Perception, 2010, volume 39, pages 851 – 862

doi:10.1068/p6538

Cross-modal influences on representational momentum and representational gravity

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Received 3 August 2009, in revised form 8 January 2010; published online 14 June 2010

Abstract. Effects of cross-modal information on representational momentum and on representational gravity (ie on displacement of remembered location in the direction of target motion or in the direction of gravitational attraction, respectively) were examined. In experiment 1, ascending or descending visual motion (in the picture plane) was paired with ascending or descending auditory motion (in frequency space); motion was congruent (both ascending, both descending) or incongruent (one ascending, one descending). Memory for visual location or auditory pitch was probed. Congruence resulted in larger forward displacement for auditory pitch, but did not influence forward displacement for visual location. In experiment 2, horizontal visual motion was paired with ascending, descending, or no auditory motion. Memory for visual location was displaced downward with descending or no auditory motion, and downward displacement was larger for visual motion paired with descending auditory motion than for visual motion paired with ascending auditory motion. Effects of cross-modal information on displacement suggest representational momentum and representational gravity reflect high-level processing.

1 Introduction

Memory for the final location of a target is often displaced in the direction of target motion. This displacement has been referred to as 'representational momentum' (eg Freyd and Finke 1984), and has been attributed to a variety of mechanisms ranging from low-level modality-specific and informationally encapsulated perceptual processes to high-level or central cognitive processes (for review, see Hubbard 2010). Although representational momentum has been reported for auditory targets (eg Freyd et al 1990; Getzmann et al 2004; Johnston and Jones 2006) and for haptic targets (eg Brouwer et al 2004), the majority of research on representational momentum involves visual targets (for review, see Hubbard 2005). Displacement of a visual target can be influenced by the presence or behavior of other (non-target) visual stimuli (eg Gray and Thornton 2001; Hubbard et al 2001; Hubbard and Ruppel 1999). However, whether displacement of a visual target can be influenced by an auditory stimulus, or whether displacement of an auditory target can be influenced by a visual stimulus, has not been examined. Whether such cross-modal influences on displacement can occur has significant implications for an understanding of representational momentum and for the question whether such displacement results from low-level processes or from high-level processes.

Hubbard (2005, 2006b) suggested it is more parsimonious to conclude that representational momentum and related types of displacement in visual, auditory, and haptic modalities reflect a single or small number of high-level or central processes rather than a multiplicity of low-level or modality-specific processes. Along these lines, similar patterns of displacement with different types of visual targets (eg targets consisting of frozen-action photographs or exhibiting implied motion or smooth motion) provide examples of the same high-level phenomenon (a bias in remembered location in the direction of anticipated motion) even if those examples are instantiated by different low-level mechanisms or in different neural structures. A single or small number of high-level processes could be influenced by, and in turn influence, multiple low-level processes, and so the displacement of a given target would result from a combination of low-level processes and high-level processes (see also Hubbard 2006a). The hypothesis that a more high-level or central process contributes to displacement is further supported by findings that high-level knowledge regarding anticipated target behavior (eg Hubbard 1994; Johnston and Jones 2006; Verfaillie and d'Ydewalle 1991) and target identity (eg Nagai and Yagi 2001; Reed and Vinson 1996; Vinson and Reed 2002) influences displacement.

This conclusion was challenged by Kerzel (2006), who suggested that a more central or high-level process would necessarily produce the same pattern of errors across different modalities. Although there are similarities in displacement across modalities (eg increases in target velocity lead to larger forward displacement for visual targets and for auditory targets; Freyd et al 1990), differences in displacement across modalities have been found (eg eye fixation and motion type interact in displacement for visual targets, cf Kerzel 2000, 2003, but not in displacement for auditory targets, Getzmann 2005). In a reply to Kerzel (2006), Hubbard (2006b) pointed out that a high-level or central process would receive inputs from, and send outputs to, different low-level modality-specific processes. These different low-level modality-specific processes could each contain or process different types of information, and to the extent that information in different modality-specific processes might differ, inputs to, or outputs from, a more high-level or more central process might differ. Therefore, the same pattern of errors would not necessarily occur across different modalities. If displacement resulted from a high-level or central process, then low-level or modality-specific information that might influence displacement in one modality would not necessarily influence displacement (or influence displacement in the same way) in a different modality.

Although it is parsimonious to hypothesize that previous findings regarding representational momentum in memory for visual targets, auditory targets, and haptic targets result from a more high-level or central process, many of the previous findings are also consistent with the hypothesis that representational momentum in memory for different observed modalities results from separate and distinct low-level modality-specific and informationally encapsulated processes that produce the same type of bias. However, if representational momentum results from a more high-level or central process, then the displacement mechanisms for a given modality might not be modality-specific or informationally encapsulated from motion information in other modalities (ie displacement in a given modality might be influenced by motion information in other modalities). Thus, one way to examine whether representational momentum involves a high-level or central process is to examine whether visual motion or auditory motion can influence displacement of an auditory target or a visual target, respectively. An influence of concurrent visual motion on displacement of an auditory target, or an influence of concurrent auditory motion on displacement of a visual target, would support the hypothesis that high-level processes (or at least processes beyond the receptor level) are at least partly responsible for displacement.

In the two experiments reported here, we examined whether cross-modal information regarding auditory motion or visual motion can influence displacement of a moving visual target or a moving auditory target, respectively. Visual motion involved changes in the vertical or horizontal coordinates of a square shape in the picture plane of a computer monitor orthogonal to participants' line of sight. Auditory motion involved changes in the pitch of a tone from a high pitch to a low pitch or from a low pitch to a high pitch. Choice of these stimulus dimensions was based on findings of a consistent mapping between a higher location in the picture plane and a higher pitch in frequency space that has been documented in several studies (eg Melara and Marks 1990; Mudd 1963; Rusconi et al 2006); specific directions of motion in each of these dimensions are reliably and easily discernible as 'upward' or 'downward'.

Also, because height in the picture plane and height in frequency space are conceptually and semantically rather than physically related, any effect of cross-modal information on displacement would more clearly implicate a high-level cognitive process. On each trial, a visual moving target and an auditory moving target were simultaneously presented, and, after the visual target and auditory target vanished, memory for the final location of the visual target or for the final pitch of the auditory target was probed.

2 Experiment 1

Participants were presented with a visual target and an auditory target on each trial. The visual target consisted of a square shape that ascended or descended in a computer-generated video display, and the auditory target consisted of a tone that ascended or descended in frequency. On half of the trials, visual motion and auditory motion were congruent (ie visual motion ascended and auditory motion ascended, visual motion descended and auditory motion descended), and, on the other half of the trials, visual motion and auditory motion were incongruent (ie visual motion ascended and auditory motion descended, visual motion descended and auditory motion ascended). In one block of trials, memory for final visual location was probed, and, in a second block of trials, memory for final auditory pitch was probed. If representational momentum reflects a more low-level modality-specific and informationally encapsulated process, then displacement in the probed modality should not be influenced by whether motion in the unprobed modality was congruent or incongruent. Alternatively, if representational momentum reflects a more high-level or central process, then displacement in the probed modality might be influenced by whether motion in the unprobed modality was congruent or incongruent. In this latter case, it could be predicted that displacement in the probed modality would be larger when motion in the unprobed modality was congruent than when motion in the unprobed modality was incongruent.

2.1 *Method*

2.1.1 *Participants.* The participants were twenty-two undergraduates who received partial course credit and were naive to the hypotheses.

2.1.2 *Apparatus.* The stimuli were generated by, and the data collected by, an Apple iMac desktop computer. Visual stimuli were presented on a 15-inch color monitor that was connected to the computer and located approximately 60 cm away from participants, and auditory stimuli were presented over headphones (Koss model UR-15C) connected directly to the computer.

2.1.3 *Stimuli.* As shown in figure 1, on each trial there were 5 successive presentations of a visual target and 5 successive presentations of an auditory target, and these are referred to as 'inducing stimuli'. Each inducing stimulus was presented for 250 ms, and there was a 250 ms ISI between successive inducing stimuli. The onsets and offsets of the visual inducing stimuli and auditory inducing stimuli were synchronized so that visual targets and auditory targets were simultaneously presented.

Visual targets and visual probes were black squares, 20 pixels (0.83 deg) in width and in height, and were presented on a white background. For ascending visual motion, the first inducing stimulus appeared between the bottom and center of the display, and each successive inducing stimulus was 40 pixels (1.66 deg) above the previous inducing stimulus; for descending visual motion, the first inducing stimulus appeared between the top and center of the display, and each successive inducing stimulus was 40 pixels below the previous inducing stimulus. The location of the final inducing stimulus varied but was always within 80 pixels (3.32 deg) of the center of the display. The horizontal coordinates of the inducing stimuli were at the horizontal midpoint of the display. The probe appeared at the same horizontal coordinates as the target and at

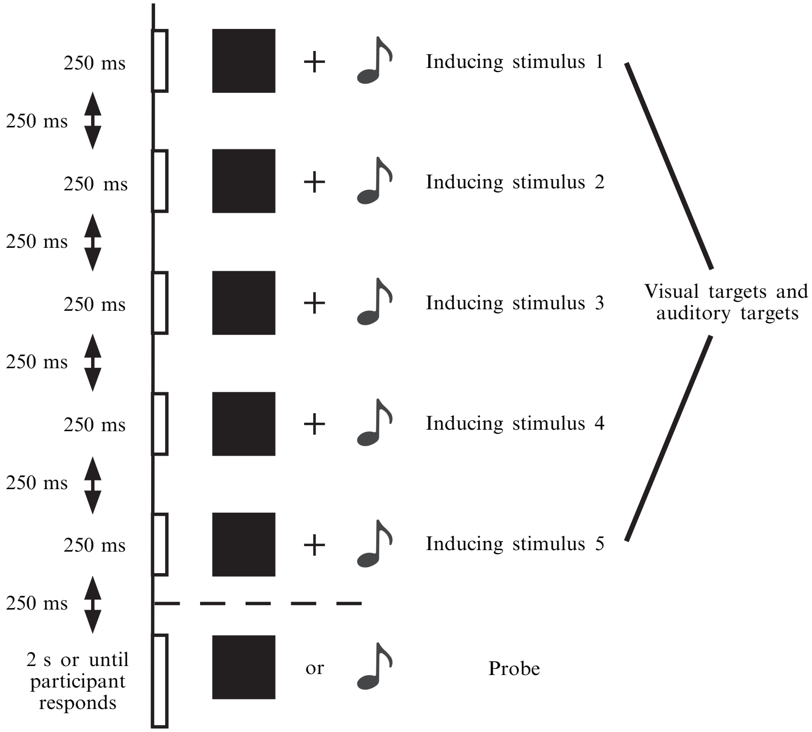

Figure 1. The structure of a trial in experiments 1 and 2. There were five visual inducing stimuli and five auditory inducing stimuli; each inducing stimulus was presented for 250 ms, and there was a 250 ms ISI between successive inducing stimuli. The probe was presented after a retention interval of 250 ms, and remained visible or audible for 2 s or until the observer responded.

one of nine vertical positions relative to the final location of the target: -12, -9, -6, -3, 0, $+3$, $+6$, $+9$, or $+12$ pixels. Probe positions denoted by a minus sign indicated probes were backward (ie shifted in the direction opposite to target motion) from the final location of the target by the indicated number of pixels, and probe positions denoted by a plus sign indicated probes were forward (ie shifted in the direction of target motion) from the final location of the target by the indicated number of pixels; the zero probe position was the same as the final location of the target.

Auditory targets and auditory probes were tones. For ascending auditory motion, the first inducing stimulus was a tone of 60 Hz, and each successive inducing stimulus increased in pitch by one octave (ie 60, 120, 240, 480, 960 Hz); for descending auditory motion, the first inducing stimulus was a tone of 960 Hz, and each successive inducing stimulus decreased in pitch by one octave (ie 960, 480, 240, 120, 60 Hz). The probe was one of nine frequencies relative to the final frequency of the target: -100, -75, -50, -25, 0, $+25$, $+50$, $+75$, or $+100$ cents (1 cent $= 1/100$ semitone). Probe positions denoted by a minus sign indicated probes were backward (ie shifted in the direction opposite to target motion) from the final frequency of the target by the indicated number of cents, and probe positions denoted by a plus sign indicated probes were forward (ie shifted in the direction of target motion) from the final frequency of the target by the indicated number of cents; the zero probe position was the same as the final frequency of the target. Loudness level was approximately 57 dB SPL and was not adjusted for changes in auditory frequency.

2.1.4 *Design.* Each participant completed two blocks of trials. The visual targets and the auditory targets were the same in each block; one block presented visual probes (ie measured displacement of visual targets), and a second block presented auditory probes (ie measured displacement of auditory targets). Each block of trials consisted of 216 trials [2 congruencies (congruent, incongruent) × 9 probe positions (−12, −9, −6, −3, 0, +3, +6, +9, +12 in the visual probe block; −100, −75, −50, −25, 0, +25, +50, +75, +100 in the auditory probe block) × 2 directions (ascending, descending) × 6 replications] in a different random order.

2.1.5 *Procedure.* Probe type was blocked, with visual probes presented in one block and auditory probes presented in a second block. There was a one-week separation between the first and second blocks, and the order of probe types across blocks was counterbalanced across participants. In each block, participants were first given a practice session consisting of 10 practice trials that were randomly drawn from experimental trials in that block. Participants initiated each trial by pressing a designated key. There was a 1 s pause, and then the visual target and auditory target appeared.(1) After the targets disappeared, a visual probe or an auditory probe was presented. Probes were presented for 2 s or until the participant responded. Participants pressed a key marked S or a key marked D to indicate whether the location or pitch of the probe was the same as or different from the final location of the visual target or the final pitch of the auditory target. Participants then pressed a key marked with an upward arrow or a key marked with a downward arrow to indicate whether motion on the other (unprobed) modality was ascending or descending. Participants then initiated the next trial.

2.2 *Results*

The probabilities of a "same" response for each probe position for trials with congruent motion and for trials with incongruent motion are shown in figure 2 for visual probes and in figure 3 for auditory probes. Consistent with previous studies in the representational momentum literature (eg Freyd and Jones 1994; Hubbard 1993; Munger and Minchew 2002), the analyses focused on estimates of displacement based on a weighted mean derived from the probabilities of a "same" response [ie the sum of the products of the proportion of "same" responses and the distance of the probe from

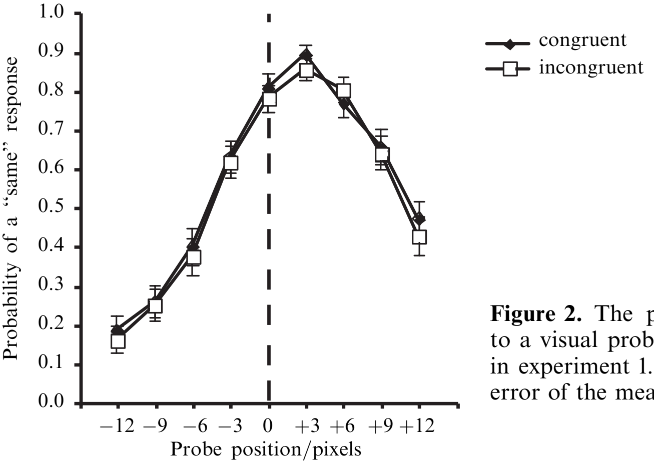

Figure 2. The probability of a "same" response to a visual probe as a function of probe position in experiment 1. Error bars indicate the standard error of the mean.

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(1) A fixation point was not employed, and there were two primary reasons. First, fixation does not influence forward displacement for implied visual motion (Kerzel 2003), and given that experiments 1 and 2 presented implied visual motion, no effect of fixation should have occurred. Second, it is unclear what the auditory equivalent of fixation would be, and so, rather than constrain visual perception but not constrain auditory perception, neither vision nor audition was constrained.

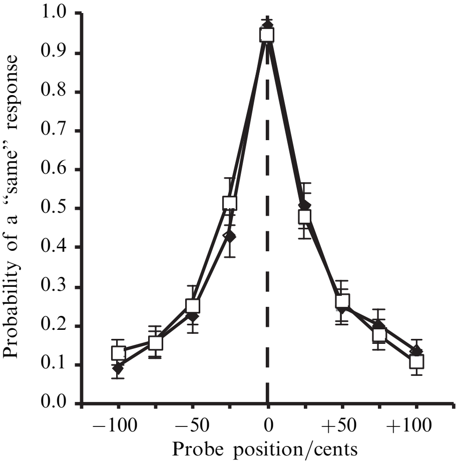

Figure 3. The probability of a "same" response to an auditory probe as a function of probe position in experiment 1. Error bars indicate the standard error of the mean.

the final location of the target, in pixels (visual probes) or cents (auditory probes), divided by the sum of the proportions of "same" responses] for each participant for each condition. The sign of a weighted mean indicated the direction of displacement (ie a minus sign indicated backward displacement in the direction opposite to target motion, a plus sign indicated forward displacement in the direction of target motion), and the absolute value of a weighted mean indicated the magnitude of displacement (ie a larger absolute value indicated larger displacement). A weighted mean significantly larger than zero would indicate representational momentum occurred.

2.2.1 *Visual displacement.* Weighted means for visual probes were analyzed in a 2 (congruence: congruent, incongruent) × 2 (direction: ascending, descending) repeated-measures analysis of variance. Visual forward displacement was not influenced by whether auditory motion was congruent ($M = 2.11$, $\mathrm{SE} = 0.27$) or incongruent ($M = 2.19$, $\mathrm{SE} = 0.30$) with visual motion ($F_{1,20} = 0.30$, $\mathrm{MSE} = 0.50$, $p > 0.62$), nor did congruence interact with direction ($F_{1,20} = 0.35$, $\mathrm{MSE} = 0.77$, $p > 0.56$). Visual forward displacement was larger for descending visual motion ($M = 2.80$, $\mathrm{SE} = 0.28$) than for ascending visual motion ($M = 1.50$, $\mathrm{SE} = 0.25$), ($F_{1,20} = 8.41$, $\mathrm{MSE} = 4.19$, $p < 0.009$). Weighted means for trials with congruent motion ($t_{21} = 7.62$, $p < 0.0001$) and for trials with incongruent motion ($t_{21} = 6.79$, $p < 0.0001$) were significantly larger than zero. Also, weighted means for trials with descending visual motion ($t_{21} = 7.22$, $p < 0.0001$) and for trials with ascending visual motion ($t_{21} = 4.47$, $p < 0.0002$) were significantly larger than zero. Participants correctly reported the direction of auditory motion on 98% of the trials.

2.2.2 *Auditory displacement.* Weighted means for auditory probes were analyzed in a 2 (congruence: congruent, incongruent) × 2 (direction: ascending, descending) repeated-measures analysis of variance. Auditory forward displacement was larger when visual motion was congruent ($M = 2.95$, $\mathrm{SE} = 1.56$) with auditory motion than when visual motion was incongruent ($M = -0.06$, $\mathrm{SE} = 1.48$) with auditory motion ($F_{1,20} = 9.18$, $\mathrm{MSE} = 20.96$, $p < 0.007$). Auditory forward displacement was larger for descending auditory motion ($M = 4.78$) than for ascending auditory motion ($M = -1.90$), ($F_{1,20} = 4.80$, $\mathrm{MSE} = 211.15$, $p < 0.05$). The congruence × direction interaction did not approach significance ($F_{1,20} = 0.70$, $\mathrm{MSE} = 18.30$, $p > 0.41$). Weighted means for trials with congruent motion were significantly larger than zero ($t_{21} = 2.26$, $p < 0.04$), but weighted means for trials with incongruent motion were not significantly different from zero ($t_{21} = -0.050$, $p > 0.95$). Also, weighted means for trials with descending auditory motion were significantly larger than zero ($t_{21} = 2.27$, $p < 0.03$), but weighted means for trials with ascending auditory motion were not significantly different from zero ($t_{21} = -1.08$, $p > 0.14$). Participants correctly reported the direction of visual motion on 100% of the trials.

2.3 *Discussion*

Forward displacement in memory for visual location occurred regardless of whether auditory motion was ascending or descending, and this forward displacement was not influenced by whether the direction of auditory motion was congruent or incongruent with the direction of visual motion. Forward displacement in memory for auditory pitch occurred when the direction of visual motion was congruent with the direction of auditory motion, but forward displacement in memory for auditory pitch did not occur when the direction of visual motion was incongruent with the direction of auditory motion. Also, forward displacement in memory for visual location or for auditory pitch was larger when motion was descending than when motion was ascending; this replicates a common finding in the literature on visual displacement attributed to effects of implied gravitational attraction (eg Hubbard 1990, 1997) and provides the first demonstration of such an effect in memory for auditory pitch. Finding a direction effect in memory for auditory pitch is especially interesting, as association of decreasing auditory frequency with downward motion in physical space reflects a conceptual or semantic relationship rather than a property of the physical environment. Additionally, participants were able to correctly identify the direction of unprobed motion in each trial, and this confirms that participants attended (at least minimally) to the unprobed modality.

Comparison of figures 2 and 3 suggests forward displacement was larger for visual targets than for auditory targets. Forward displacement for visual targets is immediately evident in the higher probability of "same" responses to forward probe positions in figure 2. However, forward displacement for auditory targets is not as immediately evident in figure 3, and it is only with more detailed comparison of -25 and $+25$ probes for the congruent condition that forward displacement becomes evident. It is not clear whether differences in the shapes of the functions for visual stimuli and for auditory stimuli reflect differences between (a) sensitivity to changes in location in visual space and sensitivity to changes in location in frequency space or (b) spacing of visual probes and spacing of auditory probes. Spacing of probes was based on spacing used in previous studies in which visual displacement and auditory displacement were separately examined, but such spacing might not be optimal for comparing displacement across modalities; the functions in figures 2 and 3 suggest that spacing of auditory probes was too broad relative to spacing of visual probes (ie a more narrow spacing for auditory probes might result in a function more similar in shape to that in figure 2). Regardless, differences in the shapes of the functions in figures 2 and 3 do not impact the conclusion that concurrent visual motion influenced auditory displacement.

There was an effect of congruence of visual motion on auditory displacement, but there was no effect of congruence of auditory motion on visual displacement. That is, displacement for visual targets did not appear to be influenced by auditory information, but displacement for auditory targets did appear to be influenced by a combination of visual information and auditory information. When representational momentum resulting from visual motion and representational momentum resulting from auditory motion were congruent, auditory displacement was larger (and significantly different from zero), but, when representational momentum resulting from visual motion and representational momentum resulting from auditory motion were incongruent, auditory displacement was smaller (and not significantly different from zero). One hypothesis is that this pattern reflects differences in probe spacing. However, such a hypothesis predicts that spacing of visual probes (ie probes in the modality not influenced by cross-modal information) was less optimal for detecting displacement, but inspection of figures 2 and 3 suggests visual probe spacing was more optimal for detecting displacement. A second hypothesis is that this pattern reflects visual dominance (eg Posner et al 1976; Sinnett et al 2007; Welch and Warren 1986) owing to greater strength or salience of visual stimuli (visual representational momentum) and auditory stimuli (auditory representational momentum).

3 Experiment 2

If the lack of an effect of auditory motion on visual displacement in experiment 1 was due to visual dominance, then it might be possible to find an effect of auditory motion on visual displacement if auditory information could be made stronger or more salient than visual information. This might be accomplished by examining whether auditory representational momentum could influence a type of visual displacement that is weaker than visual representational momentum. A horizontally moving visual target is also displaced slightly downward in the direction consistent with implied gravitational attraction; this has been referred to as 'representational gravity' (eg Hubbard 1995, 1997), and the magnitude of this downward displacement is considerably less than the magnitude of forward displacement (eg Hubbard 1990; Hubbard and Bharucha 1988). It is possible a stronger (larger) representational momentum resulting from ascending or descending auditory motion might influence a weaker (smaller) representational gravity resulting from horizontal visual motion. Accordingly, in experiment 2 the visual target was a square that moved leftward or rightward, and the auditory target was a tone that ascended or descended in frequency. If ascending or descending auditory motion can influence downward displacement of horizontally moving visual targets, then downward displacement in memory for the visual target should be larger when auditory motion is descending than when auditory motion is ascending.

3.1 *Method*

3.1.1 *Participants.* The participants were twenty-two undergraduates from the same participant pool as that used in experiment 1, and none had participated in experiment 1.

3.1.2 *Apparatus.* The apparatus was the same as in experiment 1.

3.1.3 *Stimuli.* Visual targets and visual probes were the same as in experiment 1, with the following exceptions: The target moved leftward or rightward rather than ascending or descending. For leftward motion, the first inducing stimulus appeared between the right side and center of the display, and each successive inducing stimulus was 40 pixels to the left of the previous inducing stimulus; for rightward motion, the first inducing stimulus appeared between the left side and center of the display, and each successive inducing stimulus was 40 pixels to the right of the previous inducing stimulus. The location of the final inducing stimulus varied but was always within 80 pixels (3.32 deg) of the center of the display. The vertical coordinates of the inducing stimuli were at the vertical midpoint of the display. The probe appeared at the same horizontal coordinates as the target and at one of nine vertical positions relative to the final location of the target: −8, −6, −4, −2, 0, +2, +4, +6, or +8 pixels.(2) Auditory targets were the same as in experiment 1, with the following exceptions: A control condition in which no auditory stimulus was presented was included, and so one-third of the trials presented an ascending auditory target, one-third of the trials presented a descending auditory target, and one-third of the trials did not present an auditory target. No auditory probes were presented.

(2) A smaller spacing between adjacent probe positions was used in experiment 2 than was used for visual probes in experiment 1 because the magnitude of representational gravity is less than the magnitude of representational momentum.

3.1.4 *Design.* Each participant completed one block of trials consisting of 216 trials [3 auditory motion (ascending, descending, none) × 9 probe positions (−8, −6, −4, −2, 0, +2, +4, +6, +8) × 2 directions (leftward, rightward) × 4 replications] in a different random order.

3.1.5 *Procedure.* The procedure was the same as in the visual probe block in experiment 1, with the following exception: Participants were not asked to indicate the direction of auditory motion in trials in which an auditory target was not presented.

3.2 *Results*

The probabilities of a "same" response for each visual probe position for trials with ascending auditory motion, trials with descending auditory motion, and trials with no auditory motion are shown in figure 4, and weighted mean estimates of displacement were calculated as in experiment 1. Weighted means were analyzed in a 3 (auditory direction: ascending, descending, none) × 2 (visual direction: leftward, rightward) repeated-measures ANOVA. Visual displacement was significantly influenced by whether auditory motion ascended ($M = -0.18$, $\mathrm{SE} = 0.20$), descended ($M = -0.625$, $\mathrm{SE} = 0.17$), or was not presented ($M = -0.53$, $\mathrm{SE} = 0.15$), ($F_{2,42} = 3.27$, $\mathrm{MSE} = 0.73$, $p < 0.05$); least mean squares comparisons suggested that visual downward displacement when auditory motion descended was larger than visual downward displacement when auditory motion ascended, and that downward visual displacement when no auditory motion was presented was marginally larger ($p < 0.07$) than when auditory motion ascended. Neither visual direction ($F_{1,21} = 0.02$, $\mathrm{MSE} = 0.53$, $p > 0.89$), nor visual-direction × auditory-direction interaction ($F_{2,42} = 0.83$, $\mathrm{MSE} = 0.53$, $p > 0.44$) were significant. Weighted means for trials with descending auditory motion ($t_{21} = -2.93$, $p < 0.01$) and for trials with no auditory motion ($t_{21} = -2.75$, $p < 0.02$) were less than zero, but weighted means for trials with ascending auditory motion did not differ from zero ($t_{21} = -0.71$, $p > 0.48$). When auditory motion was presented, participants correctly identified the direction of auditory motion on 98% of the trials.

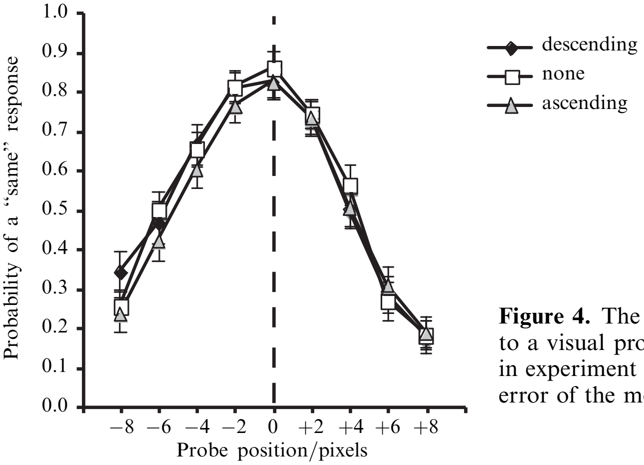

Figure 4. The probability of a "same" response to a visual probe as a function of probe position in experiment 2. Error bars indicate the standard error of the mean.

3.3 *Discussion*

Downward displacement in memory for the location of a horizontally moving visual target was influenced by the direction of auditory motion. When auditory motion descended, downward visual displacement was larger than when auditory motion ascended. Visual downward displacement when no auditory motion was presented was intermediate to visual downward displacement when auditory motion ascended or descended. Comparison of weighted means against zero revealed that visual downward displacement occurred when no auditory motion was presented and when auditory motion was in the direction consistent with implied gravitational attraction, but visual downward displacement did not occur when auditory motion was in the direction opposite to implied gravitational attraction. Downward displacement for visual motion when auditory motion was present appeared to be influenced by a combination of visual information and auditory information. When representational gravity of visual motion and representational momentum of auditory motion were congruent (ie descending auditory motion), visual downward displacement was larger (and significantly different from zero), but when representational gravity of visual motion and representational momentum of auditory motion were incongruent (ie ascending auditory motion), visual downward displacement was smaller (and not significantly different from zero).

4 General discussion

Visual motion in the picture plane and auditory motion in frequency space were concurrently presented, and memory for final visual location or for final auditory pitch was measured. The primary empirical findings are that (a) visual forward displacement for vertically moving targets was not influenced by whether auditory motion was in the same direction as visual motion or in the direction opposite to visual motion, (b) auditory forward displacement occurred when vertical visual motion was in the same direction as auditory motion but auditory forward displacement did not occur when vertical visual motion was in the direction opposite to auditory motion, and (c) visual downward displacement occurred for horizontally moving targets when there was no auditory motion and when auditory motion was in the direction consistent with implied gravitational attraction but did not occur when auditory motion was in the direction opposite to implied gravitational attraction. Effects of visual motion on auditory representational momentum and effects of auditory motion on visual representational gravity are (a) consistent with the hypothesis that cross-modal information influences displacement and that displacement involves a more high-level or central process and (b) not consistent with the hypothesis that displacement results solely from low-level modality-specific and informationally encapsulated processes.

Patterns of displacement for visual targets and patterns of displacement for auditory targets were not identical (eg in experiment 1, visual representational momentum influenced auditory forward displacement, but auditory representational momentum did not influence visual forward displacement). Coupled with the notion that a cross-modal influence on displacement suggests a more high-level or central process, the differences between patterns of displacement for visual targets and patterns of displacement for auditory targets are consistent with Hubbard's (2006b) suggestion that a high-level or central process could produce different patterns of displacement for targets in different modalities. Additionally, differences between patterns of displacement for visual targets and patterns of displacement for auditory targets suggest that in at least some conditions elements of displacement from each modality combined and that, when these elements were in opposite directions, they cancelled and the resultant displacement of the target was decreased: In experiment 1, visual representational momentum appeared to cancel auditory representational momentum when visual motion was in the direction opposite to auditory motion, and in experiment 2, auditory representational momentum appeared to cancel visual representational gravity when auditory motion was in the direction opposite to implied gravitational attraction.

The larger influence of visual representational momentum on auditory forward displacement than of auditory motion on visual forward displacement in experiment 1, and the influence of a stronger auditory representational momentum on visual representational gravity in experiment 2, is consistent with the hypothesis that a visual dominance similar to that in perception also occurs in displacement. However, a similarity between perception and displacement does not mean that displacement results from properties of perception and is not cognitive; indeed, there is ample evidence that cognition in the form of high-level or top – down information can influence displacement (Hubbard 2005). Rather, perception supplies input to displacement processes, and any bias in perceptual input to a displacement process would of course influence the resultant displacement. Influences of cross-modal information and existence of visual dominance are consistent with continuity in representation from perception to memory, a continuity in which (bottom – up) properties of perception influence memory and (top – down) properties of memory influence perception. However, potential differences in rates of change in visual motion and in auditory motion or in probe spacing in the current data do not allow strong claims regarding visual dominance in displacement, and evaluation of potential visual dominance in displacement remains for future research.

The influence of visual representational momentum on forward displacement of auditory targets, and of auditory representational momentum on downward displacement of horizontally moving visual targets, reveals an effect of cross-modal information on displacement. These data are consistent with the hypothesis that displacement results (at least in part) from high-level or central cognitive processes and not from low-level modality-specific and informationally encapsulated perceptual processes. Also, experiment 1 provided the first demonstration of representational gravity in auditory pitch, and experiment 2 provided the first demonstration of visual representational gravity with a probe methodology. Visual representational gravity and auditory representational momentum appeared to combine in experiment 2 even though representational gravity and representational momentum are statistically independent (cf Motes et al 2008) and even though the association between downward motion in the visual picture plane and downward motion in frequency space is conceptual or semantic. Indeed, this latter point strengthens the necessity of a high level or central process in displacement. Along these lines, cross-modal influences on representational momentum and on representational gravity underscore that displacement is multiply determined and reflects more than just the implied momentum of the target.

Acknowledgment. We thank Charlotte Carp for assistance in data collection.

References

Brouwer A-M, Franz V H, Thornton I M, 2004 “Representational momentum in perception and grasping: Translating versus transforming objects” *Journal of Vision* **4** 575 – 584

Freyd J J, Finke R A, 1984 “Representational momentum” *Journal of Experimental Psychology: Learning, Memory, and Cognition* **10** 126 – 132

Freyd J J, Jones K T, 1994 “Representational momentum for a spiral path” *Journal of Experimental Psychology: Learning, Memory, and Cognition* **20** 968 – 976

Freyd J J, Kelly M H, DeKay M L, 1990 “Representational momentum in memory for pitch” *Journal of Experimental Psychology: Learning, Memory, and Cognition* **16** 1107 – 1117

Getzmann S, 2005 “Representational momentum in spatial hearing does not depend on eye movements” *Experimental Brain Research* **165** 229 – 238

Getzmann S, Lewald J, Guski R, 2004 “Representational momentum in spatial hearing” *Perception* **33** 591 – 599

Gray R, Thornton I M, 2001 “Exploring the link between time to collision and representational momentum” *Perception* **30** 1007 – 1022

Hubbard T L, 1990 “Cognitive representation of linear motion: Possible direction and gravity effects in judged displacement” *Memory & Cognition* **18** 299 – 309

Hubbard T L, 1993 “The effects of context on visual representational momentum” *Memory & Cognition* **21** 103 – 114

Hubbard T L, 1994 “Judged displacement: A modular process?” *American Journal of Psychology* **107** 359 – 373

Hubbard T L, 1995 “Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force” *Psychonomic Bulletin & Review* **2** 322 – 338

Hubbard T L, 1997 "Target size and displacement along the axis of implied gravitational attraction: Effects of implied weight and evidence of representational gravity" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **23** 1484 – 1493

Hubbard T L, 2005 "Representational momentum and related displacements in spatial memory: A review of the findings" *Psychonomic Bulletin & Review* **12** 822 – 851

Hubbard T L, 2006a "Bridging the gap: Possible roles and contributions of representational momentum" *Psicologica* **27** 1 – 34

Hubbard T L, 2006b "Computational theory and cognition in representational momentum and related types of displacement: A reply to Kerzel" *Psychonomic Bulletin & Review* **13** 174 – 177

Hubbard T L, 2010 "Approaches to representational momentum: Theories and models", in *Space and Time in Perception and Action* Eds R Nijhawan, B Khurana (Cambridge: Cambridge University Press) pp 338 – 365

Hubbard T L, Bharucha J J, 1988 "Judged displacement in apparent vertical and horizontal motion" *Perception & Psychophysics* **44** 211 – 221

Hubbard T L, Blessum J A, Ruppel S E, 2001 "Representational momentum and Michotte's (1946/1963) 'Launching Effect' paradigm" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **27** 294 – 301

Hubbard T L, Ruppel S E, 1999 "Representational momentum and landmark attraction effects" *Canadian Journal of Experimental Psychology* **53** 242 – 256

Johnston H M, Jones M R, 2006 "Higher order pattern structure influences auditory representational momentum" *Journal of Experimental Psychology: Human Perception and Performance* **32** 2 – 17

Kerzel D, 2000 "Eye movements and visual persistence explain the mislocalization of the final position of a moving target" *Vision Research* **40** 3703 – 3715

Kerzel D, 2003 "Attention maintains mental extrapolation of target position: Irrelevant distractors eliminate forward displacement after implied motion" *Cognition* **88** 109 – 131

Kerzel D, 2006 "Why eye movements and perceptual factors have to be controlled in studies on 'representational momentum'" *Psychological Bulletin & Review* **13** 166 – 173

Melara R D, Marks L E, 1990 "Processes underlying dimensional interactions: Correspondences between linguistic and nonlinguistic dimensions" *Memory & Cognition* **18** 477 – 495

Motes M A, Hubbard T L, Courtney J R, Rypma B, 2008 "A principal components analysis of dynamic spatial memory biases" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **34** 1076 – 1083

Munger M P, Minchew J H, 2002 "Parallels between remembering and predicting an object's location" *Visual Cognition* **9** 177 – 194

Mudd S A, 1963 "Spatial stereotypes of four dimensions of pure tone" *Journal of Experimental Psychology* **66** 347 – 352

Nagai M, Yagi A, 2001 "Pointedness effect on representational momentum" *Memory & Cognition* **29** 91 – 99

Posner M I, Nissen M J, Klein R M, 1976 "Visual dominance: An information-processing account of its origins and significance" *Psychological Review* **83** 157 – 171

Reed C L, Vinson N G, 1996 "Conceptual effects on representational momentum" *Journal of Experimental Psychology: Human Perception and Performance* **22** 839 – 850

Rusconi E, Kwan B, Giordano B L, Umilta C, Butterworth B, 2006 "Spatial representation of pitch height: the SMARC effect" *Cognition* **99** 113 – 129

Sinnett S, Spence C, Soto-Faraco S, 2007 "Visual dominance and attention: The Colavita effect revisited" *Perception & Psychophysics* **69** 673 – 686

Verfaillie K, d'Ydewalle G, 1991 "Representational momentum and event course anticipation in the perception of implied periodical motions" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **17** 302 – 313

Vinson N G, Reed C L, 2002 "Sources of object-specific effects in representational momentum" *Visual Cognition* **9** 41 – 65

Welch R B, Warren D H, 1986 "Immediate perceptual response to intersensory discrepancy" *Psychological Bulletin* **88** 638 – 667

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 39 2010

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