

Watching a Cursor Distorts Haptically Guided Reproduction of Mouse Movement

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Participants moved a mouse along a force-feedback-defined linear path, either without vision or while watching a cursor set to 1 of 3 levels of visual:haptic gain (all >1:1). They attempted to haptically reproduce the movement without visual feedback. Errors increased with gain, reaching 70% overestimation at the highest gain. Forewarning participants about gain variability did not eliminate this effect. The gain level was potentially cued during the movement by the mismatch between visual feedback and kinesthetic feedback. Moreover, because participants did not achieve cursor-speed constancy across gain levels, visual speed was another cue to gain. Collectively, these cues failed to prevent visual distortion of movement reproduction.

Events in the world commonly give rise to multiple sources of sensory input. When people contact a physical object, they may see, hear, feel, and perhaps smell the consequences of impact. Although sensory signals impinge on different receptor populations located within different organs, people's percept is ultimately that of a coherent, unified object. This outcome requires interactions among different sensory systems, which not only integrate cues but also resolve discrepancies or conflicts. The present research is concerned with interactions between vision and touch in a now ubiquitous context, that of moving a computer mouse some distance while watching a cursor linked to its trajectory. Because of the gain adjustment on the mouse (i.e., the ratio of cursor movement to the physical movement of the mouse), this situation produces a discrepancy between the visual and haptic signals for distance.

In everyday contexts, this discrepancy may be of no consequence. Indeed, it is unavoidable given the desire to contain the mouse in a small space but to have a large-scale visual display. However, in this article, we show that the visual haptic mismatch creates the potential for distorting subsequent reproduction of hand movement. This could be problematic for computer interface systems in which visual feedback is intermittent and the system output must be controlled by fine motions of the hand. One possible such context is telesurgery.

The perceptual discrepancy paradigm is a frequently used method for investigating how sensory inputs from different modalities are combined. In a seminal study by Rock and Victor (1964), for example, participants saw and felt an object without realizing that the shape of the object was subject to optical distortion. Their reports of the perceived object were entirely driven by the visual information, a phenomenon called *visual capture*. In subsequent discrepancy studies, vision/touch conflicts have been introduced for judgments of various stimulus dimensions. Complete or partial visual capture of the haptic or kinesthetic systems has been demonstrated for spatial localization (Hay, Pick, & Ikeda, 1965), curvature (Easton & Moran, 1978; Gibson, 1933), depth (Singer & Day, 1969), and texture (Lederman & Abbot, 1981). The interactions have not always been resolved entirely in favor of vision. Instead the relative contributions of the modalities have been found to vary with a variety of factors such as age (Misceo, Hershberger, & Mancini, 1999), instructions (e.g., Lederman, Thorne, & Jones, 1986), the response modality (e.g., Heller, Calcaterra, Green, & Brown, 1999; Hershberger & Misceo, 1996), and the degree of noise in the inputs (e.g., Ernst & Banks, 2002), and with ancillary information such as sight of the hands (Heller et al., 1999).

Ferrel, Leifflén, Orliaguet, and Coello (2000) found that visual-haptic discrepancies affected movement. In their study, participants made a pointing movement to a visual target located at a constant distance (28 cm) in the sagittal plane. The entire visual display, including the hand and arm, was conveyed by a video camera at one of three levels of magnification (.75, 1.0, and 1.25). The magnitude of the reaching movement increased with the magnification factor. However, the effect of gain appeared not to depend on sight of movement per se, as the effect of gain on errors was very similar whether participants saw the magnified hand throughout the reaching interval or only before and after movement. Apparently, magnification of the statically displayed hand-

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to-target distance influenced the length of the reach (despite hand size being a cue to magnification).

Various quantitative approaches have been used to characterize the relative contributions, or weights, given to sensory modalities in determining the ultimate perceptual response to discrepant inputs (see Lederman & Klatzky, in press, for review). According to a recent model developed by Ernst and Banks (2002), the combination of haptic and visual inputs acts like a maximum likelihood integrator. An implication of this approach is that the weight given to a modality is commensurate with the variance in estimation it provides. The assigned weight will decrease as noise is added to an input, rendering it less reliable. (See van Beers, Sittig, & Denier van der Gon, 2002, for a similar model.)

In work on length perception using the discrepancy paradigm, a general trend has been for visual inputs to dominate (Kinney & Luria, 1970; Rock & Harris, 1967; Teghtsoonian & Teghtsoonian, 1970). According to the model of Ernst and Banks (2002), this should arise if haptic length perception is less reliable than with vision. In keeping with this prediction, a number of studies have found high error levels in haptic length perception, in either an absolute or relative sense (e.g., Day & Wong, 1971; Fasse, Hogan, Kay, & Mussa-Ivaldi, 2000; Hollins & Goble, 1988; Lederman, Klatzky, & Barber, 1985; Milewski & Iaccino, 1982; Teghtsoonian & Teghtsoonian, 1970). Of particular interest for present purposes is the accuracy in reproducing a movement that was previously performed. When memory for the moved distance is divorced from memory for the endpoint (e.g., by shifting the starting point between the criterion movement and reproduction), performance is generally poor, especially relative to memory for the location of the movement endpoint (e.g., Jaric, Corcos, Gottlieb, Ilic, & Latash, 1994; Marteniuk & Roy, 1972; Laabs, 1973; see Smyth, 1984 for review).

Another situation in which visual/haptic (particularly visual/kinesthetic) interactions are observed is the recalibration paradigm. In this situation, visual feedback concomitant with self-motion is altered, e.g., by having a person walk on a treadmill that is transported at a fast or a slow speed (akin to walking on the “people mover” at an airport). The change in visual feedback has been found to lead to rapid recalibration of kinesthetic cues. Rieser, Pick, Ashmead, and Garing (1995) found, for example, that when people were exposed even for a short time (8 min) to speeded optical flow while walking, they subsequently overestimated the length of a footstep when walking without vision, leading to undershooting targets. This effect persisted over eight trials without further feedback.

In the present article, we introduced discrepant visual input during a movement and asked to what extent it distorted subsequent reproduction. Using a programmable mouse with resisting forces, participants in our experiments were guided along a straight trajectory, which they then attempted to reproduce. The gain on the cursor relative to the mouse was varied, potentially producing distortion in the representation of the movement. (The reader can easily simulate this situation by moving a mouse a constrained distance while watching the screen and while looking away.)

Our paradigm differs from the usual perceptual discrepancy study, in that whereas the inputs are discrepant, they clearly come from different sources. No effort is made to persuade the participant that the visual and haptic experiences come from exploring the same object; indeed, the user is aware that longer movements

occur on the screen than those felt in the hand. Unlike the recalibration paradigm, no effort is made to simulate a natural linkage between movement and optical flow—although the movement of the cursor is temporally linked to the arm movement, it is clearly differentiable from sight of the arm. Accordingly, the question arises as to whether visual/haptic interactions will arise, and if so, of what sort.

Interactions can be expected because in general, vision during a movement acts productively to tune subsequent movement, a phenomenon called *off-line visual processing* (Elliott, Helsen, & Chua, 2001; Khan et al., 2003). It may be natural to use visual feedback concomitant with movement to guide subsequent performance, even when a direct physical link is not portrayed.

We considered two hypotheses in this regard. First, sight of the cursor may produce visual dominance as in the usual discrepancy paradigm, causing the participant to perceive and/or remember a distance as being longer than its objective magnitude. This would lead to the reproduction movement’s being longer than the distance originally moved, and the degree of overestimation would be expected to increase with the gain factor.

Alternatively, the cursor movement may lead to recalibration of haptic cues from the arm movement, so that a given kinesthetic signal is associated with a longer distance moved. If participants were to accurately encode the target distance but subsequently inflate the distance associated with kinesthetic feedback, they would underrespond in the haptically guided reproduction phase of the task. For such recalibration to occur, the sight of the cursor would have to function like seeing one’s hand move. This possibility gains some credibility from studies indicating the transfer of apparent sensation from viewed surrogate hands to one’s own (Botvinick & Cohen, 1998).

At least in theory, people could avoid being misled by the gain on the visual cursor, thus avoiding error. One possibility would be to ignore the visual input and to rely entirely on memory for the haptic (primarily kinesthetic) cues and efferent commands accompanying the movement. Research reviewed above suggests, however, that the kinesthetic system supplies only limited cues for movement reproduction, and this lack of reliability appears to make people susceptible to distortion under discrepancy conditions. Moreover, recalibration arises even when participants are aware of distorted visual cues.

Participants might be able to turn even distorted cues to their advantage if they could detect the degree of visual distortion and compensate for it to achieve constancy. There are two types of cues to distortion that they might use: First, they might directly detect the variations in the mapping from the visual display to haptically perceived distance. Second, the visual display might provide a direct cue to distortion in terms of the rate of cursor movement. The cursor should visibly move faster under a higher gain unless participants compensated for the gain and kept the cursor speed constant. To assess the extent to which participants could detect variability in the visual:kinesthetic mapping and compensate for it, in Experiment 1 we questioned them as to whether they had noticed the gain variations and in Experiment 2 we deliberately warned them about potential changes in gain. To assess whether participants kept the cursor speed constant, which would eliminate direct visual cues, we recorded kinematic data from their initial path exploration.

Experiment 1

In this experiment, participants were exposed to force-defined paths accompanied by visual feedback that had a varying relation to the actual distance moved by the hand (gain). There was also a no-vision control. Participants were not informed of the variation in the feedback. They were told that their goal was to first feel a haptic path and then duplicate the path length that they felt and that on some trials they would see a cursor accompanying the movement.

Method

Participants. The participants were 13 university students who participated for credit. All were right handed by self-report.

Stimuli and apparatus. The haptic stimuli were 10 paths, varying in length from 8.8 mm to 16.7 mm in increments of 0.9 mm (variations in step size arose from pixel conversion). They were presented by means of the Wingman mouse (Immersion Corp.). The mouse measured 104 mm long \times 74 mm wide and was 35 mm high at the apex. It slid on a planar base, on which it had a range of movement of 2.2 cm in the *x* direction (frontal) and 1.8 cm in the *y* direction (sagittal). Further movement was prevented by a tether. All paths were oriented along the *y* axis and were directed from proximal to distal relative to the observer.

To feel a path, the participant was seated in front of the computer visual display. His or her right arm entered a box with a curtain on the front so that the hand and wrist were not visible. The box was placed so that the mouse was aligned with the participant's shoulder and lay 20 cm above the surface of the desk holding the computer. The right hand grasped the mouse.

The algorithm for presenting a path was implemented in C++, using the Immersion Foundation Class library. The mouse was programmed to restrict its cursor movement to the area within a rectangular enclosure (i.e., the path) 0.5 mm wide and of varying length. Within each trial, the mouse cursor always originated at the proximal end of the enclosure, equidistant from each side wall. The edges of the enclosure were delineated by resistive "walls" that pushed the mouse back onto the path if it deviated. That is, if the mouse moved to the perimeter of the enclosure or beyond, it encountered a resistive spring that was perpendicular to the path and directed toward it. The maximum forces generated are on the order of 1 Newton (per private communication with Immersion Corp., June, 2003). If the mouse cursor went more than 0.7 mm beyond the center of the enclosure, a vibration was added to signal the error. Inside the enclosure, the cursor could move freely, subject to the friction between mouse and base.

Participants moved the cursor freely along the length of the path until the end point was reached; no instructions were given about movement speed. At the endpoint, the mouse vibrated to indicate that the end had been reached, and further mouse movement in any direction was restricted by the resistive force.

As the participant felt the path, on some trials the computer displayed a visual cursor that moved upward. The screen size was 31 \times 24 cm, and the initial cursor position was 2.0 cm above and 10.8 cm leftward from the bottom right corner of the screen. The cursor movement was related to the mouse movement by one of three levels of gain, that is, the ratio of movement of the cursor to movement of the mouse. A 1:1 gain was not considered feasible because of the very limited range of motion of the mouse. The lowest gain level (Level 1) was a ratio of 8.0 mm of visual cursor movement to 1 mm of mouse movement. Gain Levels 2 and 3 had ratios of 10.7 mm and 13.4 mm, respectively. There was also a no-vision control, in which no visual cursor appeared.

Responses were made without experimenter-imposed force feedback or a tether to limit the response distance. There was also no visible cursor. The responses were made with a response "mouse," which was placed 13 cm

directly below the Wingman mouse so that it was vertically aligned with the starting position of the Wingman mouse. The shelf holding the Wingman mouse lay above the response mouse and obscured the participant's view of his or her wrist and hand during the response. The response mouse was actually a pointer linked to a CalComp digitizing tablet with 0.1-mm resolution. As designed, the pointer is a crosshair in a rectangular manipulandum. For these purposes, however, a half-ellipsoid-shaped appendage made of plastic-covered styrofoam was attached to the manipulandum, and this was held as if it were a mouse. The appendage measured 85 mm long \times 60 mm wide and was 30 mm high at the apex. The crosshair was located 60 mm from the proximal end and 18 mm from the right side. Mounted 20 mm beyond the distal end of the appendage were four buttons, any of which could be used for making the response.

Design and procedure. Each of the 10 path lengths was combined with each of the gain conditions (1, 2, 3, and control), and the resulting 40 trials occurred in random order within each of three replications, for a total of 120 trials. There were an additional 10 practice trials at the beginning of the experiment, with varied gain and distance. A trial began with the participant placing his or her hand on the Wingman mouse inside the curtained box and clicking the left mouse button. At that point, the cursor appeared in its initial position on the screen, unless it was a control trial. The participant then followed the path as described above until the end point was felt by the vibration. He or she then moved the hand down to the response mouse and clicked any button to start, causing the cursor to disappear if it was present. The participant then moved the response mouse so as to duplicate the initial movement and clicked one of the response buttons to indicate that the path had been completed. The position of the crosshair on the digitizer was recorded at each click and sent to the computer.

At the end of the experiment, participants were interviewed to see if they noticed the different gain values. If they did not volunteer the information, they were asked. Only 4 participants indicated that they had noticed the gain; a fifth said, when queried, that she was "suspicious." However, there was no apparent difference in the data from these participants.

Results and Discussion

Mouse Kinematics

The mouse position during the exploratory phase of the trial, where the path was followed, was recorded at 50 Hz. Participants had little trouble following the paths, as shown in Figure 1, which shows typical trajectories. (There was one obviously deviant trajectory for which kinematic data were eliminated.) The velocity profiles varied within and between participants; three samples are shown in Figure 2. These figures suggest that although there were substantial variations in the speed trajectory along the path, little noise was introduced into the representation of path distance by orthogonal deviations from the path.

From the position record, the duration of the movement and its average speed (based on the distance between consecutive readings) were determined. These data are shown by gain condition for both experiments in Table 1. Results of analyses of variance (ANOVAs) on duration and speed, with factors of stimulus distance and gain, are shown in Table 2. The effect of increasing distance was to increase both the duration of the movement and the average speed. The average speed was 18.4 mm/s at the shortest distance and 24.7 mm/s at the longest, an increase of 34%; the average duration was 1.1 s at the shortest distance and 1.6 s at the longest, an increase of 45%.

As shown in Table 1, duration increased and speed decreased across the three levels of visual gain; however, the effect sizes for

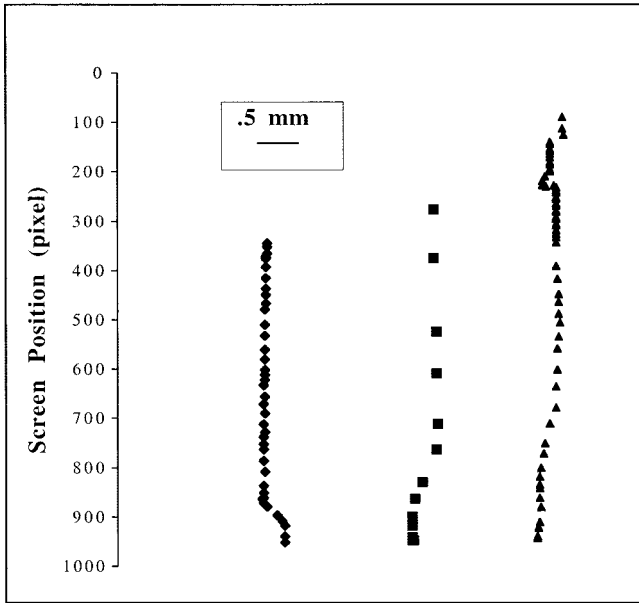


Figure 1. Sample trajectories from 3 participants in Experiment 1 with 3 different path lengths. The x-axis has been displaced for clarity. The zero pixel value is the top of the screen; motion was upward. Observations occur every 20 ms.

Table 1
Mean (and Standard Deviation over Participants) of the Duration (in s) and Speed (in mm/s) During the Initial Path Exploration by Experiment and Gain Condition

Condition	Experiment 1		Experiment 2	
	Duration	Speed	Duration	Speed
Control	1.42 (.76)	22.23 (9.30)	1.47 (.74)	21.59 (8.32)
Gain = 8.0	1.27 (.68)	24.73 (10.11)	1.37 (.76)	23.16 (9.25)
Gain = 10.7	1.32 (.76)	23.66 (9.84)	1.44 (.80)	23.06 (9.79)
Gain = 13.4	1.43 (.80)	23.08 (10.32)	1.55 (.94)	22.17 (9.68)

gain were small. The no-vision control condition was similar in duration to the highest level of visual gain. In neither the duration nor the speed ANOVA was the gain effect altered by distance.

It appears that participants compensated to a small extent for faster movement of the visual cursor by slowing down their mouse movement. Participants did not, however, fully compensate for gain so as to make the visual cursor speed constant. To make the visual cursor move as quickly at gain = 1 as at gain = 3, the mouse speed would have to increase by 67%. However, the observed increase in speed was only 7%. The lack of full compensation means that the visual cursor moved faster at higher gain. These variations in speed of visual movement might have been a direct cue to the differing gain factors in addition to the cue of the visual:haptic perceived distance ratio. However, neither the move-

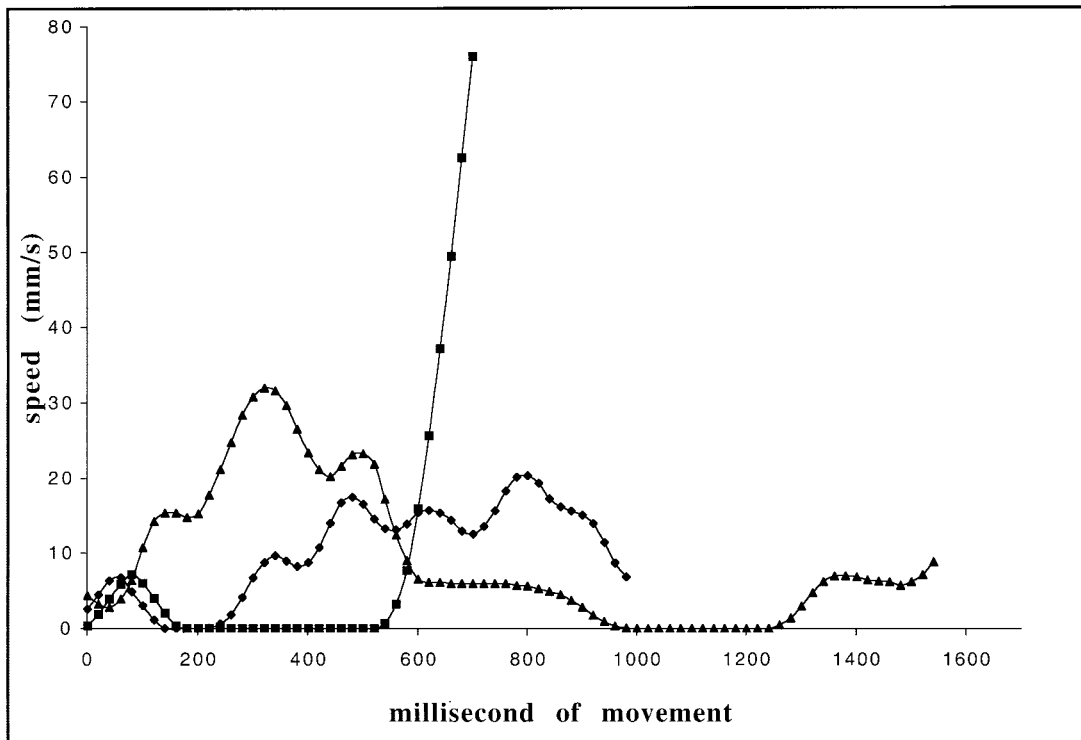


Figure 2. Velocity profiles for the same 3 participants performing the same trials as in Figure 1 (diamonds, squares, and triangles match the corresponding symbols in Figure 1). The data have been smoothed with a triangular filter having a window size of seven.

Table 2
Results of Analyses of Variance in Experiment 1 on Duration and Speed of Initial Mouse Movement

Source	Duration				Speed			
	df	MSE	F	Cohen's <i>f</i>	df	MSE	F	Cohen's <i>f</i>
Distance	9	1.59	9.77**	.41	9	0.17	12.35**	.46
Error (distance)	108	0.16			108	0.01		
Gain	3	0.78	3.58*	.14	3	0.06	6.79**	.20
Error (gain)	36	0.22			36	0.01		
Distance × gain	27	0.06	0.70	.19	27	0.00	0.48	.16
Error (distance × gain)	324	0.09			324	0.00		

* $p < .05$. ** $p < .01$.

ment ratio nor the observable speed was sufficient to achieve accuracy of the movement at reproduction, as is reported next.

Distance Responses

The average stimulus distance was 12.7 mm. The average response distance in the control condition (no visual stimulus) was 13.4 ($SD = 3.6$), which only slightly (by 6%) overestimated the actual distance value. This overall overestimation was not significant, as the 95% confidence interval around the mean included the average stimulus distance. The average response distance for gain levels 1–3 was 16.4 ($SD = 4.3$), 18.8 ($SD = 5.3$), and 21.8 mm ($SD = 6.1$), respectively. Thus at the highest gain level, participants' responses were more than 70% longer than the objective value and 63% longer than the control, and this percentage overestimation varied relatively little with distance.

Figure 3 (left panel) shows the relation of response distance to stimulus distance for each level of gain (including the control). As can be seen in Figure 3, the reproduced distance increasingly departed from the original distance as gain increased, and the magnitude of the difference tended to increase with the stimulus distance. The control condition also showed some compression of the range of response relative to the stimulus values, a common psychophysical effect (Poulton, 1979). Results of an ANOVA on stimulus distance and gain are shown in Table 3. Both factors produced a large effect size, and the magnitude of the gain effect tended to increase with the stimulus distance.

The effect of stimulus distance reflected both haptic and visual length of the stimulus, which are highly correlated when vision is present, $r(28) = .69, p < .01$. Simple correlations (excluding the no-vision control) showed that the response distance was corre-

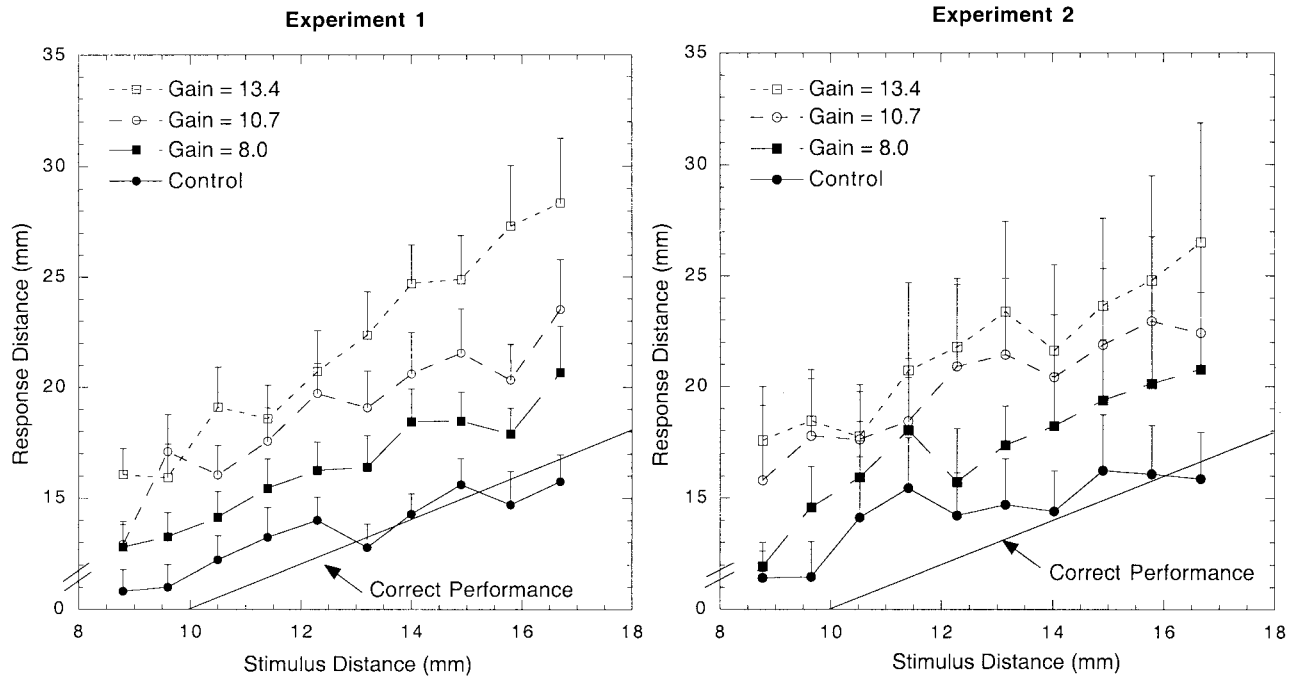


Figure 3. Response distance as a function of stimulus distance for each gain level in each experiment. Error bars represent +1 SEM.

Table 3
Results of Analysis of Variance on Response Distance in Experiment 1

Source	df	MSE	F	Cohen's <i>f</i>
Distance	9	424.76	40.17**	.83
Error (distance)	108	10.57		
Gain	3	1647.06	42.52**	.50
Error (gain)	36	38.73		
Distance × gain	27	24.83	2.95**	.39
Error (distance × gain)	324	8.42		

** $p < .01$.

lated more strongly with the visual distance, $r(28) = .94$, than with the haptic distance, $r(28) = .77$, $ps < .01$. To quantify the separate contributions of the haptic and visual modalities, we first regressed the response distance on visual distance and then regressed the residuals on haptic distance. The initial regression of the response on visual distance had a standardized beta coefficient of .96, $t(28) = 18.40$, $p < .01$, $R^2 = .92$. The second regression, which indicates the effect of the haptic distance when the visual distance has been accounted for, had a standardized beta coefficient of .11, $t(28) = 2.38$, $p < .05$, $R^2 = .17$. Thus there was a significant effect of haptic distance beyond that of visual distance.

In short, there was a substantial distortion of reproduction movement due to the gain on the visual cursor. Observed cursor movement controlled the response more than physical movement of the hand did. Without the cursor, participants were accurate overall at the task.

Experiment 2

Method

Perhaps participants in Experiment 1 could have achieved distance constancy across the visual cursor conditions if they had been fully aware of the potential for distortion. To test this idea, we performed Experiment 2, which was identical to Experiment 1 except that the participants were told that the visual feedback might vary. Specifically, they were told that the cursor would always move by some proportion of their movements, but the proportion would change. They were told that the goal of the experiment was for them to duplicate the initial distance the hand moved, but not to be fooled by the cursor. However, they were instructed to look at the cursor.

Aside from the instructions, Experiment 1 was identical to Experiment 2. The participants were 12 students who participated in exchange for credit. All were right-handed by self-report. None had taken part in the prior experiment.

Results

Mouse kinematics. Again, one trial was eliminated from the data set because of aberrant mouse movement. The effects of distance and gain on duration and speed were similar to those of Experiment 1. However, results of ANOVAs on these measures, shown in Table 4, indicate that only distance was significant. The average speed was 18.2 mm/s at the shortest distance and 28.0 mm/s at the longest, an increase of 53%. The average duration was 1.1 s at the shortest distance and 1.9 s at the longest, an increase of 72%. The gain effects are shown in Table 1 (right panel). As was noted above, the fact that participants did not significantly adjust the mouse speed according to gain means that there would have been different visible speeds in the different gain conditions. These could potentially have been used to achieve constancy, along with the ratio of visual cursor movement to mouse movement. However, distance errors were substantial, as described next.

Distance responses. The average stimulus distance was again 12.7 mm. The average response distance in the control condition (no visual stimulus) was 14.4 ($SD = 6.6$), which again overestimated the actual distance value (by 13%), but not significantly overall (by confidence interval test). The average response distance for gain levels 1–3 was 17.2 ($SD = 8.0$), 20.0 ($SD = 10.9$), and 21.6 mm ($SD = 12.0$), respectively. These mean values are very similar to those of Experiment 1 (see statistical comparison below). Thus, at the highest gain level, participants' responses were again approximately 70% longer than the objective value and 50% longer than the control. Compared with data in Experiment 1, however, the data were more variable, presumably because participants were adopting strategies to mitigate against the cursor gain.

Figure 3 (right panel) shows the relation of response distance to stimulus distance for each level of gain (including the control). Results of an ANOVA on stimulus distance and gain are shown in Table 5. As can be seen in Figure 3, as gain increased there was increasing departure of the reproduced response from the original movement, and this effect was not significantly altered by distance.

As in Experiment 1, to quantify the separate contributions of the haptic and visual modalities, the response distance was first re-

Table 4
Results of Analyses of Variance in Experiment 2 on Duration and Speed of Initial Mouse Movement

Source	Duration				Speed			
	df	MSE	F	Cohen's <i>f</i>	df	MSE	F	Cohen's <i>f</i>
Distance	9	2.85	14.61**	.52	9	0.17	6.03**	.33
Error (distance)	99	0.20			99	0.03		
Gain	3	0.61	1.63	.10	3	0.03	0.93	.08
Error (gain)	33	0.38			33	0.03		
Distance × gain	27	0.07	1.02	.24	27	0.02	0.74	.20
Error (distance × gain)	297	0.07			297	0.02		

** $p < .01$.

Table 5
Results of Analysis of Variance on Response Distance in
Experiment 2

Source	<i>df</i>	<i>MSE</i>	<i>F</i>	Cohen's <i>f</i>
Distance	9	266.38	10.94**	.45
Error (distance)	99	24.35		
Gain	3	1211.14	14.43**	.30
Error (gain)	33	83.92		
Distance × gain	27	12.79	1.18	.26
Error (distance × gain)	297	10.88		

** $p < .01$.

gressed on visual distance, and then the residuals were regressed on haptic distance. The regression of the response on visual distance had a standardized coefficient (beta) of .94, $t(28) = 14.80$, $p < .01$, $R^2 = .89$. The second regression, which indicated the effect of the haptic distance when the visual distance had been accounted for, had a standardized beta coefficient of .36, $t(28) = 2.02$, *ns*, $R^2 = .17$. Visual distance clearly dominated the response despite participants' being informed of the potential distortion.

Comparison of experiments. The two experiments were compared using *t* tests with respect to several variables: mean response distance at each gain, $t(23) = .46$ for the control and .32, .33, and .05 over increasing gain levels; mean duration of mouse movement during exploration, $t(23) = .32$; and mean speed of mouse movement during exploration, $t(23) = .25$. None of these comparisons approached statistical significance.

General Discussion

The present data indicate an important new context in which previously documented dominance of visual over haptic cues has profound effects. The experiments demonstrate a substantial overestimation error in reproducing a movement when the initial movement was coupled with a visual display having a gain greater than 1:1. The error increased with the magnitude of the visual gain, and it was essentially the same whether participants were informed about the potential distortion or not. These results are in keeping with a variety of data on the level of precision in human kinaesthesia and the relative dominance of vision over haptics in spatial tasks, as reviewed in the introduction.

The overestimation error that was observed supports the hypothesis that visual feedback distorted the haptic representation of distance used for the reproduction response. An alternative hypothesis, that visual feedback during the exploration phase recalibrates the mapping from kinesthetic cues to distance, was not supported. The distortion of perceived distance could occur as the initial path is explored, and/or visual memory traces could influence the path representation during processes of encoding into memory or retention. We note informally that our own experience suggests a perceptual locus, in that when the cursor is withdrawn, one is surprised at how small the movement suddenly seems to be. To further address the role of memory, an experiment could systematically manipulate the response delay.

There are various ways in which more accurate performance could have been attained in this task. (a) Participants could have relied completely on the kinesthetic input. The control condition,

in which there was no visual cursor, indicates that participants would have substantially reduced systematic error if they had ignored the visual display. Apparently they did not. (b) Even if visual cues were assimilated, more accurate performance could have been achieved by estimating the gain and discounting the visual input by that amount.

There were two cues that might be used to estimate gain in the present situation as described above: One would be the ratio between distance values that were perceived from vision and haptics. The second cue arises because although participants slowed their initial movement in response to higher gain, they did not fully compensate, so that the differential speed of the visual cursor would have been a direct indication of the gain.

Had these cues been assimilated, and had the resulting discounting computation been accurate, then the participants would have achieved constancy across the visual gain conditions. Again, they did not. The implications, then, are that visual input was taken into account, that discounting was not successful so that visual cues affected the magnitude assigned to the haptic input, and that the response erred as a result. In fact, the regressions indicate that the visual input dominated the response.

These results have implications for applied situations in which haptically guided motor tasks are accompanied by spatially coupled visual input with a scaling difference and vision is then withdrawn. For example, during telemanipulation, a monitor displays a remote interaction between a tool and contacted objects in order to afford online visual control. The monitor may magnify the physical system so that the gain is $>1:1$, as in the present studies. If malfunction or occlusion causes the loss of visual input, movement must be guided by kinesthetic perception and memory, which according to present results, could be distorted by the gain in the immediately preceding visual display.

One may question whether the magnitude of the gain-induced distortion found here would be meaningful in applied contexts. The effect sizes were moderate to large in a statistical sense, but a gain manipulation of 13.4:1 produced only a 70% increase in movement reproduction. It is worth noting that the magnitude of the gains used here is consistent with those that commonly occur during laparoscopic surgery. For example, magnifications during gynecologic surgery can be as high as 30× (Reproductive Science Center of the San Francisco Bay Area, 2003), and robot-controlled prostatectomy has been performed at magnifications of 4–10× (University of California School of Medicine, 2002). A 70% error in manipulating a surgical device, due to sudden loss of visual input, could have important consequences.

In practice, however, mitigating circumstances are likely to reduce or eliminate error. In many contexts the visual input is robust and continuous, in which case visually guided movements should be stably calibrated. Alternatively, there may be physical landmarks present when vision is withdrawn that convey haptic cues (e.g., mechanical stops or natural boundaries such as a change in tissue). Other cues, such as symbolic displays or auditory feedback, could be used to augment haptic control of movement, even when vision is present.

Experienced teleoperators may also adjust to differential gain, especially when feedback is presented. Such an effect was observed by Ferrel et al. (2000) in the previously described task of reaching within a magnified scene. The effect of gain vanished after four trials when feedback was provided and the magnification

was held constant. However, it persisted over 10 trials when magnification varied from trial to trial, even with feedback.

A number of research issues merit further study on the basis of these results. One is the time-course of the distortion: Would a delay between visual exposure and test reduce the gain effect, or would it even heighten it? How closely must the mouse movement be linked in time and space to the hand movement in order for distortion to occur? Will participants who are extensively trained with feedback about errors become fully accurate? Are larger scale movements, which might provide stronger kinesthetic cues, similarly vulnerable to visual distortion? We are currently addressing the fourth issue with a similar experiment using a larger scale force-feedback device. The answers to these questions will not only expand our understanding of haptically and visually guided motor control, but they will have further implications for applied settings.

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