

# **Interplay of tactile and motor information in constructing spatial self-perception**

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## Summary

During active movement, there is normally a tight relation between motor command and sensory representation about the resulting spatial displacement of the body. Indeed, some theories of space perception emphasise the topographic layout of sensory receptor surfaces, while others emphasise implicit spatial information provided by the intensity of motor command signals. To identify which has the primary role in spatial perception, we developed experiments based on everyday self-touch, in which the right hand strokes the left arm. We used a robot-mediated form of self-touch to decouple the spatial extent of active or passive right-hand movements from their tactile consequences. Participants made active movements of the right hand between unpredictable, haptically-defined start and stop positions, or the hand was passively moved between the same positions. These movements caused a stroking tactile motion by a brush along the left forearm, with minimal delay, but with an unpredictable spatial gain factor. Participants judged the spatial extent of either the right hand's movement, or of the resulting tactile stimulation to their left forearm. Across five experiments, we found that movement extent strongly interfered with tactile extent perception, and *vice versa*. Crucially, interference in *both* directions was stronger during active than passive movements. Thus, voluntary motor commands produced stronger integration of multiple sensorimotor signals underpinning the perception of personal space. Our results prompt a reappraisal of classical theories that reduce space perception to motor command information.

**Keywords:** Sensorimotor interaction, self-touch, spatial perception, motor dominance, voluntary action.

## Introduction

Self-touch is among the earliest and most ubiquitous spatial experiences for humans. Fetal hand-to-face movements occur in utero from thirteen weeks, and interlimb contact is frequent<sup>1</sup>. After birth, several forms of self-touch behaviours persist through childhood and into adulthood, including functional self-stimulation (e.g., grasping an injured body part), bimanual object handling, and tool-mediated grooming actions (e.g. brushing the hair). All self-touch behaviours involve a tight coupling between the neural information that controls the movement, and the stimulation of skin receptors in the touched body part. This contingency, sometimes termed *touchant-touché*<sup>2-4</sup> (i.e., motor touching and sensory touched, respectively), means that self-touch produces strong correlations between motor and sensory representations in the brain. Over the longer term, these correlations have been linked to the development of self-awareness<sup>3,5</sup> and own-body representation<sup>4,6-9</sup>.

Different theoretical accounts of *space perception* make alternative predictions about the relative contributions of motor and sensory information to integrated spatial percepts like self-touch, but few experimental studies have investigated the question. For example, theories of sensorimotor control<sup>10</sup> and of object perception<sup>11</sup> both emphasise the integration of multiple sources of information during skilled interactions with the external world. However, it remains unclear whether integration operates in the same way for self-touch as for object-touch<sup>3-5,8,9,12</sup>. When two body parts touch each other, it is not obvious which one of them is the counterpart of the external object in object-touch. Moreover, the signals associated with touching and with being touched remain separable and non-metameric.

Recent computational neuroscience theories also make important predictions about perception during self-touch. First, theories based on computational motor control<sup>13</sup> and predictive coding<sup>14</sup> suggest that the sensory consequences of movement should be attenuated or even suppressed, since they are predictable from an internal forward model. These models have generally been applied to intensity perception<sup>15</sup> (but see also<sup>16</sup>), and their implications for other dimensions of perception, such as spatial or temporal features, are less clear. Second, theories of multisensory integration<sup>17</sup> suggest that independent sensory channels are integrated to produce a single percept, by weighting information in each channel according to its reliability. These models have been applied to both spatial<sup>17</sup> and temporal<sup>18</sup> perception, and can successfully capture perceptual fusion of vision and touch<sup>17,19</sup>, as long as both signals provide independent evidence about a common source object or event<sup>20</sup>. However, during self-touch it is unclear what is the common source object that is perceived. Moreover, the assumption that sensory and motor signals are independent has been challenged.

For example, according to one well-established view in spatial perception, the spatial quality of a sensation ultimately derives from motor signals, making these signals non-independent. *Local sign* theories<sup>21,22</sup> explain perception of visual location in terms of the amplitude of a saccadic motor command that would be required to fixate that location<sup>23</sup>. Similarly, perception of tactile location on the skin is explained in terms of the reaching movement required to touch that location<sup>21,22</sup>. On this view, motor information should have a *logical priority* over tactile information during self-touch. In contrast, optimal integration theories<sup>17,24</sup> assume that signals are independent, and are weighted according to reliability at an integration stage. For these reasons, we have studied self-touch using an interference

framework, which makes fewer theoretical assumptions than an integration framework. Nevertheless, the two frameworks are related since automatic integration between signals can produce interference when processing just one signal.

Thus, there are different theoretical accounts of the characteristic experience of self-touch. First, the brain might maintain completely independent spatial representations for movement and for tactile sensation<sup>25,26</sup>, implying no interference between these signals. Second, the motor signal might dominate the tactile signal as suggested by local sign theories<sup>21,22</sup>. Third, motor and tactile signals might fuse, either along the lines of optimal multisensory integration<sup>17</sup>, or suboptimally, to produce a single spatial percept.

Here, we used two robots linked in a leader-follower configuration to achieve a laboratory approximation to self-touch, namely the experience of stroking one's forearm with a brush. While this situation lacks the direct skin-to-skin contact of natural self-touch, such mediated self-touch experiences are frequent in daily life, for example while wearing gloves, or while using a hairbrush<sup>15</sup>. Crucially, however, we programmatically change the spatial relation between movement and its tactile consequences (Figure 1). The ability to manipulate the gain of self-touch allowed us to directly test the above theories, seemingly for the first time.

*\*\*\*Please insert Figure 1 approximately here\*\*\**

## Results

Participants moved the handle of a leader robot with their right hand and simultaneously felt a corresponding stroking motion on the left forearm from a brush attached to a follower robot (see Figure 1). The gain of the leader-follower relation was varied to decouple the normally fixed spatial relation between motor and tactile signals. We investigated the patterns of interference between these signals by asking participants to judge either the spatial extent of the tactile stroke they felt or the extent of the movement they made. This allowed us to measure the extent to which each signal interfered with the perception of the other. To do so, we computed an *Interference Coefficient* (IC) that quantified the proportion of extent judgements attributable to the task-irrelevant signal, as opposed to the to-be-judged signal (see Methods). To investigate the role of voluntary motor commands and kinesthetic information in spatial perception of both movement and touch, the IC was measured under both active and passive movement conditions (see Methods).

We first confirmed that participants perceived variations in spatial extent both when judging movement, and when judging tactile signals. The slopes of the relation between perceived and actual extent were around unity (see Data S1E-F for ANOVA tables for each experiment and for the effect of each gain on spatial perception in each condition and experiment). Next, we analysed our experimental manipulations of motor:tactile gain to quantify how much movement extent could interfere with judgements of tactile extent, and *vice versa*. We calculated an Interference Coefficient (see Methods), that captured the interfering effects of the task-irrelevant signal on the to-be-judged signal. This was done for each cell of a 2 x 2 factorial design according to the Type of Task (Judge Touch vs

Judge Movement) and the Type of Movement (Active vs Passive movement) (see Data S1C for the individual Interference Coefficients).

Figure 2A-B shows the mean perceived extents for judgement of each signal as a function of the actual extent and the gain applied to the task-irrelevant information in Experiment 1 ( $n = 12$ ) (i.e. “Judge Touch”; Figure 2A) and Experiment 2 ( $n = 12$ ) (i.e. “Judge Movement”; Figure 2B). The raw perceptual judgements show a clear effect of motor:tactile gain, implying that changes in the spatial extent of one signal influence the perceived extent of the other. As a null hypothesis, we tested an account based on independent sensory channels for spatial perception of movement and of touch<sup>25,26</sup>. This view predicts no influence of movement on judgements of tactile extent, and no influence of tactile extent on judgements of movement extent, as the motor:tactile gain is varied. Interference Coefficients should then always be 0.

The *Interference Coefficients* were not normally distributed (see Methods), and were therefore analysed with Wilcoxon’s Sign Test (see Statistical Analysis). We compared each condition against 0 (where an IC of 0 would indicate no effect of the task-irrelevant information) and against 1 (where an IC of 1 would indicate complete dominance of one signal over the other) within each experiment. All tests were Bonferroni corrected for four comparisons per experiment, giving  $\alpha = 0.0125$  per test. The Interference Coefficients (IC) of the task-irrelevant information (Figure 2C) were significantly greater than 0 for all combinations of our 2 x 2 (Type of Judgement x Type of Movement) design (Experiment 1: Judge Touch – Active: median IC = 0.59 [95% Confidence Interval of the median = 0.52, 0.68]; Judge Touch – Passive: 0.47 [0.34, 0.58]; Experiment 2: Judge

Movement – Active: 0.42 [0.28, 0.52]; Judge Movement – Passive: 0.24 [0.21, 0.44];  
Wilcoxon’s sign test against 0,  $Z > 3.06$ ,  $p = .002$ ,  $r > .883$ , in all cases).

Thus, when participants were instructed to judge the spatial extent of the tactile  
stroking, they were nonetheless influenced by the extent of the movement, and *vice versa*.  
Both motor and tactile components of self-touch strongly influenced each other, even when  
task irrelevant. The null hypothesis that motoric *touchant* and sensory *touché* signals are  
perceptually independent can be rejected.

\*\*\*Please insert Figure 2 approximately here\*\*\*

### ***Do motor signals dominate tactile perception in self-touch?***

Motor-based theories of space perception hold that motor signals dominate over sensory  
signals<sup>21,22</sup>. Predictive coding accounts make similar predictions, though for different  
reasons. On these views, tactile stroking should thus have little interfering effect on  
perception of movement extent, implying an Interference Coefficient  $IC = 0$  for touch in  
the “Judge Movement” task. Conversely, movement should strongly influence, or even  
totally dominate tactile extent perception (i.e., an Interference Coefficient  $IC = 1$  for task-  
irrelevant movement in the “Judge Touch” task). The fact that Interference Coefficients of  
touch on movement were positive and significantly higher than 0 provides evidence against  
the first prediction of motor dominance theories. Similarly, contrary to the second  
hypothesis of the motor dominance theories, the effect of movement on touch was  
significantly less than complete dominance, since all ICs were significantly lower than 1

(Wilcoxon's sign test:  $Z < -2.82$ ,  $p < .005$ ,  $r > .814$ , in all cases; Bonferroni-adjusted for four multiple comparisons:  $\alpha = 0.0125$  per test).

Thus, our results suggest that theories that reduce spatial perception to motor signals cannot readily account for the *strong and bidirectional* interference between movement and touch in spatial extent perception during our self-touch manipulation.

### ***Partial integration of motor and tactile information during self-touch***

The results of Experiments 1 and 2 suggest that both tactile and motor information show substantial mutual interference during self-touch. To directly compare the Interference Coefficients of the irrelevant information in the two judgement types ("Judge Touch", "Judge Movement"), Experiment 3 used a within-subject design in which 24 new participants made movement and touch judgements, in separate blocks. This allowed a stronger within-participant test of asymmetric interference between movement and touch, an opportunity to correlate Interference Coefficients between movement judgements and touch judgements, and a direct test of optimal integration theories by relating Interference Coefficients to signal precision measures. Only three motor:tactile gains were tested, spanning the same range as Experiments 1 and 2 (see Methods). Mean perceived to-be-judged extents for each gain are presented in Figure 3A.

First, we analysed Experiment 3 to replicate the results of Experiments 1 and 2. As this data was normally distributed (see Methods), we used t-tests to analyse the Interference Coefficients. As in the previous experiments, all Interference Coefficients IC were significantly greater than 0 ( $t_{23} > 5.99$ ,  $p < .001$ , Cohen's  $d > 1.223$ , in all cases) and lower than 1 ( $t_{23} < -10.88$ ,  $p < .001$ , Cohen's  $d > 2.220$ , in all cases, Bonferroni adjusted for two

comparisons in each of four conditions, i.e.,  $\alpha = 0.0063$  per test) (see Figure 3B) (Judge Touch – Active: mean IC = 0.52 [95% CI of the mean = 0.43, 0.61]; Judge Touch – Passive: 0.45 [0.38, 0.52]. Judge Movement – Active: 0.40 [0.30, 0.50]; Judge Movement – Passive: 0.31 [0.21, 0.42]).

\*\*\*Please insert Figure 3 approximately here\*\*\*

Next, to test for effects of Type of Task (Judge Touch, Judge Movement) and Type of Movement (Active, Passive), and directly compare Interference Coefficients across these conditions, we used a 2 x 2 repeated measures ANOVA. The ANOVA showed a significant main effect of Type of Task ( $F_{1,23} = 5.21, p = .032, \eta_p^2 = .185$ ) with a greater Interference Coefficient of movement when participants had to judge touch (mean IC  $\pm$  95% CI:  $0.48 \pm 0.06$ ) than *vice versa* ( $0.36 \pm 0.07$ ), indicating a directional asymmetry in the interference between movement and touch signals. Moreover, there was also a significant main effect of Type of Movement ( $F_{1,23} = 10.13, p = .004, \eta_p^2 = .306$ ) with higher Interference Coefficients, indicating stronger interference, when movement was active (mean IC  $\pm$  95% CI:  $0.46 \pm 0.07$ ) than passive ( $0.38 \pm 0.07$ ). There was no significant interaction between the two factors ( $F_{1,23} = 0.18, p = .678$ ).

Finally, no correlation across participants between the interference of movement on touch and of touch on movement was found, in either active ( $r = 0.30, p = .161$ ) or passive ( $r = 0.10, p = .655$ ) conditions (see Figure 4A-B). However, Interference Coefficients for Active and Passive movement conditions in both tasks were strongly correlated (Judge Touch:  $r = 0.74, p < .001$ ; Judge Movement:  $r = 0.77, p < .001$ ; see Figure

4C-D). This suggests that, within each Type of Task, the interfering influence of irrelevant information occurs due to some process that varies across individuals, but is common to both active and passive conditions. This suggests that access to motor command information is unlikely to be the main factor that determines the level of interference, since this information is present only in the active condition, but not the passive condition.

Thus, these results show strong and bidirectional, but asymmetrical interference between the motor and tactile signals of self-touch. The interference of movement on tactile extent judgements was greater than the interference of touch on movement extent judgements.

\*\*\*Please insert Figure 4 approximately here\*\*\*

### ***Self-touch as optimal integration***

Current theories of multisensory perception focus on optimal integration of multiple sources of information<sup>17</sup>. Each source is weighted according to its reliability or precision<sup>24,27,28</sup>. Our experiments have used an interference design rather than a classical optimal integration framework, but strong interference between signals in proportion to their relative precisions would be consistent with optimal integration.

A 2 x 2 repeated measures ANOVA on the precision data of Experiment 3 showed no significant main effects (Type of Task:  $F_{1,23} = 1.37$ ,  $p = .255$ ; Type of Movement:  $F_{1,23} = 0.15$ ,  $p = .705$ ) nor interaction ( $F_{1,23} = 0.002$ ,  $p = .964$ ). Similarly, we did not find any difference in precision between the Type of Movement (Active vs Passive) in Experiment

1 and 2 ( $t_{11} = 0.06$ ,  $p = .953$  and  $t_{11} = 0.92$ ,  $p = .376$  respectively using paired t-test), nor between active (i.e. multimodal) conditions in Experiment 4 and 5 and their unimodal control conditions (see Table 1) ( $t_{11} = -1.06$ ,  $p = .311$  and  $t_{11} = -0.81$ ,  $p = .433$  respectively using paired t-test). The latter result particularly suggests that multisensory integration *per se* did not influence the precision of spatial extent judgements. Thus, patterns of interference and integration between movement and touch do not simply depend on the precision of the component signals.

\*\*\*Please insert Table 1 approximately here\*\*\*

***Could the “tau effect” explain our results? Control unimodal experiments.***

Since the movement durations of the leader and follower robots were matched, changes in motor:tactile gain in Experiments 1-3 necessarily modify velocity of tactile stroking. Extent perception can be affected by stimulus velocity or duration, a phenomenon often referred to as “tau effect”<sup>29</sup>. Because in our design movement and touch began and ended together, a high motor:tactile gain in Experiments 1-3 would result in both a greater tactile spatial extent and a higher tactile velocity, than a low motor:tactile gain. We therefore investigated whether the effects of gain on spatial extent perception in Experiments 1-3 truly reflected interference *between* the two different signals, rather than influence of stimulation velocity on extent perception *within* a single sensory channel. Therefore, we

ran two additional control experiments ( $n = 12$  in each experiment) to investigate whether a tau effect could explain the results of Experiment 1-3.

The active movement conditions of Experiments 4 and 5 were a replication of the active conditions of Experiments 1 and 2, and of the corresponding conditions of Experiments 3. In a second, “unimodal”, condition, participants were asked to judge the tactile extent in absence of any movement (Control Experiment 4) or, to judge the extent of the movement in absence of any tactile stimulation (Control Experiment 5). In these conditions, any spatial perception is both unimodal and unimanual, since only touch (Control Experiment 4) or only movement (Control Experiment 5) is present, and thus there is no interference between movement and touch. We analysed the results of Control Experiments 4 and 5 using the same formula for the Interference Coefficient described above. Given the unimodal nature of the control experiments, the index in this case would not reflect interference from the task-irrelevant modality, but would rather capture any spurious effect due to the tactile and motor stimulations themselves. If the apparent influence of irrelevant signals in Experiments 1-3 was in fact due to confounding of extent judgements by velocity, then this effect should be equally present in unimodal conditions, and our IC measure should again be greater than 0. Conversely, if the interference in Experiments 1-3 indeed represents interference from the other signal then IC in unimodal conditions should not now differ from 0. Participants in Control Experiments 4 and 5 judged spatial extents of touch, and of movement respectively, in two conditions: a

unimodal condition described above, and an active self-touch condition replicating Experiments 1-3 (Figure 5A-B).

Data violated the normality assumption (see Methods), and were therefore tested using the Wilcoxon's Sign Test. In the "unimodal" conditions of both Experiments 4 and 5, Interference Coefficients were not significantly different from 0 (Judge Touch – Unimodal, median IC = 0.06 [95% Confidence Interval of the median = -0.03, 0.15],  $Z = 1.80$ ,  $p = .071$ ; Judge Movement – Unimodal: 0.01 [-0.11, 0.05],  $Z = 0.08$ ,  $p = .937$ ; see Figure 5C). Thus, we found no significant evidence for a confounding effect of velocity on spatial extent judgements, and no reason to attribute the interference effects of Experiments 1-3 to this confound.

\*\*\*Please insert Figure 5 approximately here\*\*\*

#### *Active conditions in Experiments 4-5*

The results for the active conditions of Experiments 4 and 5 replicated the effects of Experiment 1-3. In particular, the weight of the interfering information was significantly different from 0 ( $Z = 3.06$ ,  $p = .002$ ,  $r > .883$ , in both cases; and 1 ( $Z = -3.06$ ,  $p = .002$ ,  $r > .883$ , in both cases; Bonferroni adjusted alpha for two multiple comparisons, against 0 and 1:  $\alpha = .025$  per test: Judge Touch – Active: median IC = 0.55 [95% Confidence Interval of the median = 0.46, 0.69]; Judge Movement – Active: 0.20 [0.14, 0.38]) (see Figure 4C).

## Discussion

Self-touch is widely recognized as an important psychological and physiological event. While some studies have examined the affective consequences of self-touch<sup>30-32</sup>, or the processing of self-generated stimuli<sup>15</sup>, our results provide a systematic experimental investigation of self-touch with a novel focus on *spatial* perception.

When participants were asked to report the spatial extent of their movement, their perceptual judgements were strongly influenced by the tactile stimulus extent, and *vice versa*. This bidirectional interference was stronger when participants made active rather than passive movements. Control experiments ruled out potential confounds between extent and velocity introduced by our manipulations of motor:tactile gain. Overall, our results provide robust experimental support for a degree of mutual interference between motor *touchant* and tactile *touché* signals during self-touch.

Several neurocognitive theories make contrasting predictions about the relative importance of movement and sensory information in perceptual experience. First, local sign theories<sup>21,22</sup> predict a strong influence of movement on tactile perception, without any influence in the reverse direction. Our Interference Coefficients showed a stronger effect of movement on touch than of touch on movement. However, the effects of touch on movement perception were also clearly significant. Moreover, the dominance of movement over touch for spatial perception was no greater when movements were active than when they were passive.

Neurocomputational models of predictive motor control<sup>15</sup> suggest that perceptual consequences of self-generated motor actions are attenuated by being cancelled against predictions of an internal model. On a strict version of this view, the sensory, *touché* part

of self-touch should generate no CNS activity or tactile sensation at all<sup>30,33</sup>. However, these theories focus on the perceptual dimension of *intensity*, and are typically tested using detection rates for probe stimuli that are not directly related to the movement. Temporal and spatial information may be less subject to attenuation than intensity information. In fact, motor prediction and sensory cancellation theories cannot straightforwardly explain the strong influence of tactile extent on perception of movement that we observed.

Finally, optimal integration theories predict that more reliable (precise) signals should be more strongly weighted. However, we found that movement information was more highly weighted than tactile information even though movement precision was (non-significantly) *worse* than tactile precision. This unexpected result could reflect suboptimal integration, or could arise because our self-touch scenarios violate the assumptions of independent signals arising from a common source, on which multisensory integration models are based.

Interference in both directions between motor and tactile signals was stronger during active, compared to passive movement. Attentional demands of active movement could potentially explain the increased influence of movement on tactile judgements, but could not also explain the strong increase in interference from touch on judgements for active compared to passive movements. Optimal integration theories also fail to explain this result. These theories predict that the additional efferent information in the active condition should improve the representation of motor extent, and thus reduce the interfering effects of touch. However, this prediction was not supported by the results of our precision analysis. Motor command reliability, therefore, cannot explain the active-passive differences we observed. Could causal inference models<sup>34</sup> then explain the active-

passive difference? Previous causal inference models of action have focused on temporal rather than spatial measures, and on attribution of sensory effects to motor causes<sup>35,36</sup>. Our results would suggest that causal inference also links *spatial* dimensions of movement and touch, and that percepts of motor action are modulated, as well as percepts of tactile consequences. This provides a novel addition to existing causal inference scenarios, which involved arbitrary spatial transformation *from* action *to* sensory input<sup>37</sup>.

Our results suggest that the voluntary motor command may promote integration between the multiple sensory and motor signals that are present during self-touch. This result is not a simple motor dominance effect, nor a secondary, perceptual consequence of introducing additional informative signals. Rather, motor system activation specifically promotes *merging* of multiple sources of information. Given the distinctive goal-directedness of voluntary action, motor commands should readily integrate with signals carrying information about the consequences of the action. Ideomotor and reinforcement theories indeed imply that voluntary actions are characterized by a “readiness-to-associate”<sup>38–40</sup>. Across three experiments, the presence of voluntary motor commands had the distinctive psychological effect of promoting binding and integration between diverse signals. This result is in line with previous studies investigating how voluntary actions lead to binding and integration in body representation<sup>41</sup> and time perception<sup>36</sup>.

Our design has several limitations. First, our experimental methods involve an analogue of natural self-touch, rather than direct skin-skin contact. Skin-to-skin self-touch involves sensory stimulation of the skin of the touching hand. In our experiment, instead, we produced an approximation of self-touch, using a leader-follow configuration of two robots. This maintained the crucial relation between movement and touch, while removing

368 skin-skin contact, and thus dispensing with tactile motion input to the moving hand.  
369 Second, although extreme care was taken to make sure that the participants remained as  
370 passive as possible during the passive movement condition, we did not collect  
371 electromyographic data, and cannot therefore exclude the possibility that some minimal  
372 voluntary motor command, and muscle activity was present also in the passive condition.  
373 However, if partial voluntary motor activity had occurred in this condition, it would count  
374 against the hypothesized difference between active and passive conditions.

375         To conclude, we have investigated the spatial perception that occurs during self-  
376 touch. We found strong interference of movement on judgements of touch, but also of  
377 touch on judgements of movement. This result seems inconsistent with strong theories of  
378 motor-based space, such as local sign accounts. Strikingly, interference effects in both  
379 directions were enhanced during active compared to passive movement, suggesting that  
380 voluntary motor commands facilitate binding of multiple synchronous signals. This implies  
381 a role for active self-touch in the spatial coherence of the self, akin to the binding between  
382 voluntary actions and their outcomes in instrumental agency<sup>36</sup>.

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## **Author Contributions**

Conceptualization, AC and PH; Methodology, AC, LD, HG, and PH; Software, AC and LD; Validation, AC; Formal Analysis, AC and LD; Investigation, AC and HDJ; Resources, HG and PH; Data Curation, AC; Writing – Original Draft, AC; Writing – Review & Editing, AC, LD, HDJ, HG, PH; Visualization, LD; Supervision, PH; Project Administration, AC and PH; Funding Acquisition, PH.

**Declaration of interests:** The authors declare no competing interests.

## Main-text figures/tables legends

**Figure 1. Experimental setup and stimuli.** **A.** Participants moved the handle of the leader robot with their right hand and simultaneously felt a corresponding stroke on the left forearm from a brush attached to the follower robot. A black screen (black dashed line) covered both the participants' arms and the robotic setup throughout the experiment. **B.** The physical extent of right arm movement was controlled by the position of two programmable "virtual walls" that defined unpredictable start (red dashed line) and end (green dashed line) positions for each trial. The spatial relation between the extent of movement (dark blue arrow) and touch (light blue arrow) depended on the gain of the leader:follower robot coupling. This gain value was randomized across trials (see Video S1). This setup provided a close analogy to natural self-touch. In natural self-touch, however, the spatial coupling between movement and touch is fixed, making experimental studies of the relation between the two components difficult. Our design crucially allowed programmatic manipulation of this spatial coupling, so we could investigate how the two components of self-touch experience interact. See also Video S1.

**Figure 2. Results from Experiment 1 and 2.** **A.** Mean perceived tactile extent (Experiment 1,  $n = 12$ ) as a function of actual stimulus extent, and of motor:tactile gain. **B.** Mean perceived movement extent (Experiment 2,  $n = 12$ ) as a function of actual movement extent and of motor:tactile gain. Different lines for different values of motor:tactile gain imply interference from task-irrelevant information. Error bars in **A-B** represent the Standard Deviation of the Mean (SD). **C.** Median Interference Coefficients (IC) of the task-irrelevant information (median was used because Interference Coefficients

were not normally distributed). The positive Interference Coefficients in both experiments show that motor information influences tactile extent judgement even when task-irrelevant, and that tactile information similarly influences judgements about movement extent. Error bars represent the 95% CIs for the median. See also Figure S1, S4, and S5, Table S1, and Data S1.

**Figure 3. Results from Experiment 3. A-B.** Mean perceived extent of the target sensation as a function of actual stimulus extent, and gain applied to the task-irrelevant information in Experiment 3 (n = 24). Error bars represents the SD. **C.** Mean Interference Coefficients (IC) of the task-irrelevant information in Experiment 3. Error bars represent the 95%CI of the mean. See also Figure S2 and S5, Table S1, and Data S1.

**Figure 4. Correlations between conditions of Experiment 3. A-B.** There was no significant correlation between Interference Coefficients for the two judgement types (judge touch, judge movement) in neither the active (**A.**), nor the passive (**B.**) movement condition. **C-D.** Instead, within each judgement type, the Interference Coefficients for active and passive movement conditions were significantly correlated. See also Table S1 and Data S1.

**Figure 5. Results from control Experiment 4 and 5. A-B.** In Experiments 4 and 5 (n = 12 in each experiment), the passive conditions were replaced with unimodal versions of the task where tactile (**A.**) or movement (**B.**) sensations occurred in absence of task-irrelevant information. Error bars in **A-B.** represents SD. **C.** Interference Coefficients (IC)

446 of the task-irrelevant information. Error bars represent 95% CIs of the median. See also  
447 Figure S3 and Data S1.

448 **Table 1. Precision data (cm<sup>2</sup>) for each condition of each experiment.**

## 449 **STAR Methods**

### 450 *Resource availability*

#### 451 *Lead contact*

452 Further information and requests for resources should be directed to and will be fulfilled  
453 by the lead contact, Antonio Cataldo ([a.cataldo@ucl.ac.uk](mailto:a.cataldo@ucl.ac.uk)).

#### 454 *Material availability*

455 This study did not generate new unique material.

#### 456 *Data and Code availability*

457 All data have been deposited at Open Science Framework and are publicly available as of  
458 the date of publication. DOIs are listed in the key resources table.

459 This paper does not report original code.

460 Any additional information is available from the lead contact upon request.

### 461 *Experimental model and subject details*

#### 462 *Participants*

463 The sample size for Experiment 1 ( $n = 12$ , 7 females, mean age  $\pm$  SD:  $22.7 \pm 3.1$ ) was  
464 decided a priori on the basis of a previous study on self-touch that used a robotic setup  
465 similar to ours to compare the effect of active and passive self-touch movements on  
466 bodily self-awareness<sup>9</sup>. In that study, Hara and colleagues found a significant  
467 difference between active and passive self-touch conditions, with a very large effect

size ( $\phi = 2.3$ ) for a sample of 13 participants<sup>9</sup>. Although we clearly used a different dependent variable compared to Hara et al.'s study (i.e. spatial judgement rather than ratings of illusory self-touch), we nevertheless estimated that a sample size of 12 participants would be sufficient in our study to observe an effect of Type of Movement on space perception.

The sample sizes for Experiments 2-5 (Experiment 2:  $n = 12$ , 11 females, mean age  $\pm$  SD: 25.2; Experiment 3:  $n = 24$ , 17 females, mean age  $\pm$  SD: 29.5  $\pm$  13.2; Experiment 4:  $n = 12$ , 8 females, mean age  $\pm$  SD: 24.4  $\pm$  3.8; Experiment 5:  $n = 12$ , 8 females, mean age  $\pm$  SD: 24.1  $\pm$  3.6) were instead determined through a power analysis on the results of Experiment 1. The effect size for the main effect of the robotic gain manipulation in experiment 1 was  $\eta^2 = .723$  (see Data S1E for the ANOVA Table), considered to be very large using Cohen's criteria<sup>42</sup>. With an alpha = .05 and power = .8, the projected sample size indicated to demonstrate interference effects of movement on touch perception and *vice versa* was 4 participants (G\*Power 3.1.9.2 software)<sup>43</sup>. We nevertheless set a sample size of  $n = 12$  for Experiments 2, 4, and 5 (Experiment 2: 11 females, mean age  $\pm$  SD: 25.2; Experiment 4: 8 females, mean age  $\pm$  SD: 24.4  $\pm$  3.8; Experiment 5: 8 females, mean age  $\pm$  SD: 24.1  $\pm$  3.6), and of  $n = 24$  for Experiment 3 (17 females, mean age  $\pm$  SD: 29.5  $\pm$  13.2).

Eighty-two healthy right-handed volunteers were originally recruited for the study. Two participants (Control Experiment 4) were excluded because of technical issues with the setup. Based on a priori exclusion criteria, eight further participants (three participants in Experiment 1, five participants in Experiment 3) were excluded

during the training phase because they proved unable to use the robotic device to produce smooth self-stimulation movements.

The experimental protocol was approved by the Research Ethics Committee of University College London and adhered to the ethical standards of the Declaration of Helsinki. All participants were naïve regarding the hypotheses underlying the experiment and provided their written informed consent before the beginning of the testing, after receiving written and verbal explanations of the purpose of the study.

## ***Method Details***

### *Apparatus*

Participants sat in front of a computer screen with their left arm on a fixed moulded support, and their right arm on an articulated armrest support (Ergorest, series 330 011, Finland). Both the participants' arms and the robotic setup were covered by a horizontal screen and remained unseen throughout the experiment. The sensorimotor self-touch stimulation was implemented using two six-degrees-of-freedom robotic arms (3D Systems, Geomagic Touch X, South Carolina, USA) linked as a computer-controlled leader-follower system (Figure 1). In this system, any 3D-movement of the right-hand leader robot is reproduced by the follower robot. The estimated lag between the robot trajectories was 2.5 ms (see below). The follower robot carries a paintbrush (12.7 mm width) that strokes the participant's left forearm (see Video S1). This setup allowed us to manipulate the gain between the leader and the follower robots so as to produce different combinations of motor and tactile displacements. For instance, if the motor:tactile was set to 1:1.5 then every 1

511 cm movement of the leader (movement) robot would cause 1.5 cm movement of the  
512 follower robot.

513         The extent of each movement in the anteroposterior direction was controlled by two  
514 “virtual walls” created by the force-feedback system of the leader robots. That is,  
515 participants would move the leader arm forward/backward until resistance from the force  
516 feedback wall prevented them from moving further. This allowed the movement extent to  
517 be experimentally controlled and randomized across trials. Thus, participants could not  
518 therefore predict or decide in advance the extent of the movement they made on each trial,  
519 so their judgements of movement extent had the status of perceptual reports.

#### 520 *Estimated lag between leader and follower robots*

521 The Geomagic Touch X robotic arms we used provide movement monitoring within  
522 an event loop at a frequency of approximately 950-1100 Hz. However, to estimate  
523 the actual lag in our leader-follower system, we performed a control analysis on  
524 kinematic data recorded from the two robots. We measured the time taken for the  
525 follower device to reach successively sampled positions along the forward movement  
526 axis of the leader device, in a dataset of 1728 trials at a 1:1 motor tactile gain. The  
527 mean lag was 2.47 ms (SD across 24 participants: .62 ms).

#### 528 *Experimental design*

529 Experiments 1 and 2 tested, respectively, the effect of movement on tactile extent (“Judge  
530 Touch” task) and vice versa (“Judge Movement” task). Each experiment had a 2 (Type of  
531 Movement: Active, Passive) x 3 (Extent of the To-be-Judged stimulus: 4, 6, 8 cm) x 5  
532 (Motor:Tactile Gains: 1.5:1, 1.25:1, 1:1, 1:1.25, 1:1.5) within subject design. The Type of

Movement factor (Active/Passive) was blocked and counterbalanced across participants. The spatial Extent of the To-be-Judged events (movement, or stroke) was randomized. Each of the 30 possible combinations of these factors was experienced eight times, giving a total of 240 trials per participant. The testing was divided into 16 blocks of 15 trials each, and breaks were allowed between blocks.

Experiment 3 used a full within-subjects design with a 2 (Type of Task: Judge Touch, Judge Movement) x 2 (Type of Movement: Active, Passive) x 3 (Extent of the To-be-Judged stimulus: 4, 6, 8 cm) x 3 (Motor:Tactile Gains: 1.5:1, 1:1, 1:1.5) paradigm. Each of the resulting 36 conditions was repeated eight times, for a total of 288 trials per participant. The testing was divided into 16 blocks of 18 trials each, and breaks were allowed between blocks.

Experiments 4 and 5 aimed to control for the contribution of differential stimulus velocity produced by the gain manipulation and were based on the same experimental design as Experiments 1 and 2. In these experiments, the passive movement condition was replaced with a purely unimodal, and unimanual condition in which participants judged the extent of either touch (Experiment 4) or movement (Experiment 5) in absence of any movement, or of any tactile stimulation respectively.

### *Procedure*

Participants were familiarized with the experimental setup at the beginning of the experiment, and received training before each condition. In the active movement condition, participants were instructed to perform a back-and-forth movement of the right hand from the far wall to the near wall, and then returning to the starting position (far wall).

Participants would move their hand forward/backward until they discovered the position of the virtual walls on each trial, guided by the haptic feel of force when they touched the wall. This was followed by a short auditory beep, as an additional cue they had reached the wall. This arrangement meant that participants could not predict or decide the extent of movement in advance, but had to perceive movement extent anew on each trial. In the passive movement condition, the handle of the leader robot was moved by the experimenter in the same back-and-forth trajectory described for the active condition. Participants held the handle of the leader robot with their right hand and followed passively the movements produced by the experimenter. The experimenter took care not to touch the participant, and the experimenter's movements were occluded from view. Crucially, the kinematics from active and passive (and unimodal) conditions were comparable in each experiment (see Figures S1-S4).

Each training phase ended with a practice block of the spatial extent judgement task. Participants were asked to focus only on the “to-be-judged” experience of that block – either the extent of the right hand's movement, or the extent of the stroke on the left forearm, as appropriate – and to ignore the other sensation. After each active or passive movement, the fixation cross on the screen was replaced by a vertical line of a random length (between 2 and 10 cm). Participants then used two foot-pedals (one which made the line longer, and the other shorter) to adjust the length of the line on the screen in steps of 3.25 mm. Their task was to match the line on the screen to the extent of either the movement or the tactile sensation, depending on condition. The fixation cross and judgement task line were aligned with the participants' left arm in the case of the “Judge Touch” task, and with the participants' right hand in the case of the “Judge Movement”

task. After adjusting the length of the line, participants clicked a button on the handle of the leader robot to confirm their response and start a new trial.

In all trials of the practice block, movements and tactile feedback were 8 cm in length, so the spatial extent of natural self-touch was consistent with movement extent, as in typical self-touch. The main testing phase was similar to the training phase, except that the gain between the leader and follower robots was systematically manipulated in order to obtain different extents for movement and touch sensations. The gain varied randomly across trials between the different gain values set in each experiment (see above). Thus, although a general consistency between movement and tactile extents remained, participants could not reliably predict movement extent from tactile extent or vice versa. This allowed us to investigate the perceived extent of the to-be-judged sensation (e.g. touch in the “Judge Touch” task), as a function of the task-irrelevant spatial extent of the other, task-irrelevant event (e.g. movement in the “Judge Touch” task).

## *Quantification and statistical analysis*

### *Interference Coefficients of task-irrelevant information*

The main goal of this study was to test the influences of movement on touch and of touch on movement. We first used a regression approach to extract a summary measure of the relation between perceived and actual extent of the stimulus. In particular, we fitted the following model (1) to quantify the relative influence of the task-irrelevant extent (IC) in the participant’s response. For instance, the model quantified the relative influence of tactile distance when participants had to judge movement extent.

$$y = \psi [a + \omega (b - a)] \quad (1)$$

Where  $y$  is the judged extent,  $\psi$  is an individual scaling factor to capture each participant's cross-modal mapping from motor/tactile stimulation extent to visual line response,  $a$  is the to-be-judged information,  $b$  is the task-irrelevant information, and  $\omega$  is the Interference Coefficient of the task-irrelevant extent. Supplemental analyses confirmed that the  $\psi$  factor captured the individual scale of participants responses (see Figure S5). We did not fit any intercept in this model, since we assumed a judged extent of zero in the absence of any actual spatial stimulation<sup>44</sup> (for a similar approach in perceptual judgement task, see<sup>45</sup>; see also Table S1 for a comparison of results from a model with and without intercept). In this model, an Interference Coefficient  $IC = 0$  would correspond to the situation where the participant would report the target extent independently from the task-irrelevant information (e.g. no effect of movement on touch in the “Judge Touch” task). Conversely,  $IC = 1$  would mean that the participants' to-be-judged extent perception is entirely based on the task-irrelevant information and not at all on the to-be-judged information. Finally, an Interference Coefficient between 0 and 1 would indicate the partial integration of task-irrelevant information in judged extent. Fitting this model allowed us to calculate a single summary numerical value from all the raw judgement data, capturing the influence of movement on touch, and another value capturing the influence of touch and movement.

Note that the parameter  $IC$  is expected to be between 0 and 1 in the case there is a positive relation between perceived extent and the two physical extents, which should be the general case. That is, larger physical extents should produce larger perceived extents. However, if this is not the case, due for example to errors or misperception of the stimuli,

621 IC can be greater than 1 and lower than 0. (see Database for individual Interference  
622 Coefficients for each participant in each experiment).

### 623 *Precision*

624 For each participant, and each condition, we computed the precision (Precision =  
625  $1/\text{Variance}$ ) for each combination of extent and gain. Since our interest focused on the 2 x  
626 2 arrangement of Type of Task and Type of Movement, and extent and gain were effects  
627 of no interest, we then averaged the precisions values across the different levels of extent  
628 and gain, to obtain a single mean precision value for each participant and each condition.  
629 The mean precision and its standard deviation over participants are shown in Table 1.

### 630 *Normality of data*

631 Data from Experiments 1-2 and 4-5 violated the normality assumption, therefore the  
632 different predictions were tested with a series of Wilcoxon's Sign tests contrasting the  
633 Interference Coefficient of the task-irrelevant information in the four conditions (Type of  
634 Task x Type of Movement) against 0 or 1. Data from Experiment 3 were normally  
635 distributed, thus the same analysis were conducted using a series of t-tests contrasting the  
636 Interference Coefficient of the task-irrelevant information in the four conditions (Type of  
637 Task x Type of Movement) against 0 or 1, and a 2 x 2 repeated measures ANOVA with  
638 factors of Type of Task (Judge Touch, Judge Movement) and Type of Movement (Active,  
639 Passive).

## Supplemental items legends

**Table S1. Intercept values (cm) calculated from regression of perceived stimulus extent on actual stimulus extent for each condition and each experiment, Related to Figures 2-5.**

We did not fit any intercept in our Interference Coefficient model:

$$y = \psi a + \omega (b - a) \quad (1)$$

On theoretical grounds, we assumed a judged distance of zero in the absence of any actual spatial stimulation. However, we additionally ran the same analyses on a model that additionally includes a condition-specific intercept (c):

$$y = \psi a + \omega (b - a) + c \quad (2)$$

Both models (with and without intercept) produced ICs significantly different from 0 for all conditions except the unimodal conditions (Experiment 4-5). All conditions were also significantly different from 1. Importantly, these statistical inferences were not affected by whether an intercept was included in the model or not. Overall, the addition of this new parameter in the model (1) goes against the parsimony of the model and (2) does not change the main results. The model without intercept was therefore preferred.

**Video S1. (Separate file) Experimental setup and procedure, Related to Figure 1.**

Video depicting the experimental setup, procedure, and illustrative trials with different motor:tactile gains.

**Data S1. (Separate file) All data necessary for the analyses reported in this study,**

**Related to Figures 2-5.** A. Individual raw data for Experiments 1-5. B. Tables of means for Experiments 1-5. C. Interference Coefficients (ICs) for Experiments 1-5. D. Precision data for Experiments 1-5. E. ANOVA Tables for Experiments 1-5. F. Mean slopes for regression of perceived against actual extent for each combination of condition and motor:tactile gain.

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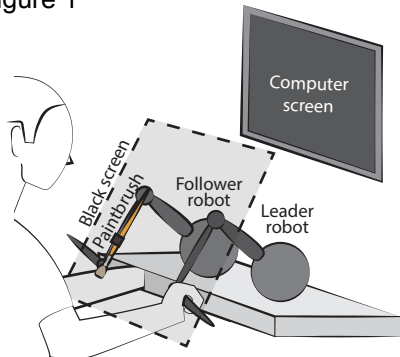
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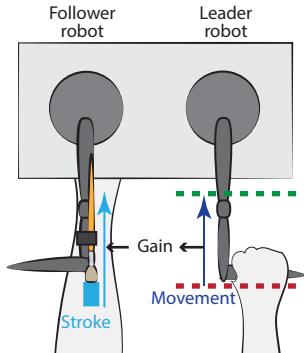
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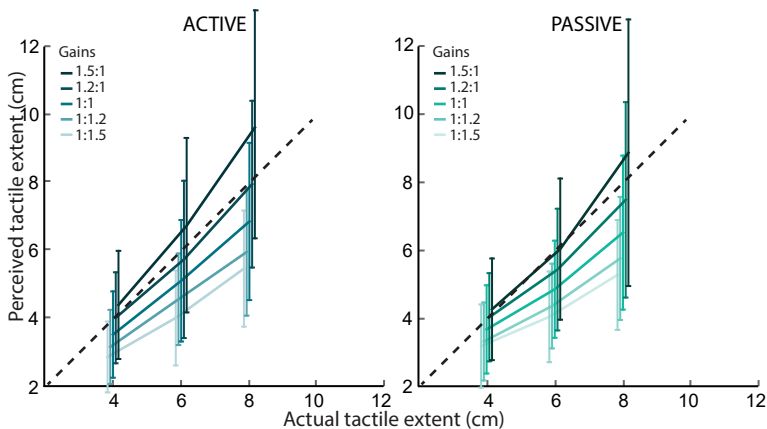
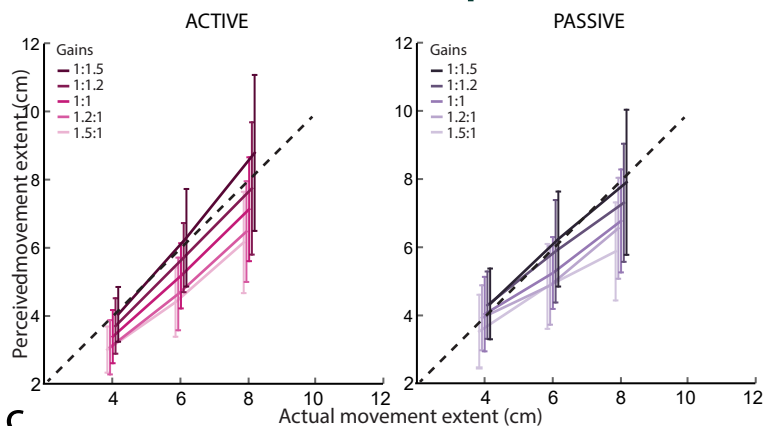
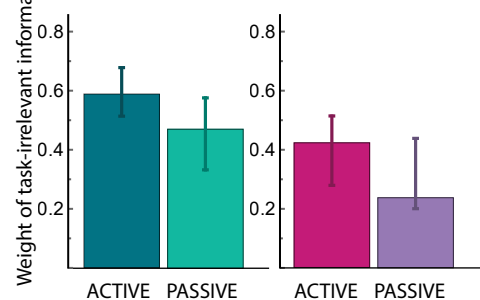
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Software and algorithms		
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Visual C++ Express 2010	Microsoft	<a href="https://www.visualstudio.com/">https://www.visualstudio.com/</a>
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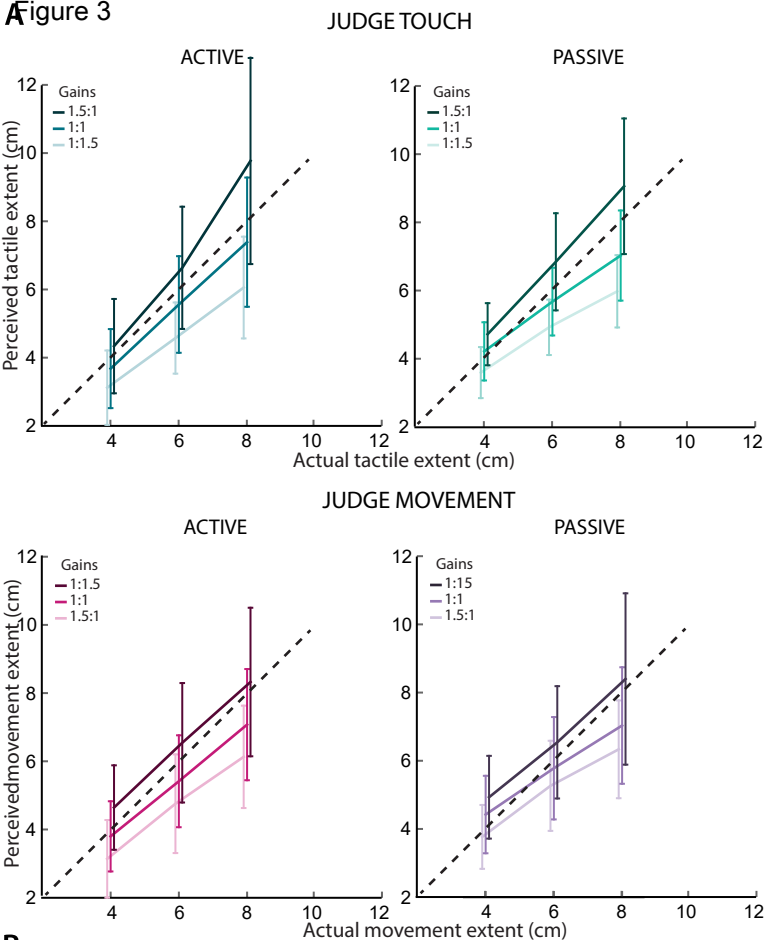
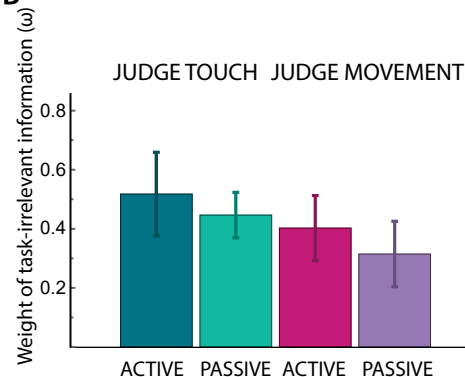
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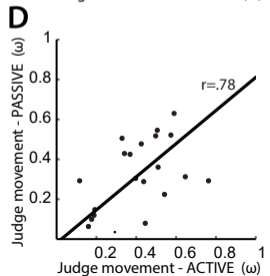
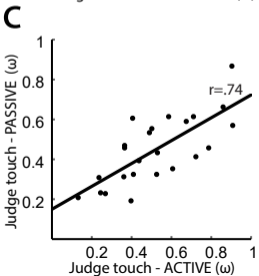
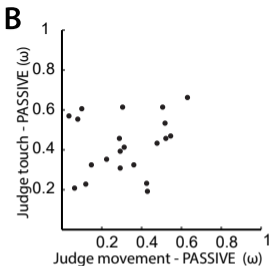
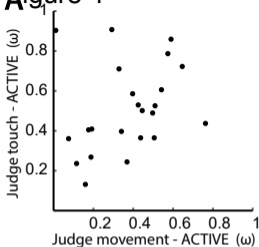
**B**



**Figure 2****EXPERIMENT 1 : JUDGE TOUCH****B EXPERIMENT 2 : JUDGE MOVEMENT****C**  
**EXPERIMENT 1 "Judge touch"**      **EXPERIMENT 2 "Judge movement"**

**Figure 3****B**

**Figure 4**



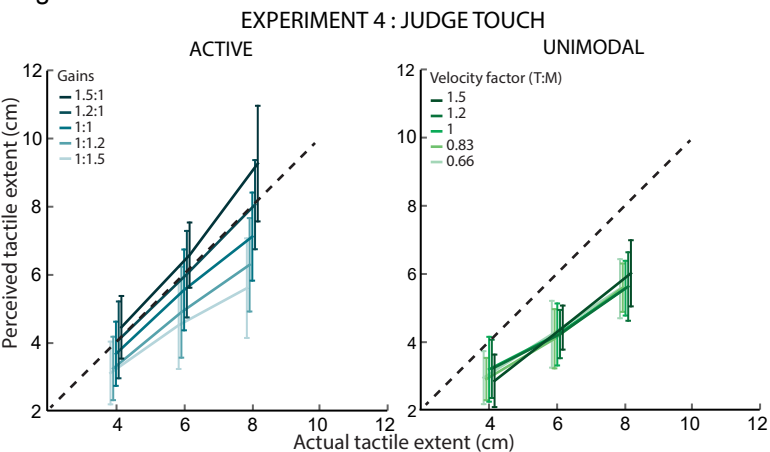
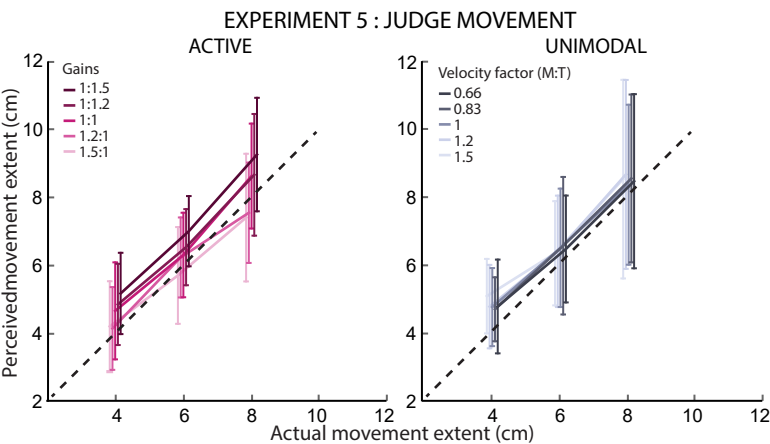
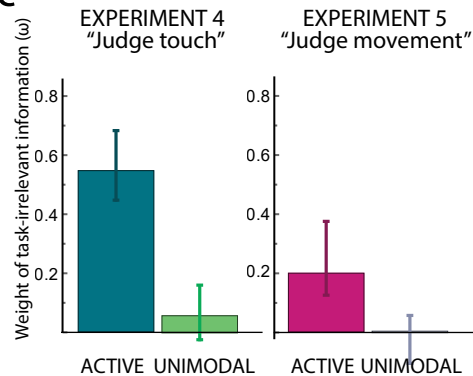
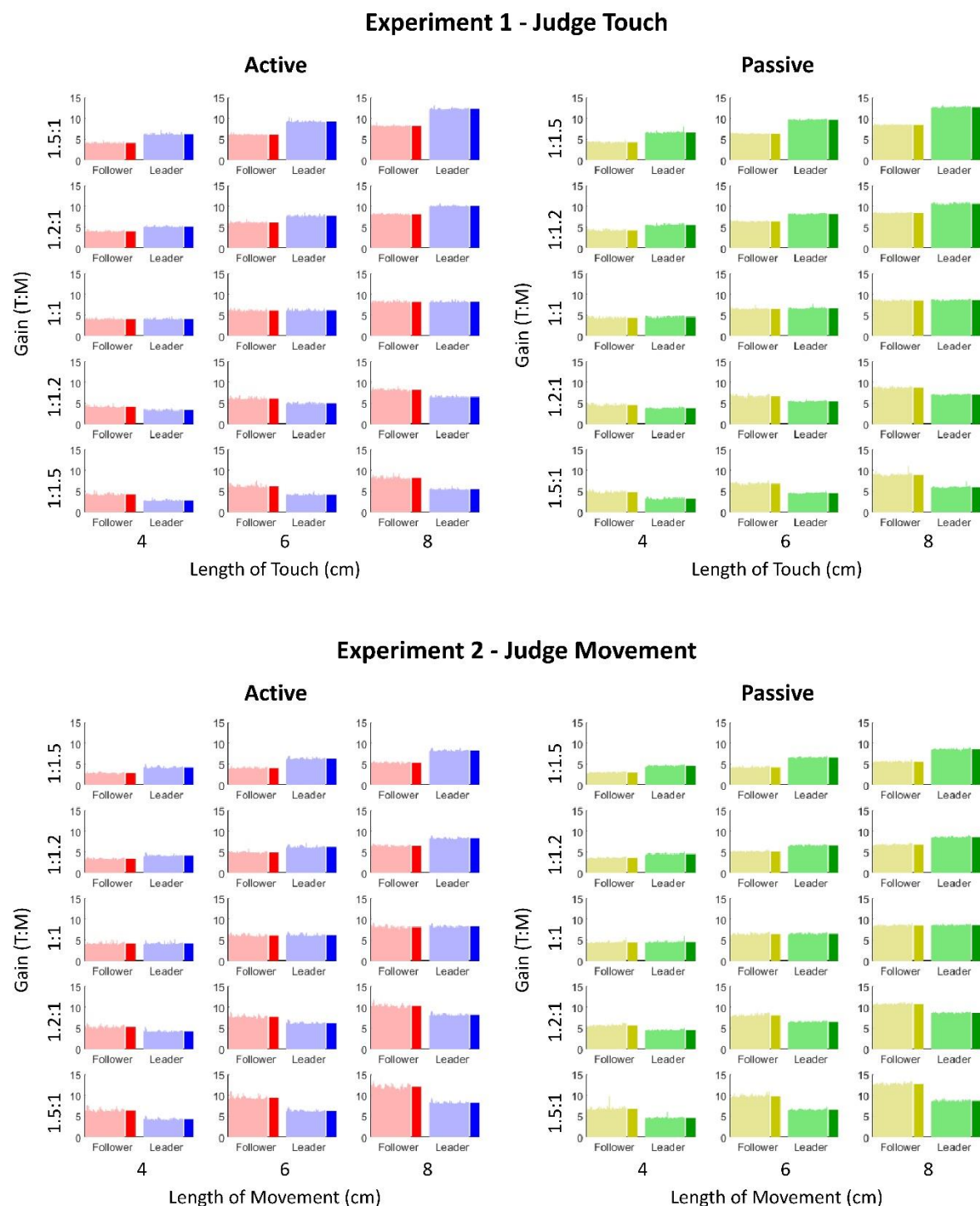
**A** Figure 5**B****C**

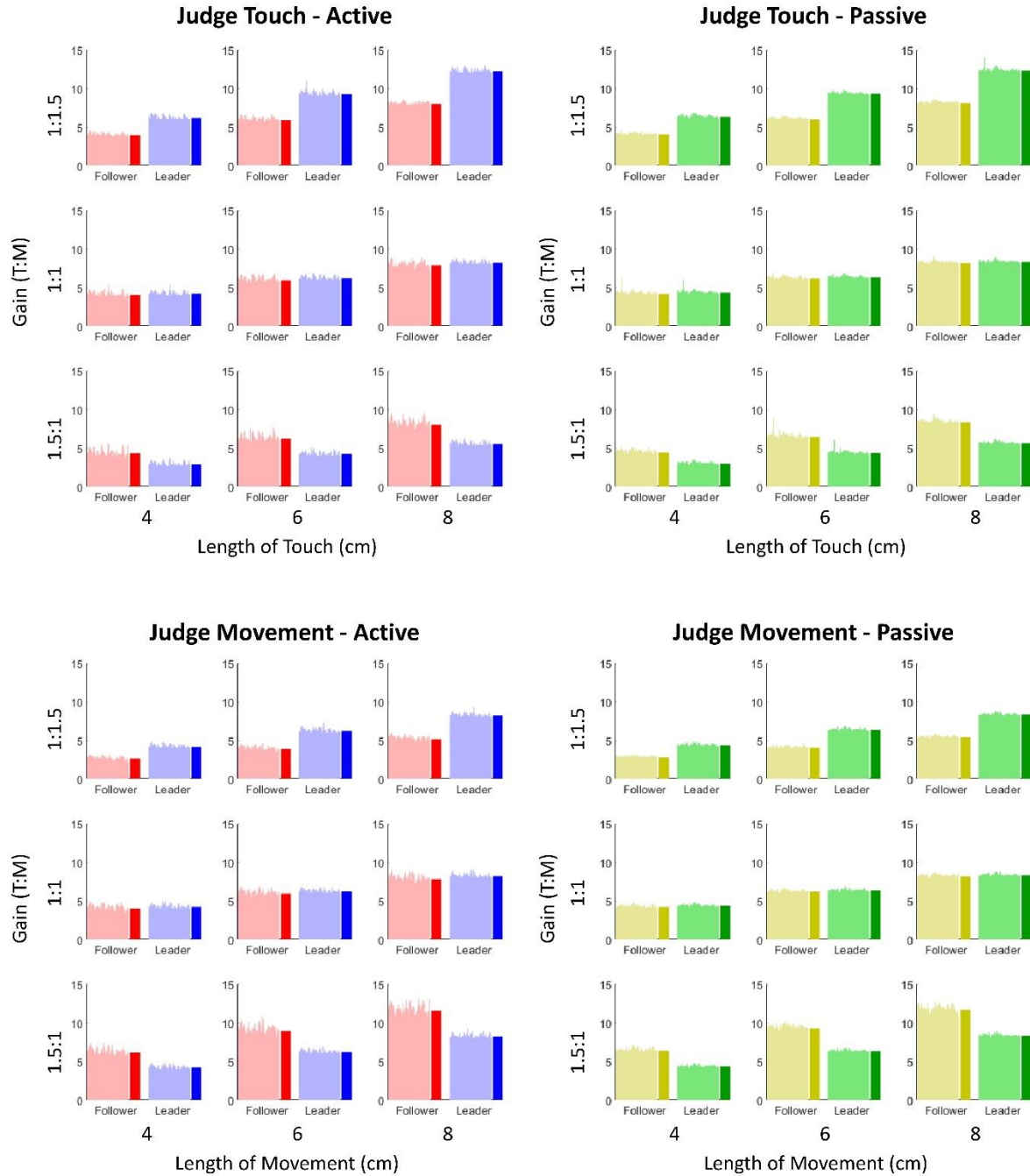
Table 1. Precision data (cm<sup>-2</sup>) for each condition of each experiment.

		Condition		
Experiment	Task	Active movement mean ± SD	Passive movement mean ± SD	Unimodal mean ± SD
1	Judge Touch	1.78 ± 1.19	1.77 ± 0.90	
2	Judge Movement	1.53 ± 0.49	1.39 ± 0.64	
3	Judge Touch	1.44 ± 0.95	1.51 ± 1.06	
	Judge Movement	1.26 ± 1.31	1.26 ± 0.67	
4	Judge Touch	1.80 ± 0.94		2.14 ± 1.40
5	Judge Movement	0.94 ± 0.48		1.08 ± 0.61

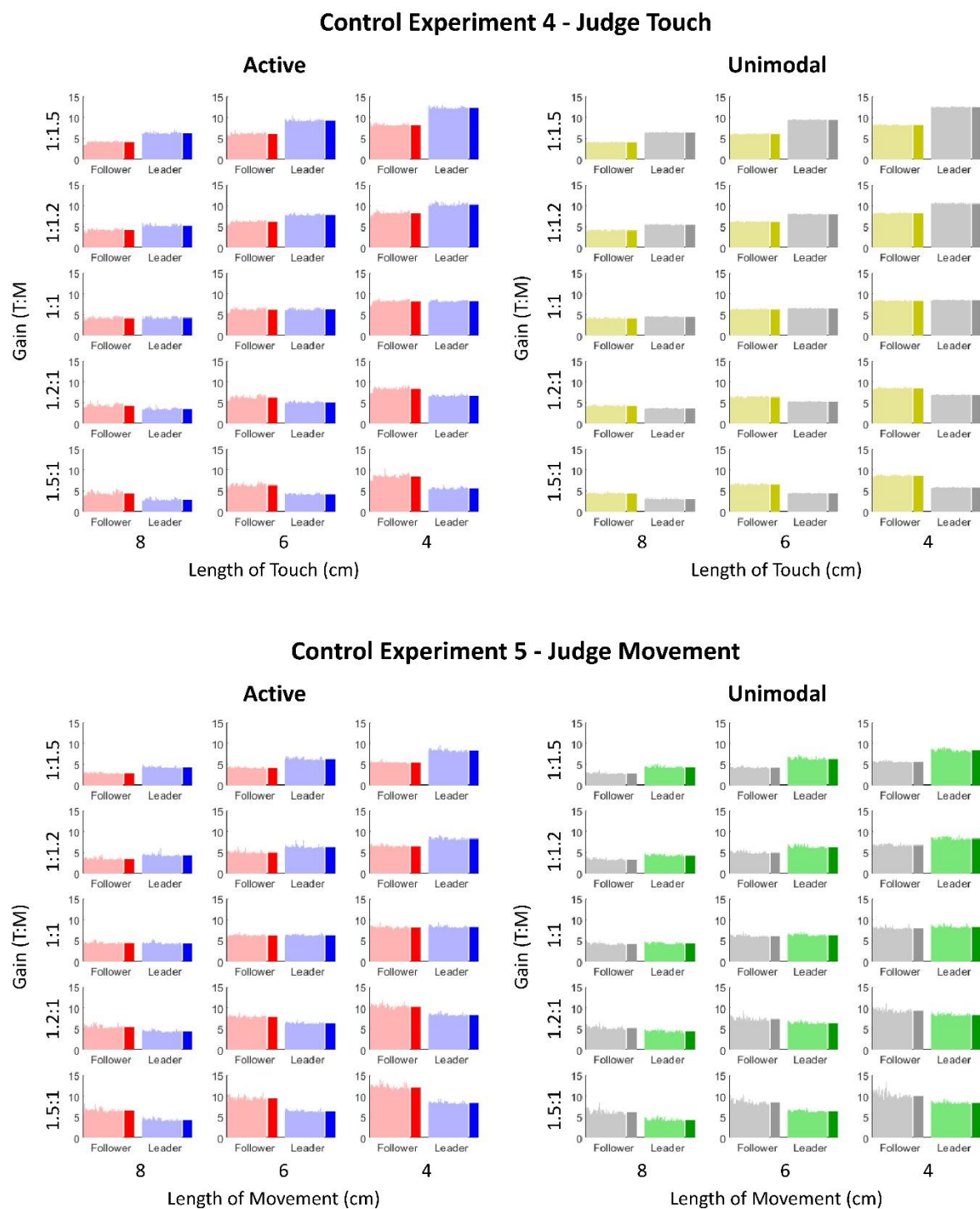


**Figure S1. Spatial extent of leader and follower robot paths in Experiment 1 and 2, Related to Figure 2.** Each vertical data column represents an individual trial. Data from all participants has been pooled. The darker bar at the right edge of each distribution represents the mean extent.

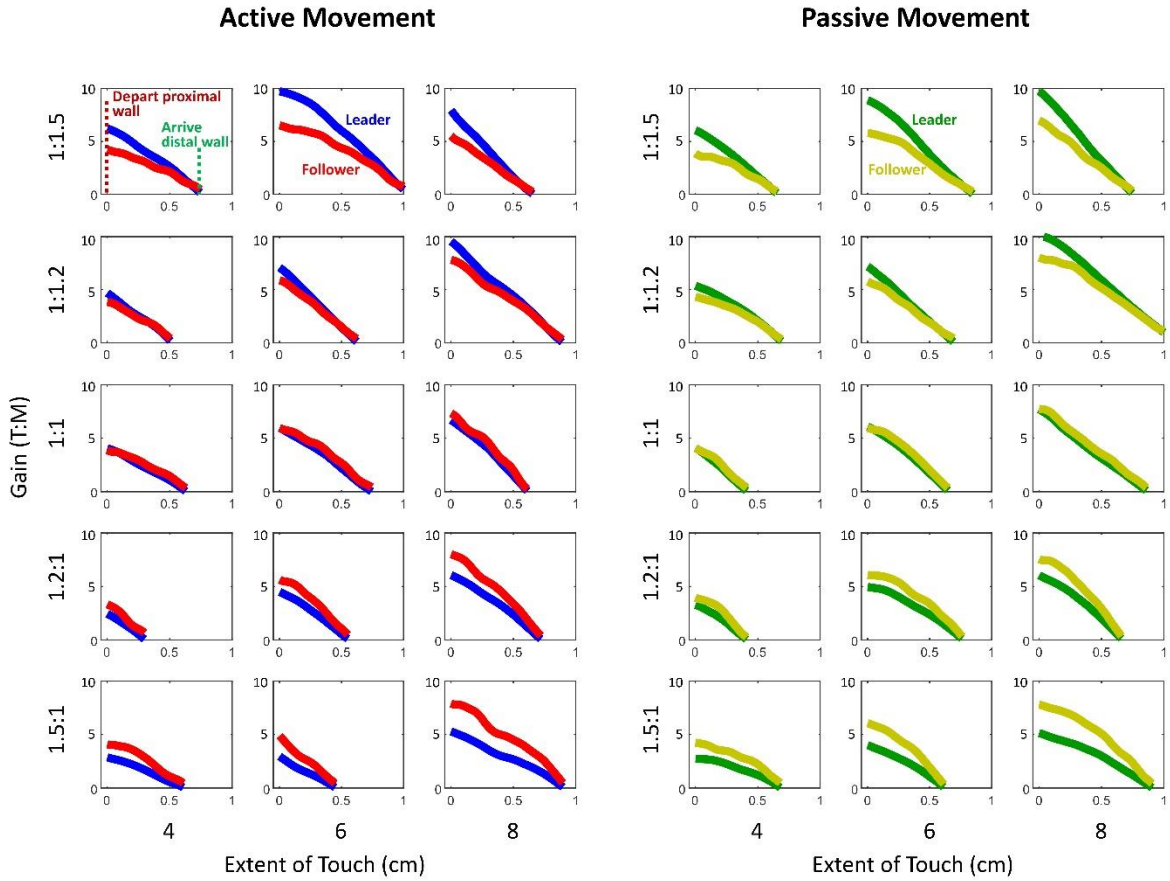
### Experiment 3



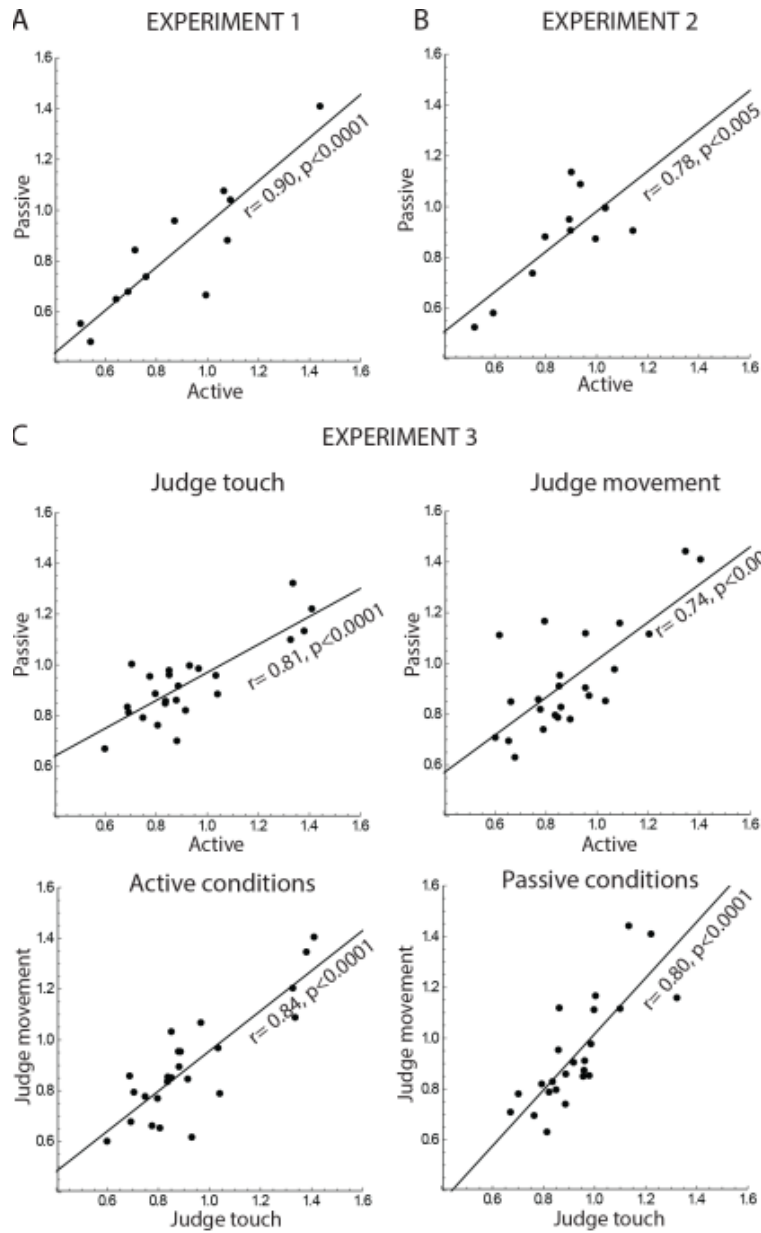
**Figure S2. Spatial extent of leader and follower robot paths in Experiment 3, Related to Figure 3.** Each vertical data column represents an individual trial. Data from all participants has been pooled. The darker bar at the right edge of each distribution represents the mean extent.



**Figure S3. Spatial extent of leader and follower robot paths in Experiment 4 and 5, Related to Figure 5.** Each vertical data column represents an individual trial. Data from all participants has been pooled. The darker bar at the right edge of each distribution represents the mean extent.



**Figure S4. Representative individual trial trajectories of the leader and follower robots, Related to Figure 2.** Each trial involves a movement from the distal to the proximal wall, and then back. Here we show the second, proximal-distal half of the trajectory. X-axes: time (s). Y-axes: position (cm) of the robot end-effector relative to the distal wall located at  $y = 0$ . Note the overlap of leader and follower traces at gain 1:1, and progressive divergence at higher/lower gains. Stimulus duration for trials with gain = 1 across all participants and conditions in Experiments 1-3 was greater in the active (mean  $\pm$  SD:  $0.68 \pm 0.39$  s) than passive movements ( $0.60 \pm 0.20$  s,  $t_{47} = 2.17$ ,  $p = .035$ , Cohen's  $d = .313$ ), but this small difference ( $\sim 8$  ms) can be considered irrelevant in the context of our spatial judgement task.



**Figure S5. Correlation of the individual scale factor ( $\psi$ ) obtained through the model (1) across the different conditions of each experiment, Related to Figures 2 and 3.** Since the Interference Coefficients are computed individually for each condition of a given experiment, we checked whether the individual  $\psi$  factors computed for the same participant in different conditions were positively correlated and did not differ between conditions. Correlations between conditions of Experiments 1, 2 and 3 are shown. The strong positive correlations are consistent with a participant-specific scaling factor affecting their extent judgements in all conditions. This might reflect individual differences in some element of perceptual judgement common to all conditions,

such as the cross-modal match with the visual line presented on the screen. Further, directly comparing the scale factors between conditions within a single experiment did not provide evidence of any significant differences: (Experiment 1, Active vs. Passive, paired t-test:  $t_{11} = .95$ ,  $p = .36$ ; Experiment 2, Active vs. Passive, paired t-test:  $t_{11} = .21$ ,  $p = .86$ ; Experiment 3, judge touch Active vs. Passive, sign test:  $p = .54$ ; Experiment 3, judge movement Active vs. Passive, paired t test:  $t_{23} = 1.33$ ,  $p = .20$ ; Experiment 3, Active conditions, judge touch vs. movement, sign test:  $p = 1$ ; Experiment 3, Passive conditions, judge touch vs. movement, paired t-test:  $t_{23} = .36$ ,  $p = .72$ ).

Expt.	Task	Active mean $\pm$ SD	Passive/Unimodal mean $\pm$ SD
1	Judge Touch	-0.002 $\pm$ 1.45	0.54 $\pm$ 1.65
2	Judge Movement	-0.39 $\pm$ 1.23	1.16 $\pm$ 1.39*
3	Judge Touch	-0.36 $\pm$ 1.77	1.01 $\pm$ 1.28*
	Judge Movement	0.56 $\pm$ 1.43*	1.51 $\pm$ 1.34*
4	Judge Touch	0.18 $\pm$ 0.94	0.36 $\pm$ 0.86
5	Judge Movement	0.90 $\pm$ 1.46	1.13 $\pm$ 1.56*

\* : Significantly different from 0 using t-test (for normal distribution) or sign test (for non-normal distribution).

**Table S1. Intercept values (cm) calculated from regression of perceived stimulus extent on actual stimulus extent for each condition and each experiment, Related to Figures 2-5.**

We did not fit any intercept in our Interference Coefficient model:

$$y = \psi a + \omega (b - a) \quad (1)$$

On theoretical grounds, we assumed a judged distance of zero in the absence of any actual spatial stimulation. However, we additionally ran the same analyses on a model that additionally includes a condition-specific intercept (c):

$$y = \psi a + \omega (b - a) + c \quad (2)$$

Both models (with and without intercept) produced ICs significantly different from 0 for all conditions except the unimodal conditions (Experiment 4-5). All conditions were also significantly different from 1. Importantly, these statistical inferences were not affected by whether an intercept was included in the model or not. Overall, the addition of this new parameter in the model (1) goes against the parsimony of the model and (2) does not change the main results. The model without intercept was therefore preferred.



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