: arms uncrossed, arms crossed, or arms uncrossed in the opposite hemisphere. In this last condition, hands were uncrossed and positioned in the hemisphere opposite their somatotopic side in a trunk- and head-centered frame of reference (Figure 3). Whether the right or the left hand was closer to the body in the opposite hemisphere condition, and hand configuration in the crossed position (e.g., left arm over right arm, right arm over left arm) were counterbalanced across participants. Block order was also counterbalanced across participants. Each block consisted of 36 practice trials followed by 100 test trials. Otherwise, all procedures were the same as in Experiment 1.

Results

Participants failed to respond within the 1,500-ms deadline on 0.01% of trials, and 2.32% of trials were outliers. As before, we found a significant stimulus foot by response hand interaction, $F(1, 11) = 109.3, p < .001$, because participants were 43 ms faster on somatotopically congruent trials than on somatotopically incongruent trials. It is apparent from Figure 4 that the somatotopic Simon effect, far from being attenuated or reversed in the opposite hemisphere condition, was at least as large in this condition as in the uncrossed and crossed conditions. A significant three-way interaction was observed, $F(2, 22) = 3.78, p = .039$, indicating that the magnitude of the Simon effect varied across conditions. In all three conditions, there was a significant somatotopic Simon effect (all $ps < .001$). However, the soma-

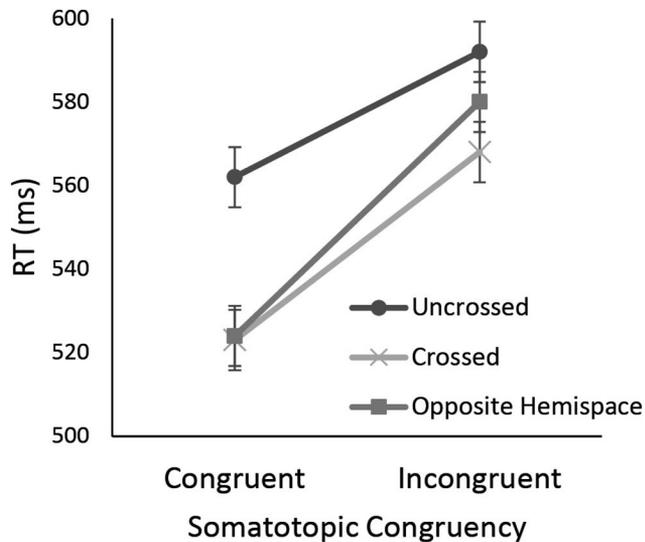


Figure 4. Mean reaction times (RTs) by condition in Experiment 3.

totopic Simon effect was significantly larger in the opposite hemisphere condition (56 ms) than in the uncrossed condition (30 ms, $p = .024$), with no other significant differences in the magnitude of the somatotopic Simon effect (crossed vs. uncrossed, $p = .133$; opposite hemisphere vs. crossed, $p = .280$).

There was also a main effect of limb position, $F(2, 22) = 6.58$, $p = .006$. Specifically, relative to the uncrossed condition (576 ms), participants were significantly faster to respond with the arms crossed (545 ms, $p = .002$) and in the opposite hemisphere condition (552 ms, $p = .022$).

For error data, there was a significant stimulus hand by response foot interaction, $F(1, 11) = 17.3$, $p = .002$, because participants made significantly fewer errors on somatotopically congruent trials (1.9%) than on somatotopically incongruent trials (6.2%). No other comparisons were significant.

Discussion

In Experiment 3, we found a strong somatotopic Simon effect in all three conditions. These results provide further support for somatotopic encoding of the stimulus location and also indicate that the failure to find evidence of external stimulus coding in Experiment 2 was not because of the arm crossing manipulation, because the somatotopic Simon effect was also seen when the arms were in the opposite hemisphere and uncrossed. Why the somatotopic Simon effect was largest in the opposite hemisphere condition is unclear. However, this result clearly cannot be attributed to an effect of external stimulus codes, because external stimulus coding would have reduced or eliminated the somatotopic Simon effect in the opposite hemisphere condition, rather than enhancing the effect. Furthermore, as in Experiment 2, we found that participants responded faster overall with the hands in the opposite hemisphere (either crossed or uncrossed) compared with when the hands were in their typical hemisphere.

Experiment 4: Manipulating Stimulus and Response Position

In Experiments 2 and 3, we compared the magnitude of the Simon effect with arms uncrossed and crossed to examine whether stimulus location is represented based on somatotopic and/or external reference frames. We found an equally strong somatotopic Simon effect in both postures, suggesting that *stimulus* codes were generated primarily based on a somatotopic reference frame in this task. As discussed earlier, Wallace (1971) manipulated effector position (uncrossed and crossed) and found that *response* codes could be generated based on an external reference frame in a visual Simon effect task. In Experiments 2 and 3 of our study, the participants' legs were uncrossed. As a result, we were unable to tell whether *responses* in the context of tactile stimuli are represented in a somatotopic or external frame of reference, or what the interaction might be between stimulus and response codes. Therefore, in Experiment 4 we manipulated leg posture along with arm posture to examine the reference frames used to encode both stimulus and response location. In Figure 5, the four test conditions are referred to as II, IX, XI and XX, with the first letter indicating the hand posture (I = uncrossed, X = crossed) and the second indicating the leg posture. With the arms and legs uncrossed, we previously found a consistent somatotopic Simon effect. If response codes are also generated strictly based on a somatotopic reference frame, then we would expect the magnitude of the somatotopic Simon effect to be comparable regardless of leg crossing. For example, participants should respond more quickly with the left foot to stimuli presented to the left hand, regardless of whether the legs are crossed or uncrossed. In contrast, if response codes are generated solely based on an external representation, we would predict that leg crossing would change the direction of the somatotopic congruency effect. For example, for stimuli presented to the left hand with the arms uncrossed, participants would respond more quickly with the left foot with legs uncrossed, and with the right foot with legs crossed. A third possibility is that crossing the legs could reveal that both somatotopic and external response codes are generated, with different strengths in different conditions. For example, generation of a weak external response code with the legs crossed would result in a reduction (rather than

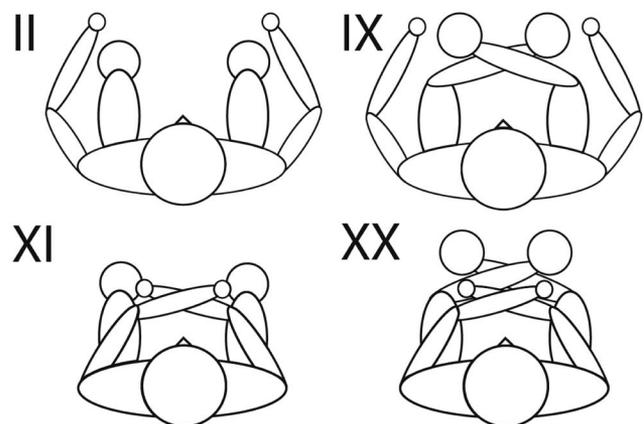


Figure 5. Body postures for the four conditions in Experiment 4.

a reversal) in the magnitude of the somatotopic congruency effect on crossed versus uncrossed leg trials.

A further consideration that has not yet been discussed is that task instructions could influence congruency effects by potentially affecting whether responses are encoded in somatotopic or external coordinates. When the legs are crossed, participants can represent stimulus-response mappings based on the location of the effector (e.g., right *foot*, high intensity stimulus) or the response goal (e.g., Hommel, 1993a), which is likely to be encoded in an external reference frame (e.g., left foot *pedal*, high intensity stimulus). To examine whether task instructions of this sort can influence the response codes generated in the tactile Simon paradigm, participants in Experiment 4 were instructed to map stimulus properties either to specific feet or to specific foot pedals.

Method

Sixty-six undergraduates at the University of Delaware were tested (30 men, 36 women, research approved by the University of Delaware Institutional Review Board). Each experiment consisted of four blocks varying both arm and leg posture (crossed, uncrossed) as within-participant conditions. To aid responding in the more difficult crossed leg position, the same leg posture (either crossed or uncrossed) was maintained for the first two blocks and then switched for the last two blocks.

Half of the participants were instructed to respond based on the somatotopically defined foot (e.g., respond with the left foot for the high intensity stimulus), whereas the other half of the participants were instructed to respond based on the externally defined foot pedal (e.g., respond with the left foot pedal for the high intensity stimulus). The mapping from stimulus type (high or low intensity) to response side (left or right foot pedal) did not change within each participant. Stimulus-response mapping and block order were counterbalanced across participants. Two participants were dropped for failing to respond on more than half of the trials in a block, and were replaced with participants tested on the same block order and S-R mapping to ensure counterbalancing. Each block consisted of 12 practice trials followed by 72 test trials. All other procedures were the same as in Experiment 1.

Results

Participants failed to respond by the 1,500 ms deadline on 1.42% of trials, and 2.29% of trials were outliers. Reaction times and error rates were analyzed in separate mixed design ANOVAs, with arm posture, leg posture, stimulated hand, and response foot as within-subject factors, and response instruction (by foot or by side of space) as a between-subjects factor.

For RT, there was a significant main effect of leg crossing on performance, $F(1, 62) = 24.5, p < .001$, because participants were 41 ms slower with legs crossed versus uncrossed (Figure 6). The main effect of response instruction only approached significance, because participants were 31 ms slower when instructed to respond based on pedal compared with foot, $F(1, 62) = 3.10, p = .083$. In contrast to Experiments 2 and 3, there was no main effect of hand crossing, $F(1, 62) = .23, p = .633$, because participants were only 2 ms faster with the hands crossed versus uncrossed.

In terms of interactions, there was, overall, a highly significant somatotopic Simon effect as demonstrated by a stimulus hand by

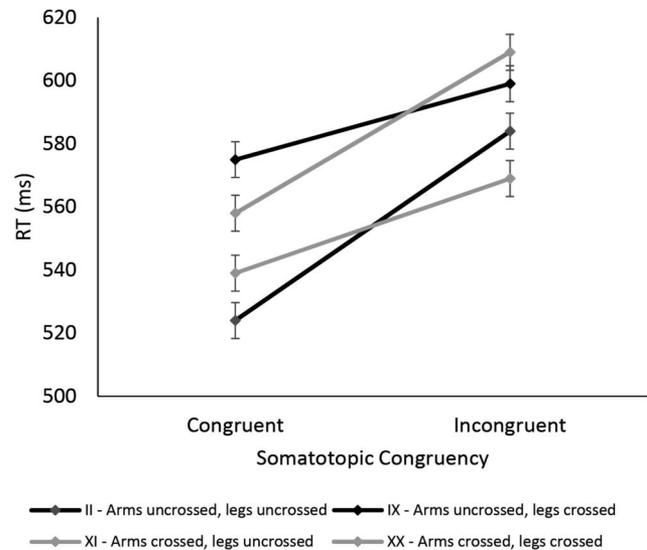


Figure 6. Mean reaction time (RT) by condition for Experiment 4.

response foot interaction, $F(1, 62) = 210.5, p < .001$. Participants were 41 ms faster on somatotopically congruent trials than on somatotopically incongruent trials.

It is important that there was a significant four-way interaction between arm posture, leg posture, stimulated hand and response foot, $F(1, 62) = 34.8, p < .001$. In other words, the magnitude of the Simon effect differed depending on leg and arm posture (Figure 6).

Using paired t tests, we carried out planned comparisons examining the magnitude of the somatotopic Simon effect across conditions. As seen in Experiments 1–3, participants demonstrated a large somatotopic Simon effect in all four conditions (all $ps < .001$). In the two conditions in which leg posture was different than arm posture (IX and XI), the somatotopic Simon effect was smaller (23 ms and 30 ms, respectively) than in the conditions in which leg and arm position were the same (II, 59 ms and XX, 51 ms). In the II and XX conditions, S-R congruency is the same for both somatotopic and external reference frames. For example, with both arms and legs crossed, a trial with a left hand stimulus and left foot response would be congruent in a somatotopic and external reference frame. However, in the IX and XI conditions, S-R congruency differs in somatotopic and external reference frames. Somatotopically congruent trials in the II condition are also externally congruent, whereas the somatotopically congruent trials in the IX condition are externally incongruent. Therefore, a decrease in the size of the somatotopic Simon effect in a condition where arm and leg position differ (i.e., IX and XI) compared with when they are the same (i.e., II and XX) can provide evidence for the influence of external representations on stimulus and response coding.

These comparisons can be specifically examined for the contribution of stimulus and/or response codes based on an external frame of reference. For example, let us again examine a trial with a left hand stimulus and left foot response in two postural conditions. In the II condition, this trial is both somatotopically congruent (left hand stimulus, left foot response) and externally congruent (left side stimulus, left side response). Comparing this trial in the

II condition to the same trial in the IX condition (arms uncrossed, legs crossed), the only difference in spatial codes is in the external *response* code. In the IX condition, this same trial is somatotopically congruent (left hand stimulus, left foot response) but externally *incongruent* (left side stimulus, *right* side response). Comparing performance on the same trial in the II versus IX condition, the difference in external congruency across these two postural conditions is because of a change in the external *response* code. Therefore, by contrasting performance in conditions where only external response coding differs, one can examine the influence of external representations on response codes.

To do this, we compared the size of the somatotopic Simon effect across conditions in which only externally based response codes differed—that is, leg position varied across the conditions while arm position was the same. Using post hoc paired *t* tests, we found a significant decrease in the size of the Simon effect for both relevant comparisons, II vs. IX, $t(63) = 4.72, p < .001$; XI vs. XX, $t(63) = 3.02, p = .003$. We also examined the influence of external representations on *stimulus* codes, by comparing the size of the somatotopic Simon effect across conditions in which only response codes differed in an external frame of reference. These were conditions in which arm position varied across the conditions while leg position was the same. We found a significant decrease in the size of the Simon effect, II vs. XI, $t(63) = 3.89, p < .001$; IX vs. XX, $t(63) = 2.60, p = .011$. Post hoc paired *t* tests showed no significant difference in the size of the Simon effect between the II and XX conditions, or between the IX and XI conditions, respectively, $t(63) = 1.07, p = .288$ and $t(63) = .87, p = .389$.

There was also a significant interaction of hand posture by stimulated hand, $F(1, 62) = 5.60, p = .021$, such that participants were 7 ms faster when stimulated on the left hand with the arms uncrossed, and 3 ms faster when stimulated on the right hand (positioned on the left side) with the arms crossed. All other comparisons, including the interaction between stimulated hand, response foot, and response instruction, $F(1, 62) = 2.02, p = .161$, were not significant.

As can be seen in Figure 7, the results were comparable in terms of accuracy. There was a main effect of leg posture, $F(1, 62) = 52.9, p < .001$, because participants made fewer errors responding with the legs uncrossed (5.8%) compared with the legs crossed (11.6%). Not observed in the RT analysis, there was a main effect of response foot, $F(1, 62) = 6.23, p = .015$, because participants were 1.7% more accurate when responding with the right foot versus the left foot—likely reflecting the effects of lateralized response dominance. There was no main effect of response instruction, $F(1, 62) = 1.82, p = .182$.

Regarding interactions, there was a significant stimulated hand by response foot interaction, $F(1, 62) = 69.8, p < .001$, because there was a 5.3% somatotopic Simon effect observed over all conditions. A significant hand posture by stimulated hand interaction was also observed, $F(1, 62) = 9.68, p = .003$, because participants were 1.9% more accurate on the right hand with the arms uncrossed, but 0.5% more accurate on the left hand (on the right side of space) with the arms crossed. Considering that participants were significantly faster on the left side of space, this may reflect a spatially mediated speed–accuracy trade-off. Finally, there was a significant four-way interaction of hand posture, leg posture, stimulated hand and response foot, $F(1, 62) = 16.4, p <$

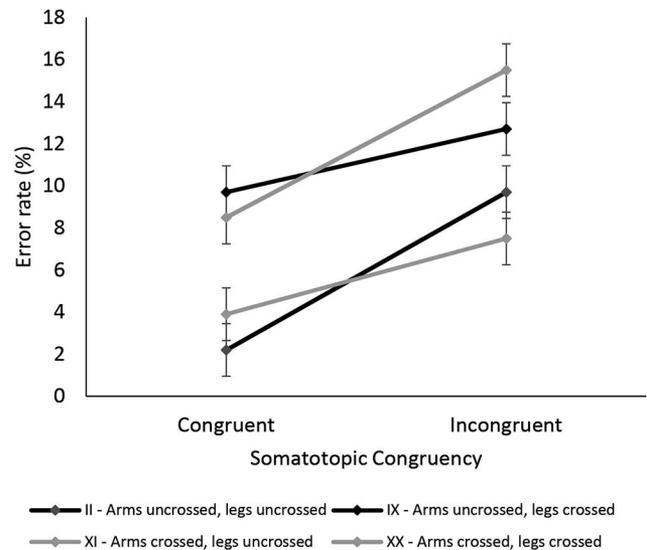


Figure 7. Mean error rate by condition for Experiment 4.

.001, reflecting differences in the size of the somatotopic Simon effect because of arm and leg posture. The somatotopic Simon effect was significantly greater in conditions where the corresponding arms and legs were on the same side of space (7.5% for arms and legs uncrossed, II; 6.9% for arms and legs crossed, XX) compared with when they were on the opposite side of space (3.0% for arms uncrossed, legs crossed, IX; 3.6% for arms crossed, legs uncrossed, XI). As in the RT analysis, we found a significant decrease in the somatotopic Simon effect with the addition of leg crossing in conditions where arm position did not differ, II vs. IX, $t(63) = 3.40, p = .001$; XI vs. XX, $t(63) = 3.80, p < .001$, and a similar decrease in the somatotopic Simon effect with the addition of arm crossing where leg position did not differ, II vs. XI, $t(63) = 3.89, p < .001$; IX vs. XX, $t(63) = 2.60, p = .011$. No other comparisons, including the interaction between response instruction and the Simon effect, $F(1, 62) = .47, p = .494$, were significant.

Discussion

In Experiment 4, we manipulated leg position to understand response coding in a tactile Simon effect task. First, the results revealed the presence of a significant somatotopic Simon effect for all four conditions, replicating previous findings regarding somatotopic stimulus coding in Experiment 2 and 3. Second, this effect was attenuated in conditions in which the arms and legs were not in the same posture (IX and XI). For example, when comparing conditions in which the arms were uncrossed, there was a significantly smaller Simon effect with the legs crossed (IX) versus uncrossed (II). These results provide evidence that changing effector position leads to some contribution of external response codes on this task. However, a subset of the results of Experiment 4 contrast with findings from Experiments 2 and 3. In those experiments, no difference was observed for crossing the hands when effector position was static throughout the experiment (i.e., XI vs. II). However, Experiment 4 did find a significant decrease in Simon effect magnitude for the same comparison, indicating a

contribution of external stimulus codes. These results will be discussed in the General Discussion.

General Discussion

In the present study, we used the Simon paradigm to explore the reference frame(s) for encoding the spatial location of tactile stimulation and responses to touch. First, we found that participants showed a *somatotopic* Simon effect for tactile stimuli, responding more quickly when the stimulated hand was somatotopically congruent with the response foot regardless of arm or leg position. This effect occurred across all experiments and conditions. This finding constitutes novel evidence for representations based on *somatotopic reference frames* for *tactile stimulus codes* in the context of the Simon paradigm. Second, we found evidence (in Experiment 4) for representations based on *external reference frames* for *both response and stimulus codes*. It is noteworthy that, in this context, we also found that instructing participants to respond based on an external frame of reference did not significantly enhance the effect of the external reference frame. Third, we found that the presence of stimulus code representations based on an external reference frame *varied with experimental conditions* as it was present in the Experiment 4 (in which arm and foot postures were both manipulated) but not in Experiments 2 and 3 (where only hand posture was manipulated). Finally, we found an unexpected effect—in Experiments 2 and 3 participants were faster overall when the arms were located in the opposite hemispace versus their typical hemispace. However, this effect was not evident in Experiment 4, in which leg posture was also manipulated. Below we discuss these key findings.

Somatotopic Simon Effects

Across the four experiments we found evidence of somatotopic representation for both the stimulus (Experiments 1–4) and response codes (Experiment 4) generated in a Simon paradigm requiring motor responses to tactile stimuli. Previously, only a few studies had examined the Simon effect with tactile stimuli, and none had used arm and/or leg crossing to contrast somatotopic and external reference frames. Therefore, we turn to the literature on visual Simon effects where these issues have been more extensively examined.

In terms of response codes in visual Simon paradigms, arm crossing manipulations (Hommel, 1993a; Riggio et al., 1986; Simon et al., 1970; Wallace, 1971, 1972) have all demonstrated that the position of the effector (or response goal) in external space, but not the somatotopic identity of the effector, was used to generate the *response* code. In contrast, our findings clearly demonstrate that tactile response codes can be based on a somatotopic frame of reference, rather than being based on the position of the effector (in this case, the feet) in external space. Why might effector position influence response code generation for somatosensory, but not visual stimuli? One possibility is that somatosensory and motor systems are more tightly coupled than visuomotor systems, because of the dense and short-range neural connectivity between somatosensory and motor cortices (Porter, 1997). A second possibility may be that responses are encoded based on the modality of the stimulus. For example, Bernier and Grafton (2010) reported that anterior precuneus represents visual targets using a

gaze-centered reference frame, but instead uses a body-centered reference frame for proprioceptively defined targets. Furthermore, most other examinations of response coding in the Simon effect paradigm involved manipulation of (and responding with) the arms versus the legs. Therefore, a second possibility is that the external location of an action is less robustly represented for the legs than for the arms, because the legs are used far less often as goal-directed effectors. This may lead to greater use of somatotopic, as opposed to external, response codes for foot responses. Further experimentation presenting tactile stimulation to the feet while manipulating arm position could address this hypothesis.

In terms of stimulus codes in visual Simon paradigms, there is evidence that these may be represented in various external reference frames, including attention-centered (Nicoletti & Umiltà, 1989), retinocentric (Lamberts et al., 1992), and object-centered (Hommel & Lippa, 1995). Furthermore, visual stimulus codes can also be generated based on stimulus location on the receptor surface—the visual analog to the somatotopic reference frame in the tactile domain (Schankin et al., 2010; Valle-Inclán et al., 2003). The present investigation provides novel evidence for the somatotopic representation of tactile stimulus codes in the Simon paradigm, similar to previous findings of receptor surface Simon effects. Why would tactile stimulus codes be generated based on a somatotopic, as opposed to an external, reference frame? A number of studies (Azañón & Soto-Faraco, 2008; Groh & Sparks, 1996; Overvliet et al., 2011; Yamamoto & Kitazawa, 2001) have provided evidence for somatotopic dominance at stimulus presentation, with tactile spatial remapping into external coordinates starting at approximately 70 ms (Soto-Faraco & Azañón, 2013) and not complete until approximately 150–350 ms after stimulus onset. Previous visual Simon effect experiments have shown that stimulus codes are generated immediately after stimulus onset and well before response execution (Hommel, 1993b). For example, ERP studies of the horizontal Simon effect have found that the lateralized readiness potential, a marker of response preparation, shows signs of stimulus-response conflict at approximately 200 ms after stimulus presentation (the “Gratton-dip,” see Vallesi, Mapelli, Schiff, Amodio, & Umiltà, 2005). Visual stimulus codes in this task must be generated, at the very latest, 200 ms after stimulus presentation. If, as in visual Simon effect experiments, tactile stimulus codes are generated shortly after stimulus presentation, it is possible that the dominant representation of tactile stimulus position is somatotopic when stimulus codes are generated. If so, this would result in primarily somatotopic, as opposed to external, tactile stimulus codes.

Salience and Differentiation of Multiple Reference Frames

As demonstrated in visual Simon paradigm studies, stimulus and response codes can be generated based on multiple frames of reference (Lamberts et al., 1992; Roswarski & Proctor, 1996), allowing for a number of possible stimulus-response code congruency mappings. As noted earlier, there is also evidence for both somatotopic and external representations of touch in space. In this investigation, we were specifically interested in understanding how or if these multiple representations contributed to stimulus and response encoding in a task that involved spatially directed responses to tactile stimuli. The tactile Simon effect could be based

on the congruency between somatotopic stimulus and response codes and also separately between externally defined stimulus and response codes—presenting the possibility of multiple, separate Simon effects in a given task. In Experiments 2 and 3, crossing the hands and positioning the hands in the opposite external hemisphere still resulted in a strong somatotopic Simon effect with no evidence of an external Simon effect. However, in Experiment 4, where both the arms and legs could be crossed or uncrossed, there was evidence for both somatotopic *and* external representations of both stimulus and response codes. This raises the question of why the evidence for stimulus codes based on an external reference frame differed for Experiments 2 and 3 versus Experiment 4. We propose that the external Simon effect in Experiment 4 may have been because of the increased salience of the external reference frame generated by the characteristics of the experimental conditions.

In the visual domain, researchers have shown that the relative salience of specific dimensions can affect the magnitude of the Simon effect. Proctor, Vu and Nicoletti (2003) tested participants in a two-dimensional Simon effect task in which red or green stimuli were presented at one of four locations on a computer screen (upper left, upper right, lower left, lower right), with all locations equidistant along both dimensions. Response buttons were positioned orthogonally across both dimensions—for example, an upper left and lower right button—allowing for separable horizontal and vertical compatibility effects. In one experiment, Proctor et al. manipulated the salience of a particular dimension by changing stimulus position along that dimension. They found a greater Simon effect for the salient dimension compared with the nonsalient dimension, suggesting that stimulus salience could affect the strength of stimulus codes. Other two-dimensional visual Simon effect studies have shown that stimulus and response codes can be made more salient by changing the spatial orientation of the response (Ansorge & Wuhr, 2004) or by priming a particular dimension (Memelink & Hommel, 2005), prompting a number of researchers to discuss the role of salience in S-R compatibility effects (Hommel, Musseler, Aschersleben, & Prinz, 2001; Memelink & Hommel, 2013; Rubichi, Vu, Nicoletti, & Proctor, 2006; Vu & Proctor, 2001).

In the context of our investigation, we suggest that the addition of the leg crossing manipulation in Experiment 4 increased the salience of the external reference frame in this experiment relative to Experiments 2 and 3. First, it is likely that response codes are generally more salient than the stimulus codes since response instructions need to be explicitly understood and encoded in order to carry out the task (i.e., participants need to remember which foot is assigned to which specific stimulus property). Adding the crossing manipulation to the response would have increased the salience of the response codes. Furthermore, an external frame may provide a more stable representational format by anchoring responses to locations external to the changing body configuration. If, in fact, both frames of reference were active in Experiment 4, we would expect to see the observed pattern of responses in which somatotopic frame effects were attenuated by the presence of external frame effects.

The finding that both somatotopic and external reference frames contributed to both stimulus and response codes raises the question of whether S-R congruency effects arise not only *within* a reference frame but also *across* reference frames. The standard S-R

congruency effect arises when, within a reference frame, stimulus and response codes differ. The question is whether there are also “across” S-R mappings in which somatotopic stimulus codes interact with external response codes (and vice versa). The findings from Experiment 4 speak to this issue. If both external and somatotopic frames are active on all trials for both stimulus (hand) and response (leg) codes, the “across frame congruency hypothesis” would predict Simon effects with a different magnitude for II and XX conditions. This is because (as can be seen in Figure 5) stimulus-response pairs (e.g., left-hand stimulus + left-foot response) that are S-R compatible within both external and somatotopic frames differ in their degree of across frame compatibility in II and XX. For example, in II trials, the left-hand stimulus + left-foot response pair is encoded as left + left in both frames of reference, while in XX trials it would be encoded as left + left in a somatotopic frame and as right + right in an external frame. In this latter situation, there would be no within frame inconsistency of stimulus and response codes, but there would be across-frame inconsistency (e.g., left somatotopic stimulus code, right external response code). The fact that Simon effect magnitude is not different in II and XX trials indicates that across-frame inconsistencies are not affecting performance, at least under these experimental conditions.

It is worth noting that task instructions directing attention to the response pedal (external frame) did not significantly change the results. This is despite the fact that at least some other studies have found significant instructional effects (Hommel, 1993a, 1996). There are various possible explanations for why these effects were absent in Experiment 4. One possibility is that the external frame was maximally active because of the saliency considerations discussed above, and as a result task instructions emphasizing the external locations of responses had no additional effect. Certainly further research is required to clarify this issue.

Faster Responding in the Opposite Hemisphere

We found that participants responded significantly more quickly with the arms crossed versus uncrossed (Experiments 2 and 3), with these speeded responses also occurring in the opposite hemisphere condition (Experiment 3). Given the consistency of this effect, the question arises as to why it was not found in Experiment 4.

In the uncrossed condition, the hands occupy a fairly typical, “default” position in their own hemisphere. If that is the case, then it is possible that we are more likely to allocate resources to somatotopic representations when the hands are outside of their typical space, because these are situations in which we are often using discriminative touch. In these situations when the hands are in an atypical position, it may be important to identify which hand is being stimulated in order to send motor commands to the correct hand. For example, imagine that your left hand is crossed over to the right side of your body to pick up a slippery bar of soap. Even though it’s on the right side (in an external frame of reference), it is important to make sure that you represent that it is your left hand so that you continue to send motor commands to your left hand to adjust your grip and pick it up. If so, then it would be important to increase somatotopic attention when the hands are in atypical positions.

This potential interpretation is supported by studies that have examined somatosensory ERP components with the arms crossed versus uncrossed. Heed and Roder (2010) presented participants with tactile stimuli to either the hands or feet while instructing participants to attend to a limb. As expected, tactile attention to a limb resulted in a positive deflection of the N140 – a component typically associated with increases in activity in SII (Allison, McCarthy, & Wood, 1992). However, they also found a larger positive deflection of the N140 component to the *unattended* location when participants' hands were crossed versus uncrossed. Furthermore, they also found an effect of hand crossing on unattended stimuli from 190–300 ms after stimulus onset. Even when participants are not actively attending, there is some evidence for enhanced representation of tactile stimuli with the hands crossed, suggesting involuntary changes in tactile attention dependent on limb position. This potential enhancement of the tactile representation with the arms crossed may result in faster detection of stimulus properties (high vs. low intensity) and shorter RTs.

Shorter RTs with the arms crossed is a somewhat counterintuitive finding, because RTs are substantially longer with the arms crossed versus uncrossed in tactile temporal order judgment tasks (Roberts & Humphreys, 2008; Yamamoto, Moizumi, & Kitazawa, 2005). We propose that the longer RTs in the crossed condition in tactile TOJ tasks are likely related to conflicts in representing the *location* of touch in somatotopic versus external representations when the hands are crossed. For example, in Roberts and Humphreys (2008), they found that crossing led to longer TOJs when the response involved explicit localization of the two tactile stimuli (e.g., which position was stimulated first), but they found no effect of crossing when the response was defined based on nonspatial attributes (e.g., which frequency was presented first). We note that our experiments do not involve any explicit localization of touch, and instead involve making a response to a nonspatial attribute (stimulus intensity). We believe that the longer RTs in the crossed posture on spatially defined TOJ experiments are because of conflicts between somatotopic and external processing that occur when explicitly localizing touch with the arms crossed. Therefore, because our task does not involve explicit localization, we would not predict slower responses with the arms crossed in our task. It is important that the omission of an explicit localization judgment may have allowed us to find effects of tactile attention for crossing the hands. We note that effects of tactile attention in our experiments are relatively small compared with the effect of crossing in spatially defined tactile TOJ experiments. Any potential improvements because of increased attention would likely be masked because of the large effects of crossing in tactile TOJ tasks that involve explicit spatial localization.

Finally, why was there a failure to find this increased attention in the hands crossed condition (XI) in Experiment 4? One possibility is that introducing a leg crossing condition may lead to increased attention to the feet over the entire experiment in order to focus on responding correctly. This increased attention to the responding limbs may decrease attention toward the stimulated arms, thus eliminating the advantage that was observed for the arms crossed condition in Experiments 2 and 3. However, we note that these explanations are speculative, and that further experimentation is necessary.

Conclusions

In summary, this study demonstrates that both tactile stimulus and response codes are generated based on a somatotopic representation in a tactile Simon effect task. These results are consistent with accounts in which somatotopic representations are more salient during the initial stages of stimulus processing. There was also evidence for the generation of external stimulus and response codes, but only in an experiment in which effector position was also manipulated, providing evidence that leg crossing increases the salience of external representations. Finally, separate from the observed tactile Simon effect, we also found that participants responded more quickly with the arms crossed versus uncrossed only in experiments in which the legs are uncrossed. This may be because of increased allocation of attentional resources to tactile representations when the hands are crossed, with less attention directed to the hands when both the hands and feet can be crossed.

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