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Visual Short-Term Memory Is Influenced by Haptic Perception

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The present study investigated whether and how visual memory and haptic perception are related. Participants were required to compare a visual reference velocity with a visual test velocity separated by a 4-s interval. During the retention interval, a fast or slow hand movement was performed. Although the hand movement was not visible, effects of the speed of the distracting body movement occurred. Slow movements resulted in a lowering of the represented visual velocity, whereas fast movements heightened the represented velocity. Subsequent experiments extended the effect to body movements that differed from the visual motion and ruled out the possibility that the effect was due to changes in visual perception or interference from semantic, verbal, and acoustic memory codes. Perhaps haptic velocity information and visual velocity information stored in short-term memory are blended.

Visual short-term memory has been studied extensively. Particular attention has been devoted to the short-term retention of position and velocity. Although visual memory is surprisingly accurate, a number of processes have been identified that interfere with the storage of visual information. In the present series of experiments, it is suggested that the perception of velocity information in the haptic modality interferes with visual short-term memory. When participants were asked to perform a slow or fast body movement while retaining velocity information in visual short-term memory, the remembered visual velocity showed a shift toward the haptically perceived velocity. The intermodal visual–haptic interference is consistent with recent findings showing that visual and somatosensory perception are tightly coupled. In order to claim that changes in visual memory are due to haptic perception, intermodal interference has to be contrasted with other processes known to interfere with visual short-term memory. Generally speaking, three processes have been identified that may disrupt short-term memory.

First, visual information kept in short-term memory may be influenced by high-level cognitive mechanisms, such as implicit or explicit knowledge about physical principles. For instance, Freyd and Finke (1984, 1985) showed that observers who had seen successive views of a rotating rectangle judged an orientation slightly past the orientation of the final view as being the same as the last-seen orientation. Freyd and Finke's explanation of this effect was that the implied motion of the object was mentally extrapolated into the future. As the extrapolation cannot be stopped with the last presentation (representational momentum), a forward shift results. Hubbard demonstrated that mental representations of the final position of a moving target may be influenced by physical principles other than momentum, such as gravity, friction, mass, and context (see Hubbard, 1995, for an overview).

More information about ongoing work on this and related topics may be found at www.mpipf-muenchen.mpg.de/~kerzel.

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Second, Loftus showed in a classic series of studies (Loftus, 1979; Loftus, Miller, & Burns, 1978) that misleading verbal information presented after an event to be remembered impairs memory reports of the event (Loftus, 1977, 1979; Loftus & Palmer, 1974; but see McCloskey & Zaragoza, 1985, for a different view). In a typical experiment of Loftus and colleagues, participants viewed a sequence of slides depicting an event such as a traffic accident or a theft. Participants in the misled condition received distracting (wrong) postevent information about a critical detail in a written narrative of the event. The misled participants were more likely to accept the distractor item as having occurred in the original event than participants who had not received wrong postevent information. Loftus and colleagues claimed that the original visual item and the verbal distractor were blended in memory, thus impairing memory of the event (Loftus, Schooler, & Wagenaar, 1985). Evidence for blended memories was found when critical details concerned the colors of objects (Loftus, 1977) or their velocity (Loftus & Palmer, 1974).

Third, visual distractors may influence the short-term retention of velocity information. Magnussen and Greenlee (1992; Greenlee, Lang, Mergner, & Seeger, 1995) asked participants to remember the velocity of a drifting sine-wave grating and to compare it with the velocity of a second test grating presented at the end of retention intervals ranging from 1–30 s. Discrimination thresholds were independent of retention interval. However, discrimination thresholds increased after a third distractor grating moving at a different velocity was inserted between the test and the reference gratings. The disruption of visual short-term memory increased with the deviation of the distractor velocity from the reference velocity but was independent of the direction of motion.

The previously cited examples demonstrate that visual short-term memory is susceptible both to distracting information presented in the same modality as well as to conceptual and verbal distractors. The goal of the present study was to examine whether there is cross-talk between visual short-term memory and haptic perception and to work out whether the cross-talk is related to factors known to influence visual short-term memory. In support of a tight coupling of the two systems, it has been demonstrated that the human visual cortex is implied in tactile perception in both blind and sighted people (L. G. Cohen et al., 1997; Sadato et al., 1996; Sadato et al., 1998; Zangaladze, Epstein, Grafton, & Sathian, 1999). However, haptic and visual memory codes are generally thought of as being distinct because haptic memory, in contrast to visual memory, does not require central processing capacity (Broadbent, 1958; Posner, 1967; Stelmach & Wilson, 1970). Thus, the interdependence of visual and tactile perception would suggest interrelations of visual memory and haptic perception, whereas the independence of visual and haptic memory favors a separation of the two systems.

Experiment 1A

The purpose of the first experiment was to establish whether haptic perception interferes with visual short-term memory. A two-alternative, forced-choice procedure was used to probe visual short-term memory. Participants had to judge whether velocities presented with a temporal separation of 4 s were the same or different. During the retention interval, one of two distracting movements had to be performed. Either a fast or a slow lateral hand movement was required. If haptic and visual systems were interrelated, I expected the representation of the visual velocity to be influenced by the haptic information about the velocity of the hand movement. A strict separation of the two systems, on the other hand, would predict no effect of the haptic distractor.

Method

Participants. Nine students at the Ludwig-Maximilians-University of Munich, Germany, were paid for their participation. All participants reported normal or corrected-to-normal vision and no motor impairments. None of the participants was informed about the purpose of the study.

Apparatus. Stimuli were generated by a Matrox Millenium graphics adapter at a resolution of 1280H × 1024V pixel and were presented on a 40H × 30V-cm screen with a refresh rate of 60 Hz. Movements were recorded by a CalComp Drawing Board III with an accuracy of 394 lines per cm. The graphics table was covered by a wooden board that contained a 1 × 16-cm rectangular aperture. Inside the aperture, a narrow 15-cm opening in a plastic sheet attached to the board guided the tip of the drawing pen. The hand and arm holding the pen were covered by a board such that the movements performed were invisible to the participant (see Figure 1).

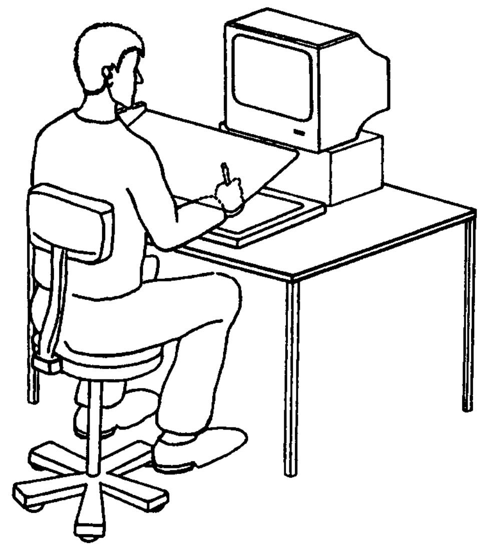

Figure 1. Experimental setup. Participants performed lateral hand movements on a graphics table. The movements were hidden from the observer by means of a board. The monitor was placed behind the graphics table.

Stimuli. A white rectangular frame similar to the aperture on the graphics table surrounded the trajectory of the target. The right edge of the frame was at the center of the screen. The target moved from left to right inside the frame until it reached the inner right edge of the frame. Three velocities were used: 7.0, 9.4, and 11.8 cm/s. To make the start of the motion look smooth, a brief acceleration phase with a logistic velocity profile was added (see Figure 2). Constant velocity was reached after approximately 1 s such that more than half the 15-cm trajectory was passed at a constant velocity. No attempts were made to suppress pursuit eye movements. Thus, velocity information was gained either from induced background motion when the eye followed the target or from motion of the target with respect to the background.

Design. Three reference velocities of 7.0, 9.4, and 11.8 cm/s and five test velocities that differed from the respective reference velocity by ±2.4, ±1.2, and 0 cm/s were used. The interfering movements were faster or slower than the visually presented reference velocities. Reference, probe, and interfering movement were fully crossed, and each condition was shown once in each of four consecutive blocks for a total of 120 trials.

Procedure. The drawing board was placed in front of the participants at a height that allowed for comfortable drawing movements. Behind the drawing board, the monitor was positioned slightly higher than the drawing board. The participants were seated approximately 70 cm from the monitor. At the start of each trial, the stylus had to be placed in its starting position at the left edge of the aperture on the drawing board. Exact positioning was achieved by aligning a blue pen-controlled disk with a stationary white disk (the target) on the screen. After the two disks had been aligned for 1 s, the blue disk disappeared and the target started to move from the left edge of the frame to the right at one of the three reference velocities. When it reached the end of the trajectory, it disappeared and an auditory signal indicated which movement was to be performed. A high-pitched beep had to be responded to by a fast movement and a low-pitched beep by a slow movement. Informal observation of participants' behavior suggested that assigning high pitch on fast responses and low pitch on slow responses was a compatible mapping (Fitts & Seeger, 1953); that is, it was easier to perform. In order to reduce memory load, the compatible mapping was used. Responses with an average velocity lower than 7.0 cm/s and higher than 11.8 cm/s were accepted as slow and fast responses, respectively. If the mean velocity of the movement was outside the acceptable range or if the movement was initiated later than 1.5 s after the auditory signal, an error message appeared and the trial was repeated at a random position in the remainder of the block. Four seconds after the imperative beep, the target reappeared at the left edge of the frame and moved from left to right at one of the five test velocities. Finally, participants were asked to press one of two keys to indicate whether they thought that the probe velocity was the same as the reference velocity or differed from it. Before starting the experiment proper, participants were trained to respond to the high- and low-pitched beeps with fast or slow movements and were given approximately 15 practice trials.

Results

Mean proportion "same" judgements are graphed in Figure 3. The interfering movement was outside the required range in 3.8% of the trials. A Scheffé test ($p < .05$) showed that observers were able to discriminate between the physically identical velocity and velocities differing by ± 2.4 cm/s. To identify the influence of the interfering movement, test velocities were grouped according to the sign of the deviation from the reference velocity. That is, trials

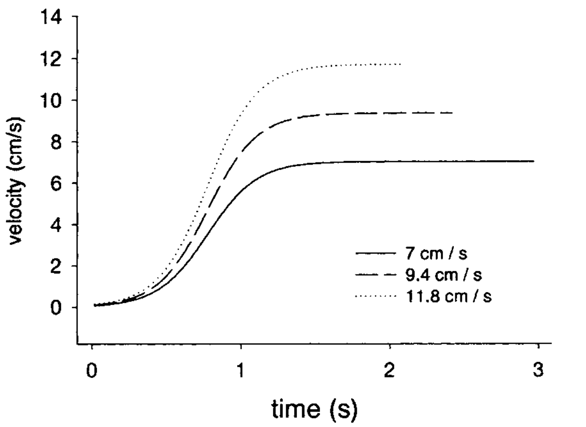

Figure 2. Velocity profiles used in Experiments 1–4. The onset of the motion was smooth.

with test velocities slower (–2.4, –1.2 cm/s) and faster (+2.4, +1.2 cm/s) than the reference velocity were combined. A two-way analysis of variance (ANOVA) revealed a significant interaction of interfering movement and sign of the test velocity deviation, $F(1, 8) = 28.69$, $p < .001$. With a slow interfering movement, more "same" judgments were given with slower test velocities than with faster test velocities (.58 vs. .37), indicating that the point of subjective equality (PSE) was lower than physical equality. In contrast, with a fast interfering movement more "same" judgements were given with higher than with slower test velocities (.63 vs. .41), indicating a shift of PSE in the opposite direction.

Discussion

The results show that haptic perception of body movements interferes with visual short-term memory. When a fast movement had to be performed during the retention interval, the PSE was shifted toward the velocity of the limb movement. That is, more "same" judgements were obtained for test velocities that deviated from the reference velocity in the same direction as the limb movement. Before interpreting this effect any further, an alternative explanation of the effect had to be tested: In order to reduce memory load, I selected a compatible mapping of imperative stimulus and response. High-pitched tones had to be responded to by a fast movement and low-pitched tones by a slow movement. Thus, the effects of tone and movement would be confounded. To rule out the possibility that the presentation of a single high- or low-pitched tone produced the effect, the tone was presented but no hand movement had to be performed.

Experiment 1B

Method

Participants. Nine students at the Ludwig-Maximilians-University of Munich who fulfilled the same criteria as those in Experiment 1A participated in the experiment.

Apparatus, stimuli, design, and procedure. The apparatus, stimuli, design, and procedure were the same as in Experiment 1A, with the exception that no movement had to be performed during the retention interval.

Results

Mean proportion "same" judgments are graphed in Figure 4. A Scheffé test ($p < .05$) showed that observers were able to discriminate between physically identical test velocities and test velocities differing by ± 2.4 cm/s. A two-way ANOVA (Interfering Movement × Sign of Test Velocity Deviation) yielded no significant effect. It was important that the interaction term was far from significant ($p > .75$).

Discussion

On the basis of the present experiment, the possibility that the presentation of a single high- or low-pitched tone interferes with visual short-term memory can be rejected. Rather, it appears to be the case that the haptic perception of body movements changed the representation of visually presented motion. This result supports

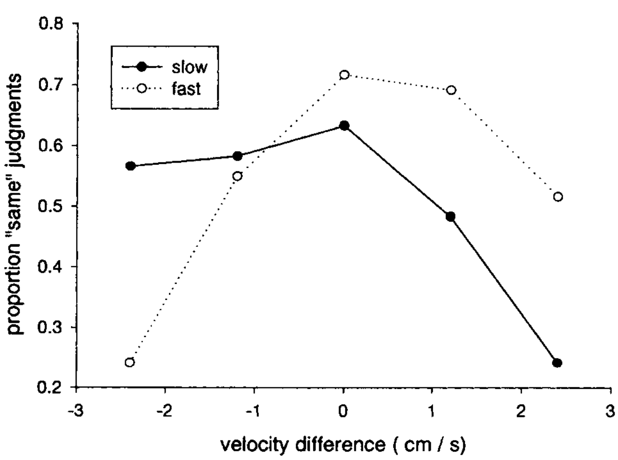

Figure 3. Mean proportion "same" judgments as a function of test velocity and velocity of the hand movement in Experiment 1A.

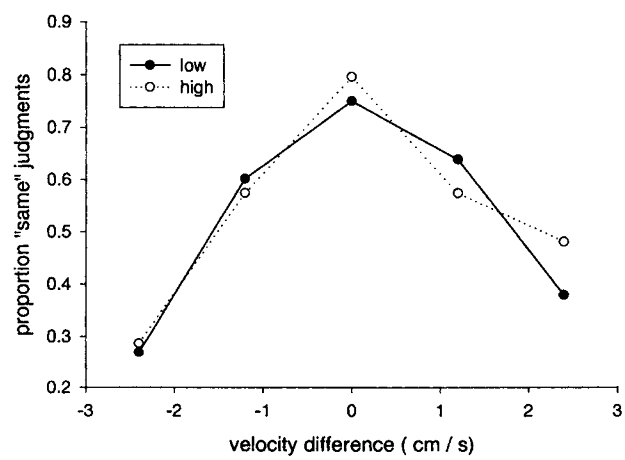

Figure 4. Mean proportion "same" judgments as a function of test velocity and pitch in Experiment 1B.

the view that tight links exist between the processing of somatosensory stimulation and visual memory. Similar to cross-modal interference of transcranial magnetic stimulation applied to the visual cortex in a tactile discrimination task (Zangaladze et al., 1999), haptic stimulation interferes with visual memory. The nature of the interference resembles what Loftus et al. (1985) referred to as memory blending. When a fast movement had to be performed, test velocities that were higher than the reference velocity were judged to be more similar to the reference stimulus than slower test velocities. The reverse pattern was observed with slow movements. In other words, the representation of the visual velocity was altered so as to be more similar to the haptic information. Thus, it appears that memories of visual velocities and haptic velocity information are assimilated or blended.

In the studies of Loftus (1977; Loftus & Palmer, 1974), visual information about a particular event and wrong verbal information about this event were confounded in memory. In Loftus and Palmer (1974), a visually specified velocity stored in memory was confounded with the velocity insinuated by verbs presented in the question about the velocity. Thus, estimates of an observed velocity were higher when the verb suggested a high velocity (e.g., "crash"), whereas estimates were lower with neutral verbs (e.g., "contacted"). In the same vein, the representation of the velocity of a causal movement is assimilated to the strength of its apparent effect (Kerzel, Bekkering, Wohlschläger, & Prinz, 2000). The present study suggests a similar integration of haptic and visual information.

Experiment 2

However, it may well be the case that it was not the stored representation of the velocity that was altered by the intervening hand movement but the subsequent perception of the test stimulus velocity. It has been demonstrated that performing an action reduces sensibility to visual features resembling the action (Müsseler & Hommel, 1997a, 1997b). For instance, pressing a left button makes the detection of an arrow pointing to the left less likely. In a similar manner, it may be the case that performing a slow (fast) movement renders the perception of visual stimuli sharing this attribute less likely such that the motion of the test stimulus appears faster (slower). On the other hand, haptic information may serve as a contrasting reference; that is, the haptic sensation produced by a slow (fast) movement may increase (decrease) the perceived speed of visual motion. In both cases, the observed pattern of results is expected. To distinguish between memory-related and perceptual explanations of the observed shift in velocity judgments, the distractor movement was executed before the reference velocity was presented. A perceptual explanation predicts no systematic effects of slow and fast distractors preceding presentation of the reference velocity because perceptual changes should equally affect the perception of reference and test velocity. In contrast, blending of visual and haptic velocity information in memory may occur irrespective of the temporal order in which distractor and reference velocity are presented. In other words, memory blending predicts both retro- and proactive interference of haptic perception and visual memory, whereas a perceptual explanation predicts only retroactive interference.

Method

Participants. Nine students at the Ludwig-Maximilians-University of Munich who fulfilled the same criteria as those in Experiment 1A participated in the experiment.

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were the same as in Experiment 1A, with the exception that the interfering movement was to be performed before the reference velocity was presented. To this end, the pen had to be placed in its starting position by the same alignment procedure as in Experiment 1. Then the auditory signal was presented that informed the participant which movement was to be performed. Four seconds after the beep, the reference velocity was presented. Following a 4-s retention interval, the test velocity was presented.

Results

Mean proportion "same" judgments are graphed in Figure 5. The velocity of the hand movement was outside the required range in 3.1% of the trials. A Scheffé test ($p < .05$) showed that observers were able to discriminate between the physically identical test velocity and velocities differing by $\pm$ 2.4 cm/s. A two-way ANOVA confirmed a significant interaction between interfering movement and sign of the test velocity deviation, $F(1, 8) = 34.07$, $p < .001$. Slow test velocities received more "same" judgments when a slow movement had to be performed (.52 vs. .36), whereas faster test velocities were perceived as more similar to the reference velocity with a fast interfering movement (.61 vs. .28).

Discussion

Lateral hand movements that preceded the velocity to be remembered affected visual short-term memory. This finding is consistent with the assumed blending of haptic and visual velocity codes but not with an interpretation claiming that perceptual processes are altered by the haptic distractor. Thus, the effect of an interpolated hand movement may be attributed to interactions between visual memory and haptic perception. However, it may be possible that it was not the haptic input that influenced the visual memory but a verbal code representing the body movement. For

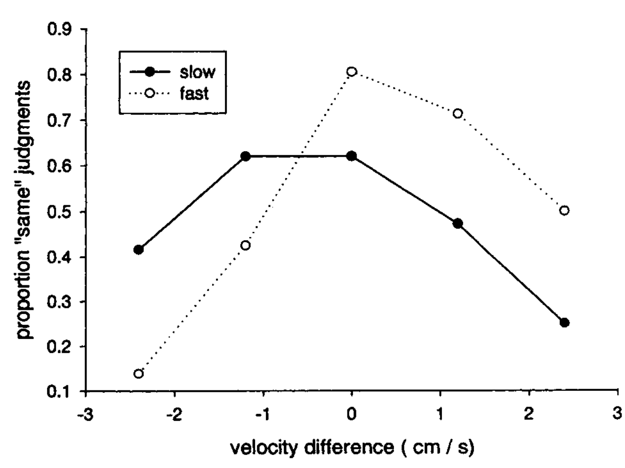

Figure 5. Mean proportion "same" judgments as a function of test velocity and velocity of the hand movement in Experiment 2.

instance, participants may have translated the imperative auditory signal into a verbal command ("fast," "slow") that subsequently altered the memory trace. As outlined in the introduction, higher level cognitive processes (Hubbard, 1995) and verbal information (Loftus, 1977; Loftus & Palmer, 1974) have been shown to influence short-term retention of visual information.

Experiment 3

To investigate whether the assimilation of velocities retained in short-term memory and velocities perceived haptically is mediated by verbal codes, the formation of verbal codes and the haptic feedback about the performed hand movement were separated in time. To this end, the imperative signal indicating which movement had to be performed was presented, but the execution of the hand movement was delayed until after the presentation of reference and test velocities. Thus, a potential translation of the imperative signal into a verbal command and a subsequent assimilation of verbal and visual information could take place. However, blending of haptic perception and visual memory was prevented because the hand movement had to be performed after encoding and retention of the visual velocities. As a consequence, the temporal order of events precluded blending of haptic and visual information but allowed for the assimilation of verbal and visual codes.

Method

Participants. Nine students at the Ludwig-Maximilians-University of Munich who fulfilled the same criteria as those in Experiment 1A participated in the experiment.

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were the same as in Experiment 2, with the exception that the interfering movement was to be performed after the "same–different" judgment had been obtained. The presentation of both the reference and the test velocity was preceded by a 4-s interval. The instruction as to which response was to be performed at the end of the trial was given before the reference velocity was presented and had to be retained in memory until the end of the trial.

Results

Mean proportion "same" judgments are graphed in Figure 6. The interfering movement was outside the required range in 5.4% of the trials. A Scheffé test ($p < .05$) showed that observers were able to discriminate between the physically identical test velocity and velocities differing by ± 2.4 cm/s. A two-way ANOVA revealed a main effect of the sign of the test stimulus velocity, $F(1, 8) = 16.66, p < .005$, indicating that more "same" judgments were given to faster test velocities (.56 vs. .35). However, no interaction between test stimulus velocity and interfering movement was observed ($p > .85$).

Discussion

Maintaining the instruction to perform a fast or slow movement in memory did not influence visual short-term memory. If a recoding of the imperative signal in verbal format had occurred and if this verbal code was responsible for the effect of body movements on visual memory, the contrary result was expected. Thus, it may be concluded that verbal codes are insufficient to produce a change in the visual memory codes; that is, the (verbal) command used to trigger the movement does not account for the effect. Rather, interference with visual memory depends on the haptic stimulation resulting from the execution of the movement.

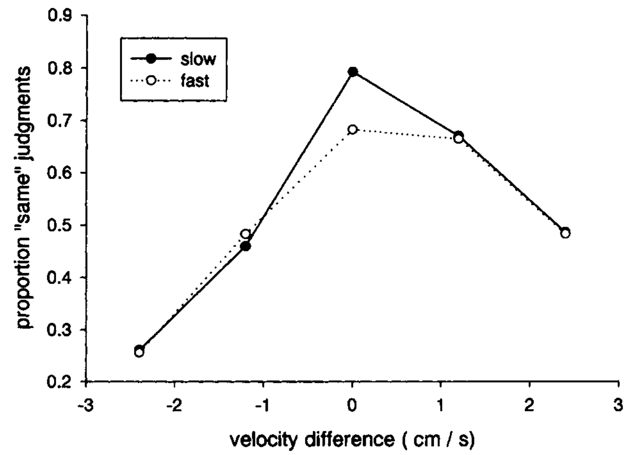

Figure 6. Mean proportion "same" judgments as a function of test velocity and velocity of the hand movement in Experiment 3.

Experiment 4

The purpose of the present experiment was to investigate the specificity of the interference effect. In the previous experiments, the similarity between the visually presented movement and the interfering hand movement was high. Both movements involved lateral displacements. Either the target moved from left to right, or the hand moved from left to right. A plausible hypothesis is that memory blending is restricted to velocity information from movements that share a number of spatial attributes. For instance, identical directions of motion may be a prerequisite for blending. On the other hand, one may assume a rather abstract velocity code that is largely independent of spatial features. Evidence in support of this view is the finding that disruption of visual short-term memory by a visual distractor does not increase when the direction of movement of the distractor deviates from the direction of the reference velocity compared with a condition in which distractor and reference velocity have the same direction of movement (Magnussen & Greenlee, 1992). In the present experiment, the nature of the distracting movement was varied. Instead of a lateral hand movement on a graphics table, tapping movements of different frequencies were used as distractors. Tapping movements require repetitive raising and lowering of the finger such that no uniform direction of motion is present. However, the velocity of the movement may be manipulated by varying tapping frequency. High-frequency tapping generally yields high movement speeds, whereas low-frequency tapping yields low movement speeds. If the interference from haptic feedback presupposes identical directions of motion of visual velocity and distractor, no interference is expected. In contrast, if somewhat more abstract representations underlie visual and haptic codes, interference may be obtained.

Method

Participants. Nine students at the Ludwig-Maximilians-University of Munich who fulfilled the same criteria as those in Experiment 1A participated in the experiment.

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were the same as in Experiment 1A, with the exception that the interfering movement was changed. Instead of performing a lateral hand–arm movement as a distractor between reference and test velocity, participants were asked to tap at either a fast or a slow frequency. Taps were registered by the computer's keyboard. Slow tapping required less than 2 taps/s and a minimum of one tap. Fast tapping required at least 4.5 taps/s. As in the previous experiments, the hand was covered such that the movement was invisible to the observer.

Results

Mean proportion "same" judgments are graphed in Figure 7. The tapping response was outside the required range in 3.7% of the trials. A Scheffé test ($p < .05$) showed that observers were able to discriminate between the physically identical test velocity and velocities differing by ± 2.4 cm/s. A two-way ANOVA revealed a main effect of interfering movement, $F(1, 8) = 8.24$, $p < .05$, indicating that more "same" judgments were made with high-frequency tapping (.52 vs. .47). The interaction of interfering movement and sign of the test velocity deviation reached significance, $F(1, 8) = 30.54$, $p < .005$. When fast tapping was required, faster test velocities received more "same" judgments than slower test velocities (.66 vs. .39). The opposite was true for slow tapping (.38 vs. .56).

Discussion

The same pattern of results as in Experiment 1A was obtained with a distracting movement that did not show a high degree of similarity to the visual motion. Slow tapping decreased the remembered speed, whereas fast tapping increased the remembered speed. Thus, the observed effect of haptic feedback on visual short-term memory generalized to a qualitatively different body movement. Changing the direction of the hand movement (lateral vs. up–down) did not eliminate the effect. Therefore, the visual and haptic codes are abstract to a certain degree. That is, memory codes of the movements are independent of the direction of motion. The observation that visual–haptic memory blending occurs irrespective of a mismatch of the direction of motion parallels the finding that visual–visual memory masking is independent of the direction of visual motion (Magnussen & Greenlee, 1992).

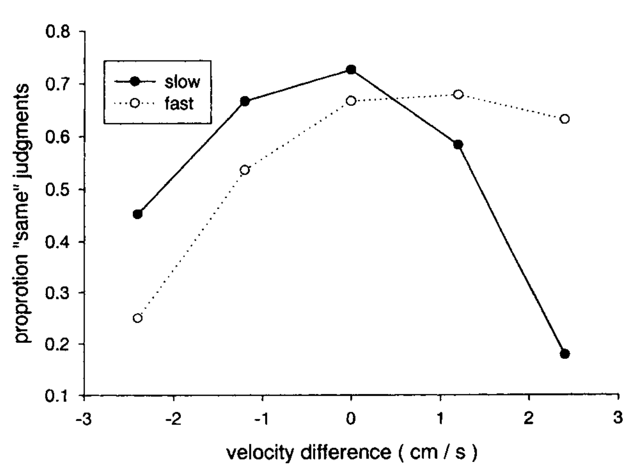

Figure 7. Mean proportion "same" judgments as a function of test velocity and frequency of the tapping movement in Experiment 4.

Experiments 5A and 5B

Although encoding or retention of visual velocity information is largely independent of the direction of motion, other parameters are known to affect motion processing, such as contrast (McKee, 1981), spatial frequency (Diener, Wist, Dichgans, & Brandt, 1976), and duration (Smith, 1987). These effects have been observed with drifting luminance gratings. Because our stimulus was a locally defined target, it appears implausible that changes in contrast and spatial frequency account for the effect. However, because the trajectory length was fixed, the duration of the movement varied as a function of target velocity. Thus, it may have been the case that temporal cues were used in the comparison of reference and test velocity. As a consequence, the influence of the interfering hand movement may be attributed to the disruption of temporal codes stored in memory. To rule out this possibility, we replicated Experiments 1A and 4 with randomized durations of reference and distractor velocities.

Method

Participants. Seventeen students at the Ludwig-Maximilians-University of Munich who fulfilled the same criteria as those in Experiment 1A participated in the experiment. Eight students participated in Experiment 5A and nine students in Experiment 5B.

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were the same as in Experiment 1A, with the exception that the trajectories of the reference and test stimulus were changed. Instead of the smooth motion onset used so far, constant linear motion was presented. For each of the reference velocities, the length of the trajectory of the test stimulus was adjusted such that the duration of either the fastest or the slowest test velocity was equal to that of the reference velocity. Thus, the trajectory length was either longer or shorter than that of the reference stimulus. Each test velocity was presented an equal number of times on the long and short trajectory. Thus, presentation time was no longer a valid cue to stimulus velocity. The start position of the test stimulus varied among four positions that were 2 cm apart. In Experiment 5A, participants had to perform a fast or slow lateral hand movement as a distractor (see Experiment 1A). In Experiment 5B, fast or slow tapping was required (see Experiment 4).

Results

Mean proportion "same" judgments are graphed in Figures 8 and 9. The interfering movement was outside the required range in 5.4% and 3.9% of the trials in Experiments 5A and 5B, respectively. Separate Scheffé tests for each experiment showed that observers were able to discriminate between the physically identical velocity and velocities differing by ±2.4 cm/s. A two-way ANOVA on the data from Experiment 5A confirmed a significant interaction of interfering movement and sign of the test velocity deviation, $F(1, 7) = 140$, $p < .001$. With a slow interfering movement, more "same" judgments were given with slower test velocities than with faster test velocities (.62 vs. .38). In contrast, with a fast interfering movement more "same" judgments were given with higher than with slower test velocities (.57 vs. .41). A second two-way ANOVA on the data from Experiment 5B revealed a significant interaction of interfering movement and sign

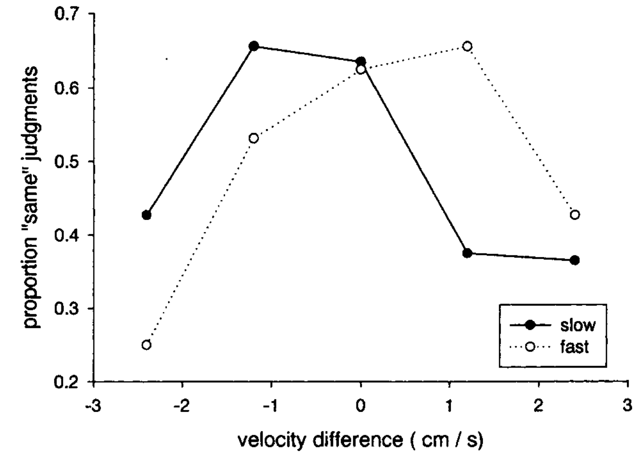

Figure 8. Mean proportion "same" judgments as a function of test velocity and velocity of the hand movement in Experiment 5A.

of the test velocity deviation, $F(1, 8) = 28.95$, $p < .001$. When participants tapped slowly, more "same" responses were given to slow than to fast test velocities (.56 vs. .40), whereas the opposite was true when participants tapped fast (.38 vs. .61).

Discussion

Even when the presentation times of reference and test velocities were unpredictably different, an effect of a distracting body movement could be observed. Therefore, the possibility that the haptic distractor interfered exclusively with the storage of temporal information can be ruled out.

Experiment 6

The last experiment was carried out to deal with another possible confound in the experimental setup. Although the differences in the acoustic signal resulting from fast and slow lateral hand movements may be negligible, fast and slow tapping movements produced noticeable sounds at two distinct frequencies. To isolate the potential effects of acoustic frequency, the sound resulting from striking the computer keyboard was mimicked, but no body movement had to be performed.

Method

Participants. Nine students at the Ludwig-Maximilians-University of Munich who fulfilled the same criteria as those in Experiment 1A participated in the experiment.

Apparatus, stimuli, design, and procedure. Apparatus, stimuli, design, and procedure were the same as in Experiment 5A, with the exception that no distracting movement had to be performed. Instead, participants passively listened to an acoustic distractor. In the fast distractor condition, bursts of noise (clicks) were presented at a frequency of 4.5 clicks/s. In the slow distractor condition, the frequency was 2 clicks/s. Random jitter of up to 22% was added to the fast frequency or subtracted from the slow frequency.

Results

Mean proportion "same" judgments are graphed in Figure 10. A Scheffé test ($p < .05$) showed that observers were able to discriminate between the physically identical velocity and velocities differing by ± 2.4 cm/s. A two-way ANOVA (Distractor × Sign of Test Velocity Deviation) yielded no significant effects. The interaction of the two factors was far from significant ($p > .35$).

Discussion

The present results show that visual short-term memory is unaffected by auditory clicks of either fast or slow frequency. Presenting acoustic signals having approximately the same temporal characteristics as the haptic distractor used in Experiments 4 and 5B failed to alter the memory trace of visual velocity information. Therefore, blending of information is not a universal mechanism operating between all sensory modalities. At least the variation of the acoustic signal used here did not yield acoustic–visual interference of this kind. The reason may be that the variation of the acoustic signal was exclusively defined in the

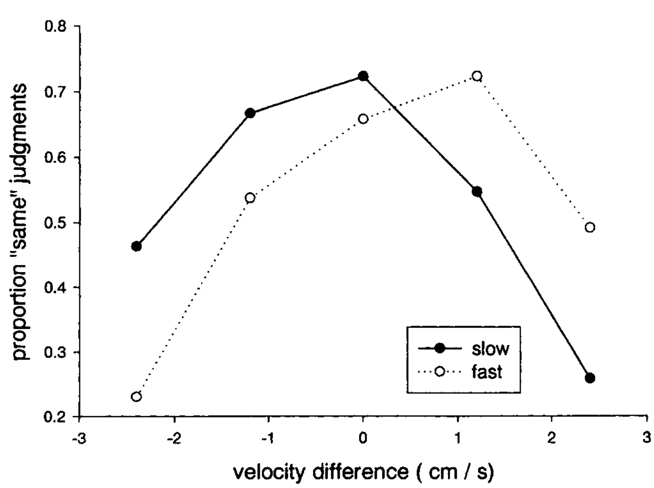

Figure 9. Mean proportion "same" judgments as a function of test velocity and frequency of the hand movement in Experiment 5B.

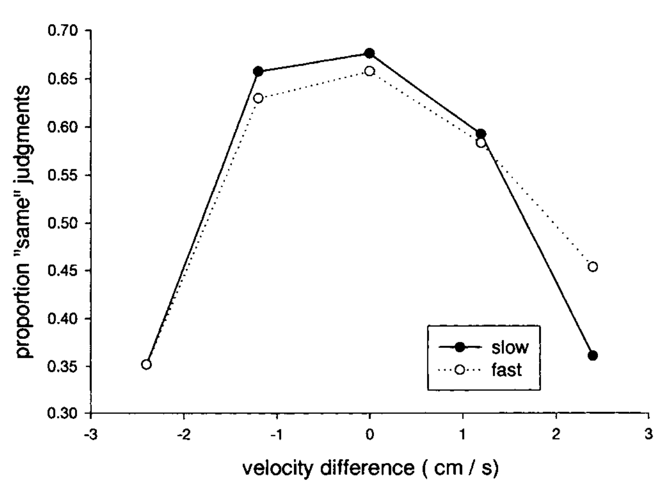

Figure 10. Mean proportion "same" judgments as a function of test velocity and frequency of the auditory clicks in Experiment 6.

temporal domain. Velocity, however, is defined spatially and temporally. Therefore, it remains an open question whether an acoustic signal indicating spatio-temporal variation—for instance, the sound made by an object passing by—may interfere with visual memory.

In addition, the present experiment provides further evidence against the view that semantic or verbal coding accounts for the observed blending of velocity information. The click frequencies used in the present experiment were easily labeled as "fast" and "slow." Thus, if verbal codes interfered with memory of the last seen velocity, blending should have occurred. This was not the case.

General Discussion

In the present series of experiments, the interplay of haptic perception and visual short-term memory was examined. Recent research has demonstrated that somatosensory perception depends on visual cortex (Zangaladze et al., 1999). To further evaluate the relation between somatosensory and visual information processing, the working hypothesis pursued in this article was that visual memory and haptic perception are interrelated. Consistent with this idea, the retention of visual velocity information was disrupted by lateral hand movements. Participants were required to compare a reference velocity with a test velocity separated by a 4-s interval. During the retention interval, a fast or slow hand movement had to be performed. Although the hand movement was not visible, effects of the speed of the distractor movement were observed. Slow movements resulted in a lowering of the represented velocity, whereas fast movements heightened the represented velocity. In Experiment 2, it was demonstrated that the effect was due to interactions of visual memory and haptic perception and not to a change in visual perception. The potential role of semantic or verbal memory codes was investigated in Experiments 3 and 6. These higher level cognitive processes failed to produce memory interference. Experiment 4 was designed to examine whether decreasing the similarity between haptic distractor and visual motion eliminates the effect. For body movements that differed from the visual motion with respect to the direction of movement, this was not the case. Experiment 5 ruled out that the effect was due to the disruption of temporal codes. Experiment 6 showed that an acoustic signal providing distracting temporal information failed to produce memory interference. Thus, it can be concluded that the haptic distractor disrupted memory of the spatio-temporal pattern and not exclusively the temporal pattern.

The main finding of this study is that visual memory and haptic perception are interdependent. The implications of this result are far-reaching. Given that haptic feedback is inevitably coupled to human motor performance, distortions of visual memory may be easily provoked. This situation supports theories claiming that human sensory systems and human action are inseparable units that may even share common representational domains (Prinz, 1997). For instance, it has been demonstrated that the perception of ambiguous motion sequences is influenced by hand movements (Wohlschläger, 2000), suggesting that visual perception and motor action are closely coupled. In a similar vein, the present article demonstrates that visual memory and sensory feedback from a performed action are processed in a dependent manner.

This is not the first study reporting that memory and sensory consequences of action are interrelated. In studies on memory for subject-performed tasks (SPTs), it has been found that participants recall more action phrases when they performed them during study than when they just listened to them in a verbal task (for overviews, see R. L. Cohen, 1989; Engelkamp & Zimmer, 1994), presumably because of the additional sensory and motor information in the SPT condition (Helstrup, 1987; Zimmer & Engelkamp, 1989). The SPT effect has been obtained even when participants were asked to plan or intend to perform the action (Engelkamp, 1997; Koriat, Ben-Zur, & Nussbaum, 1990), demonstrating that motor preparation or planning may also enrich the memory trace. In contrast, no effect of the intended action was found in Experiment 3. This finding points to the importance of haptic feedback in our experiments and speaks against a strong role of motor preparation processes.

In the present study, evidence for linkages between visual memory and haptic perception was accumulated. In studies on intermodal perception, a host of findings points to the fact that input from different sensory modalities is processed in an integral manner. The most compelling piece of evidence is Garner interference (Garner, 1974). Garner interference is observed when participants are required to classify a stimulus on one dimension while the same or a different stimulus shows variation on another dimension. For instance, classification of dim or bright light is slowed when the visual stimulus is accompanied by randomly changing low- and high-pitched tones compared with a condition in which either a low- or a high-pitched tone is presented (Marks, 1987). Thus, participants are unable to process the two stimulus dimensions separately such that variation on an irrelevant dimension increases processing time. In a similar manner, linguistic and nonlinguistic dimensions may interact (Melara & Marks, 1990). One can presume that the influence of irrelevant dimensions on classification along one dimension is due to the holistic nature of early processing (Melara, Marks, & Potts, 1993). In light of strong perceptual interactions between different modalities, the influence of haptic perception on visual memory appears to be another finding supporting the general principle of intermodal information transfer. However, further research is required to reveal the exact mechanisms of intermodal information transfer in memory and how they relate to perceptual mechanisms.

To summarize, the interaction of haptic perception and visual short-term memory suggests that memory codes representing visual velocity are not immune to distracting information from a different sensory modality. Thus, actions and visual memory are more closely coupled than previously thought.

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