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Does temporal asynchrony affect multimodal curvature detection?

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Abstract

Multiple sensory modalities gather information about our surroundings to plan appropriate movements based on the properties of the environment and the objects within it. This study was designed to examine the sensitivity of visual and haptic information alone and together for detecting curvature. When both visual and haptic information were present, temporal delays in signal onset were used to determine the effect of asynchronous sensory information on the interference of vision on the haptic estimate of curvature. Even under the largest temporal delays where visual and haptic information were clearly disparate, the presentation of visual information influenced the haptic perception of curvature. The uncertainty associated with the unimodal vision condition was smaller than that in the unimodal haptic condition, regardless of whether the haptic information was procured actively or under robot assistance for curvature detection. When both visual and haptic information were available, the uncertainty was not reduced; it was equal to that of the unimodal haptic condition. The weighting of the visual and haptic information was highly variable across subjects with some subjects making judgments based largely on haptic information, while others tended to rely on visual information equally or to a larger extent than the haptic information.

Keywords

Arm movements; Curvature; Haptics; Multisensory; Vision

Introduction

Advances in the field of robotics and teleoperated robot-assisted surgery have led to questions about how best to represent haptic information to the surgeon in order to improve the accuracy of the human–robot interaction. It has been suggested that adding haptic feedback would contribute significantly to the safe performances of robot-assisted surgeries (Okamura 2004, 2009). The combination of haptic feedback with a visual display could enhance the surgeon's ability to perform surgery by adding the ability to sense slip and applied forces (Westebring-van der Putten et al. 2008). Thus, understanding how multiple sensory modalities are combined and utilized to achieve the highest level of performance is essential for the development of new technologies.

If haptic feedback is to be added to teleoperated robotic systems, it is necessary to understand how visual and haptic feedback is integrated in order to best present stimuli from each modality. Generating the visual display or the haptic feedback can introduce time

delays between the two sensory modalities, a matter that must be addressed for telemanipulation systems (Hashtrudi-Zaad and Salcudean 2002). As the design of new systems advances to incorporate haptic information such as force and tactile feedback to the operator, it will be important to know the temporal parameters within which this feedback must be given and the acceptable range of temporal delays for each sensory parameter.

Little is known about this question. The most extensive studies on the effects of temporal delays on multisensory integration have been conducted on neural activity in the deep layers of the superior colliculus, a midbrain structure that is involved in orientation behaviors (see Stein 1998 for review). Activity of neurons in the superior colliculus is significantly enhanced when spatially congruent auditory, visual, or somatosensory stimuli are presented simultaneously (Meredith and Stein 1986). However, the response is sensitive to the temporal relation between sensory inputs (Rowland et al. 2007). The maximum amount of response enhancement occurs when the sensory signals are presented such that there is an overlap in the periods of peak discharge in response to each modality separately (Meredith et al. 1987). Furthermore, the response enhancement goes to zero or changes to depression as the peak discharge periods become more disparate (Meredith et al. 1987). Thus, the temporal relation between sensory signals is an important factor in multisensory integration at the neuronal level.

The stimuli used to elicit orienting behavior are usually very brief, and it is not known how important temporal disparities are for stimuli that extend over longer periods. However, it is known that the perception of hand paths is influenced by vision (Flanagan and Rao 1995; Goodbody and Wolpert 1999; Schwartz et al. 2004). In fact, if proprioceptive and visual information about the position of the body are available the CNS will use them both (van Beers et al. 1996). Visual information dominates when visual and tactile stimuli are presented simultaneously, and visual dominance increases when the stimuli are presented in the same spatial location or when the intensity of the stimuli is subjectively matched (Hartcher-O'Brien et al. 2008). While vision tends to dominate for spatial tasks, haptic information may be more useful for analysis of material properties such as texture (Lederman et al. 1986; for review see Lalanne and Lorenceau 2004).

The present study was designed to examine the reliability of visual and haptic information alone and together in a task requiring subjects to detect curvature of hand motion. The first goal of the study was to determine the thresholds for curvature detection under unimodal (vision or haptic alone) and bimodal conditions. Based on previous results, one might expect that in the unimodal condition vision would be more reliable than haptic information and that under normal bimodal conditions, the performance would be better than for either of the modalities alone. However, in our study, we also manipulated the visual information in order to determine the extent to which the combination of sensory information was sensitive to temporal asynchronies. Thus, the main goal of our study was to determine the effect of temporal asynchrony on interference of visual information on haptic sense of curvature, thereby examining the effect of delays between the two sensory modalities. We used haptic conditions of robot-assisted presentation and active exploration of the curved boundary, and we hypothesized that active exploration would lead to better performance and stronger haptic weighting in the bimodal conditions. Finally, we determined the ability of subjects to detect temporal delays in movement onset between the visual and haptic signals used for the aforementioned task. This provided evidence that subjects were able to easily perceive the temporal delays we used to test the effects of temporal delays between the two sensory modalities.

Methods

A total of 23 right-handed subjects participated in the study (11 male, 12 female, 19–32 years, 1.54–1.95 m in height). Each of the three experiments had ten subjects (five subjects completed two or more of the experiments). Subjects had no history of sensory, perceptual, or motor disorders. The experimental protocol was approved by the University of Minnesota's Institutional Review Board and all subjects gave informed consent prior to each experimental session.

Apparatus

A two-joint robot arm (Interactive Motion Technologies, Cambridge, MA) was used to present haptic stimuli. Simulated boundaries were created with a defined curvature that was contained within a rectangle (30 cm wide $\times$ 10 cm deep) centered on the robot's origin ($x, y = 0$) with a stiffness of 2 N/mm and viscous damping of 0.05 N/mm/s (Henriques and Soechting 2003). For experiments 1 and 3, the robot arm moved the subject's hand in the horizontal plane along a boundary with a sinusoidal velocity profile with a peak lateral velocity of 0.24 m/s (McFarland and Soechting 2007) and a duration of 2 s. For experiment 2, subjects actively explored these boundaries with an average peak velocity of 0.61 m/s at an average rate of 1.20 Hz. The visual stimulus was presented as a cursor on a vertically oriented monitor above the robot arm. Like the movement of the robot arm, the cursor's movement across the screen was bounded within a rectangle (30 cm wide $\times$ 10 cm high), and had a horizontal velocity profile that was identical to the lateral motion of the robot arm.

A two-alternative forced-choice task and an adaptive staircases algorithm (Kesten 1958; Treutwein 1995) with randomly interleaved ascending and descending staircases (Henriques and Soechting 2003) were used to find curvature detection thresholds for each subject under different conditions of sensory input for experiments 1 and 2. Each staircase began with a stimulus curvature of $\pm 2.0 \text{ m}^{-1}$ (radius of curvature 0.5 m) with an initial step size of 0.25 m^{-1} . The curvature value was adjusted on subsequent trials based on the subject's response, the step size decreasing and reversing sign whenever the response on one trial was inconsistent with the response on the previous trial. Trials with positive (*inward*) and negative (*outward*) curvatures were randomly interleaved. The bias (point of subjective straightness) was defined as the point where the curvature values from the two staircases converged to a value where the subject was equally likely to respond "in" or "out", and the threshold for detection was determined by computing the uncertainty in the responses (see "Analysis").

Procedure

Curvature detection: experiments 1 and 2

For experiments 1 and 2, subjects were asked to determine if a path was curved inward or outward using visual and/or haptic information. The difference between the two experiments was in the method of obtaining haptic information about the path. For experiment 1 (robot assisted), the robot arm moved the subject's arm through a defined path, while in experiment 2 subjects actively moved the robot arm to explore a curved boundary. At the start of each session, subjects first completed the unimodal vision and haptic conditions which each consisted of 60 trials. For the unimodal vision condition, subjects were asked to watch a cursor traverse 30 cm from left to right on a monitor and report whether it curved 'in' which was in the downward direction or 'out' which was upward on the vertically oriented monitor. Subjects' arms were kept at their sides during this condition.

For the unimodal haptic condition, subjects were instructed to grasp the vertical handle of the robot arm with their right hand and close their eyes. In experiment 1, prior to the start of each trial, the handle moved slowly to the point from which each trial's movement began (15 cm left of the subject's midline). The start of the trial was signaled with a beep, and the handle moved along the boundary once from left to right. In experiment 2, subjects actively explored the boundary, by moving back and forth along the boundary. In both experiments, subjects responded whether the path of the handle had curved in (toward the subject) or out (away from the subject).

For each of the bimodal conditions, subjects completed a block of 150 trials during which they received both haptic and visual information as described for the unimodal conditions. Subjects were instructed to watch the cursor but make their responses according to the haptically sensed motion of their hand only. Vision of the arm was blocked by an opaque screen. As illustrated in Fig. 1, within each bimodal condition, visual information was manipulated so that the curvature of the cursor's motion was greater than, equal to, or less than the curvature of the haptic boundary. The adaptive staircase procedure was used as described previously, but for the bimodal conditions three pairs of staircases, one for each visual offset ($\pm 0.5 \text{ m}^{-1}$, 0), were randomly interleaved to prevent adaptation to the visual stimulus. Differences in response biases indicated the extent to which the visual information affected the responses to haptic stimuli.

Bimodal conditions were defined by the temporal asynchrony between the visual and haptic stimulus (visual delay). For experiment 1, where the subject's arm was moved by the robot along the boundary, bimodal conditions had visual delays of 0, ± 200 , and ± 400 ms. For experiment 2, where subjects actively explored the boundary, bimodal conditions had visual delays of 0, $+200$, and $+400$ ms. The order in which subjects completed the blocks of bimodal conditions was counterbalanced across subjects, except for the 0-ms condition which was always the first to be completed. For experiment 1, subjects completed the two unimodal conditions and one to three bimodal conditions per session; thus typically completing the experiment within two or three sessions (different days). A typical experimental session lasted between 2 and 3 h. For experiment 2, subjects typically completed the experiment within one session lasting approximately 3 h. Subjects were allowed to rest whenever needed to prevent fatigue.

Temporal asynchrony detection: experiment 3

Experiment 3 consisted of one block of 60 trials during which subjects received both haptic and visual information. Similar to experiment 1, for experiment 3 the robot arm moved the subject's hand along a boundary, while the cursor moved across the screen. Motions of the robot arm and of the cursor were identical except for a temporal offset between the two, and the subjects were asked only to report whether the cursor or handle began the movement first. A two-alternative forced-choice task and a pair of adaptive staircases were used to find temporal detection thresholds for each subject between visual and haptic inputs. The staircases began with a temporal offset of ± 400 ms with an initial step size of 50 ms. The temporal offset was adjusted on subsequent trials based on the subject's response. Trials with positive (haptic first) and negative (vision first) delays were randomly interleaved. The temporal detection bias was defined as the point where the temporal values from the staircases converged to a value where the subject was equally likely to respond that the cursor or robot arm started to move first. Subjects completed this experiment within one session lasting approximately 15 min.

Analysis

The bias and uncertainty for curvature detection were determined in two ways. First, we calculated the mean (bias) and standard deviation (uncertainty) of the last twenty trials of the staircase for each condition/delay manipulation (Fig. 2a) (during this interval, the subjects' responses oscillated about a mean). Second, we fit a psychometric function to the response curve where the bias is the curvature value at 50%, and the range of uncertainty is the range between the curvature values at the 25 and 75% (Fig. 2b). Although statistics were done on both bias calculations, we only report the biases computed from the mean of the last twenty trials since the statistical results agreed 100% of the time.

ANOVA with repeated measures was used to test for an effect of bimodal delay conditions (IVs: $H > V$, $H = V$, $H < V$) for each dependent variable (bias, uncertainty). MANOVA with the Games-Howell post hoc test with a significance level set at $P \leq 0.05$ was used to test for the effect of condition (without delays) on bias and uncertainty (Games-Howell does not assume population variances are equal or that sample sizes are equal). All values are mean ($\pm$ SD) unless otherwise noted. For two subjects in the active experiment, the forced-choice staircases did not converge in the unimodal haptic condition; therefore their haptic data were not included in the statistical analyses.

We used a simple model to determine the extent to which subjects used visual and haptic information to make their curvature determination for the bimodal conditions. The HV bias estimates were computed as:

$$HV_{\text{perc}} = aV_{\text{bias}} + (1 - a)H_{\text{bias}} \quad (1)$$

where HV_{perc} is the estimated bias for the bimodal condition and a is the visual weighting (from 0 to 1). The best fit was determined as the weighting (a) that resulted in the smallest total deviation from the actual HV biases. Assuming a linear summation of the two sensory signals, the expected uncertainty in the bimodal condition (σ_{HV}) can be predicted from the uncertainties in the two unimodal conditions (Ernst and Banks 2002):

$$\sigma_{HV}^2 = a^2 \sigma_{\text{vis}}^2 + (1 - a)^2 \sigma_{\text{hap}}^2 \quad (2)$$

Results

Response bias and uncertainty

In the unimodal vision condition, subjects determined the direction of the curvature by watching a cursor move across a screen. Not surprisingly, subjects could detect curvature quite accurately with little bias. The mean bias across subjects was -0.02 ± 0.06 and $0.01 \pm 0.11 \text{ m}^{-1}$ for experiments 1 and 2, respectively (Fig. 3). As shown in Fig. 4, the uncertainty during the robot-assisted and active experiments was also small (0.08 and 0.07 m^{-1} , respectively). When subjects had haptic information alone to detect curvature, the mean biases were positive, 0.13 ± 0.29 and $0.01 \pm 0.39 \text{ m}^{-1}$ for the robot-assisted and active experiments, respectively (Fig. 3). Therefore, subjects were equally likely to report curvature as 'out' or 'in' when the boundaries were curved inward with a peak distance from a straight line of 0.15 and 0.01 cm for the robot-assisted and active experiments, respectively. The mean uncertainty for the robot-assisted and active experiments was 0.17 ± 0.06 and $0.16 \pm 0.07 \text{ m}^{-1}$, respectively (Fig. 4). Neither bias nor uncertainty differed between the robot-assisted and active experiments (MANOVA, $F_{(1,16)} = 0.523, 0.182, P = 0.480, 0.675$, respectively). The haptic condition had a larger uncertainty than the vision

condition (Games-Howell, $P = 0.007$, robot-assisted; $P = 0.040$, active), but there was no difference between the bias values ($P = 0.539$, robot assisted; $P = 1.000$, active).

When subjects were presented with both visual and haptic information, the visual signal presented a curved path either equal to that presented haptically ($H = V$) or with a curvature that was $\pm 0.5 \text{ m}^{-1}$ relative to the haptic presentation ($H < V$, $H > V$). Although both visual and haptic signals were presented, subjects were instructed to report the haptically presented curvature only. Bimodal conditions were also performed with delays in movement onset between the visual and haptic signal up to 400 ms. The mean biases and uncertainty values from each delay are shown in Figs. 3 and 4 (gray bars). Surprisingly, there was no effect of delay for any condition or measurement variable (bias and uncertainty, $P > 0.35$), therefore, we will only present the differences between the bimodal conditions (averaged across delays) in detail below. For the robot-assisted experiment, the bimodal conditions were all significantly different from one another (all $P \leq 0.010$) with $H > V$ having the largest positive bias while $H < V$ had the largest negative bias, differing by 0.44 m^{-1} (Fig. 3a). Only the $H > V$ condition, which had the largest positive bias (0.33 m^{-1}), was different than the other bimodal conditions for the active experiment ($P \leq 0.005$, both comparisons; Fig. 3b). Thus, the biases for the bimodal conditions tended to change in direction of the visual offset although there was a large amount of variability across subjects. The uncertainty for the bimodal conditions was larger than the visual condition, and tended to be more similar to the haptic condition. There were no differences in uncertainty for the active condition ($P \geq 0.308$, all comparisons; Fig. 4b), although for the robot-assisted experiment the uncertainty for the $H = V$ condition was less than $H > V$ ($P = 0.042$; Fig. 4a). Only the biases and uncertainty from the $H < V$ condition were significantly different across the two experiments ($P \leq 0.001$ and $P = 0.012$, respectively) with the robot-assisted experiment having a larger negative bias and higher uncertainty.

For both experiments, compared to vision alone, the bias was larger in the $H > V$ condition ($P \leq 0.001$, both comparisons). Correspondingly, in the robot-assisted experiment, the bias in the $H < V$ condition was more negative than it was for vision alone ($P = 0.001$). For both experiments, the uncertainty was larger when subjects had haptic and visual information, compared to when subjects completed the task with visual information alone ($P < 0.05$; Fig. 4). The positive haptic condition bias was significantly different than the large negative bias of the $H < V$ condition only for the robot-assisted experiment ($P = 0.025$). There were no other significant differences in the bias for the haptic condition for either experiment. The uncertainty in the combined vision and haptic condition did not differ from the uncertainty in the unimodal haptic condition ($P \geq 0.607$).

The range of uncertainty around the bias, determined from the psychometric curve fit onto the data (see “Methods”; Fig. 5), is similar to the measure of uncertainty presented previously. A regression between these two uncertainty measures revealed a significant correlation between the measures ($P < 0.001$) with R^2 values of 0.48 and 0.52 for the robot-assisted and active experiments, respectively. The statistical results for the two measures were the same with a few exceptions. For $H = V$ in the robot-assisted experiment, the range of uncertainty was not significantly smaller than $H > V$ ($P = 0.075$), while it was significantly smaller than the haptic condition ($P = 0.012$). For the active experiment, the range of uncertainty for vision was not significantly different than $H < V$ ($P = 0.228$). All other comparisons agreed with the statistical results of the uncertainty reported earlier.

Bimodal sensory integration

The results in Fig. 3 show that subjects were biased incompletely toward the visual stimulus in the bimodal condition, suggesting that they weighted visual and haptic information by varying amounts. We estimated this weighting according to Eq. 1, and the results for each

subject in the robot-assisted and active experiments are shown in Fig. 6. Interestingly, the weighting of each modality varied widely across subjects within each experiment ranging from no contribution of vision to complete dominance of vision. The average absolute deviation from the actual biases to the HV_{perc} estimate was $0.11 \pm 0.06 \text{ m}^{-1}$ for the robot-assisted experiment and $0.19 \pm 0.10 \text{ m}^{-1}$ for the active experiment.

The variance for the bimodal condition was underestimated with the exception of two subjects in each experiment. From the weighting factor for each subject, we also estimated the variance expected if information from the two modalities was summed (Eq. 1). The estimate of bimodal variance was less than the actual variance in the bimodal condition on average by 73 ± 16 and $74 \pm 22\%$ for the robot-assisted and active experiments, respectively. For the two subjects in each experiment not included in this calculation, the HV_{perc} variance estimate exceeded the actual variance in the bimodal condition. All four of these subjects relied heavily on the haptic information (Fig. 6a: subjects 3, 4 and Fig. 6b: subjects 1, 5). Even though these subjects were not biased by the visual information when it was present, the presence of visual information did decrease their uncertainty.

Temporal asynchrony

There was no effect of delay for any dependant variable in the experiments described previously. Therefore, the third experiment was conducted to determine the threshold for detection of a temporal asynchrony between the movement onset of a visual and haptic movement (Fig. 7). The average response bias was $40 \pm 31 \text{ ms}$, indicating that if the handle (haptic stimulus) began moving 40 ms prior to movement of the cursor (visual stimulus), the movement onsets would be perceived as simultaneous. A one-sample *t*-test revealed that the average response bias was significantly different than zero ($P = 0.003$). The average range of uncertainty across subjects was $78 \pm 16 \text{ ms}$. Temporal delays outside of this range should be easily detectable by subjects. Therefore, in experiments 1 and 2, our delay conditions were well within the range where subjects would perceive differences in the movement onset of the visual and haptic stimuli. Consistent with this result, subjects sometimes commented on the discrepancy between movement start times.

Discussion

In summary, the presence of visual information biased the haptic percept of curvature even when there was a large ($\pm 400 \text{ ms}$) temporal disparity between the two stimuli. This bias did not depend on the temporal offset between visual and haptic information, even when the two stimuli were clearly asynchronous. Based on the biases, the results suggest that subjects estimated the curvature using a weighted combination of visual and haptic information. However, an analysis of the uncertainty in the subjects' reports suggests that information from the two sensory modalities was not combined in a simple combinatorial fashion under our experimental conditions.

The main task in this study was to determine the curvature of a felt or seen boundary. As expected, subjects were very good at this task with visual information alone. When subjects only felt the boundary (haptic condition), subjects were equally likely to report curvature as 'out' or 'in' when the boundaries were curved inward with a bias of 0.13 ± 0.29 and $0.01 \pm 0.39 \text{ m}^{-1}$ for the robot-assisted and active experiments, respectively. Another study (Henriques and Soechting 2003) also found that subjects were biased toward inward curves for sideways boundaries, although their mean bias of 0.38 m^{-1} was larger but still within one standard deviation of our results. In that previous study, subjects explored a shorter boundary (15 cm compared to 30 cm) and it is possible that path length affects the bias. It is known that the range of uncertainty decreases with increasing path length (Gordon and Morison 1982; Pont et al. 1999; Wijntjes et al. 2009). We expected subjects to be more

accurate (smaller biases) when they actively explored the boundary compared to a robot-assisted presentation. Although the active experiment tended to have smaller biases for the unimodal haptic condition, the difference was not significant.

Subjects also performed this task when the boundary could be seen and felt at the same time. However, the visual information was manipulated in a random manner so that it did not always match the haptic information (i.e., $\pm 0.5 \text{ m}^{-1}$ curvature difference). Subjects were instructed to report the curvature that was felt (haptic), thus allowing examination of the influence of visual information under circumstances where it may not be useful. Since subjects did not know whether or not visual information was veridical on any given trial, a comparison of the actual response bias with the estimated bias provided a measure of the extent to which information from the two modalities was integrated to formulate a response. It is clear from the results (Fig. 3) that subjects did not ignore the visual information since the response biases tended to change in the direction of the visual offset. However, vision was not completely integrated with the haptic information. The HV_{perc} estimate was used to examine the extent to which vision contributed to the perception of curvature of the hand path. There was a wide range visual contribution across subjects within each experiment (Fig. 6). About half of the subjects tended to rely on haptic information (as instructed) with very low visual contributions for the curvature detection, while vision tended to be weighted at a much higher level for the other half of the subjects. While HV_{perc} provided a reasonable estimate of the bias when visual and haptic information are available for the task, the availability of visual cues did not decrease the uncertainty in the estimates of curvature, as would be expected from a summation of sensory cues. It is possible that the noise in the two sensory modalities was correlated. Alternatively, if the weighting of visual information varied from trial to trial, the variability of the estimate would be increased.

Whether the arm movement along the boundary was robot assisted or actively explored, the only difference between the experiments was found for the $H < V$ bimodal condition where vision did not appear to have an effect on the response bias during active exploration. Another study also found that active exploration did not improve curvature detection thresholds over those found during a passive movement (Konczak et al. 2008). A comparison between guided and active exploration for determining the aspect ratio of a square and the radial-tangential illusion size also revealed no differences for either measure based on the mode of haptic sensing (McFarland and Soechting 2007).

Surprisingly, the movement onset delays tested in these experiments had no effect on curvature detection when both visual and haptic information were present (bimodal conditions). The results of the asynchrony test (Exp. 3) made it clear that subjects perceived the difference in movement onset between the visual and haptic stimuli since subjects could discriminate temporal offsets of the visual and haptic stimuli at much smaller time intervals than those used in the curvature detection experiments. Subjects tended to have an average bias of 40 ms, which indicates that if handle movement was initiated 40 ms before the cursor, subjects would be equally likely to indicate that either the handle or the cursor moved first. Even with an average range of uncertainty of 78 ms, temporal delays of 200 ms or more would be easily perceived by the subjects. The bias we observed is consistent with a previous observation (Dassonville 1995) that a mechanical stimulus delivered to the finger that occurred 0–38 ms prior to onset of a visually cued movement was judged as occurring during the movement. Thus, there appears to be a delay in the processing of haptic information of around 40 ms with respect to vision that is consistent for our task and a previous haptic localization task (Dassonville 1995).

Thus, the lack of effect on the bias due to temporal delays (Fig. 3) was clearly not a result of subjects' inability to perceive the movement asynchrony. This result was surprising since we

had expected that the visual information would bias the haptically sensed movement when the two motions were perceived to be synchronous, but that any visual bias would be attenuated when the two motions were clearly asynchronous. Visual information appears to influence haptic sensing of hand trajectory irrespective of temporal asynchrony. Nevertheless, delayed visual feedback is detrimental to perform skilled movements, including telerobotic surgery (Kim et al. 2005). This decrement in performance appears to derive mainly from the influence of delayed visual feedback on the temporal features of sequentially executed movements (Pfordresher and Palmer 2002; Stetson et al. 2006; Wing 1977).

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Fig. 1.

Representation of the bimodal conditions to illustrate the visual bias that was introduced relative to the control $H = V$ bimodal condition for a sample outward curve (negative curvature). The *light gray line* represents hand path in the $H < V$ condition where the visual bias was the haptic curvature $+0.5 \text{ m}^{-1}$, while the *black line* represents the hand path in the $H > V$ condition with a visual bias haptic curvature -0.5 m^{-1} .

Fig. 2.

a The forced choice staircase from the unimodal vision condition from one subject is shown. The bias and uncertainty were calculated by taking the average and standard deviation, respectively, of the curvature values of last 20 trials for each block (*gray area*). For positive biases, subjects report with equal probability that curves directed inward by the amount of the bias are inward or outward. **b** The best fit psychometric function is shown for the same data displayed in **a**. The point of equal probability is defined as the curvature at the 50% point on the psychometric curve and is a measure that is equivalent to the bias calculated in **a**. The range of uncertainty around the point of equal probability is defined by the range of curvature values in the area between 25 and 75% on the psychometric curve (*gray area*)

Fig. 3.

The mean ($\pm$ SD) response bias calculated across subjects is shown for each unimodal and bimodal condition for the robot-assisted (**a**) and active (**b**) experiments. For each bimodal condition, the bias is also shown for each delay within that condition (*gray bars and error bars*). In the robot-assisted experiment, the visual display could lead or lag the hand movement, whereas in the active experiment, the visual display always lagged the movement. Significant differences between conditions are indicated by *** $P \leq 0.001$; ** $P \leq 0.01$; * $P < 0.05$. *Note:* There was no significant effect of delay for any condition

Fig. 4.

The mean $\pm$ SD uncertainty of the response bias calculated across subjects is shown for each unimodal and bimodal condition for the robot-assisted (**a**) and active (**b**) experiments. *Gray bars and error bars* are values for each delay within the bimodal conditions. Significant differences between conditions are indicated by *** $P \leq 0.001$; ** $P \leq 0.01$; * $P < 0.05$.

Note: There was no significant effect of delay for any condition

Fig. 5.

The mean range of uncertainty calculated from the psychometric curves across subjects is shown for each condition for the robot-assisted (**a**) and active (**b**) experiments. The width of each *box* indicates the mean range of uncertainty for that condition with the *plus sign* indicating the mean bias for that condition. Significant differences in the range of uncertainty between conditions are shown on the *left side* of each figure and are indicated by *** $P \leq 0.001$; * $P < 0.05$

Fig. 6. The contributions of the visual and haptic modalities are shown for the best fit HV_{perc} estimate for each subject for the robot-assisted (a) and active (b) experiments

Fig. 7.

The response bias from the asynchrony test (Exp. 3) is shown for each subject. Positive bias values indicate that the handle (haptic stimuli) movement begins before the cursor (visual stimuli) movement. The average response bias is 40 ± 31 ms indicating that the onset of the visual and haptic stimuli is perceived as simultaneous when movement of the haptic stimulus begins 40 ms prior to the visual stimulus