

Auditory representational momentum: Surface form, direction, and velocity effects

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In a series of four experiments, subjects were presented with inducing sequences consisting of either a series of discrete tones or a continuous frequency glide. A probe tone was then presented, and subjects judged whether the probe was the same pitch as the final pitch in the inducing sequence. When the final frequency of the inducing sequence was prolonged, subjects' memory for the final pitch was displaced forward in the direction of implied motion. When the final frequency of the inducing sequence was not prolonged, no consistent pattern of displacement was found. With descending auditory motion, faster velocities led to larger forward displacements than slower velocities, but with ascending auditory motion, velocity did not significantly affect displacement. In general, displacements were influenced by the direction and velocity of motion and by the duration of the final frequency, but not by whether the stimulus was presented in a continuous form or a discrete form. These results are consistent with Freyd's (1993) hypothesis that representational momentum does not depend upon the surface form of the stimulus and can be found when stimuli drawn from a continuous dimension are presented in either a continuous form or a discrete form.

When people visually perceive a moving target and that target then vanishes, memory for the final location or orientation of that target is typically "shifted" or "displaced" in the direction of anticipated motion. This memory shift has been referred to as *representational momentum* in studies of the remembered orientation of targets undergoing implied rotation (e.g., Freyd & Finke, 1984; Kelly & Freyd, 1987) and as *displacement* in studies of the remembered location of targets undergoing apparent linear motion (e.g., Hubbard, 1990; Hubbard & Bharucha, 1988). The direction and magnitude of this memory shift are influenced by a number of factors: velocity (Freyd & Finke, 1985; Hubbard & Bharucha, 1988), acceleration (Finke, Freyd, & Shyi, 1986) and direction of target motion (Hubbard, 1990), direction of anticipated target motion (Hubbard, 1994), direction of context motion (Hubbard, 1993b), constancy of target shape (Kelly

& Freyd, 1987), duration of time between disappearance of the target and probing of remembered location (Freyd & Johnson, 1987), coherence of the inducing sequence (e.g., whether motion in a consistent direction is implied; Freyd & Finke, 1984; Kelly & Freyd, 1987), interaction of the target with other elements in the display (Hubbard, 1994, 1995), similarity of the final target to a prototypical member of a category (Kelly & Freyd, 1987) or schematically proper ending (Hubbard, 1993a), and whether motion of the target is embedded in an event hierarchy (Verfaillie & d'Ydewalle, 1991).

Until recently, the majority of research on representational momentum has been carried out using visual stimuli. Kelly and Freyd (1987) reported one experiment in which subjects heard a series of three ascending or descending inducing stimulus tones and were then presented with a probe tone. Subjects judged whether the pitch of the probe matched the pitch of the final inducing stimulus. Typical representational momentum-like patterns were found, that is, subjects were more likely to respond *same* to a probe when the frequency of the probe was slightly higher than the frequency of the final inducing stimulus in the ascending trials and slightly lower than the frequency of the final inducing stimulus in the descending trials. Freyd, Kelly, and DeKay (1990) replicated the basic finding of representational momentum with auditory stimuli, and compared inducing sequences which implied motion in a consistent direction with a control condition in which inducing sequences did not imply motion in a consistent direction. Freyd et al. found significantly more representational momentum when the stimuli implied motion in a consistent direction, but they did not find any effect of stimulus musicality, musical background of the subjects, or direction of motion. They also reported velocity and acceleration effects analogous to those found with visual stimuli.

A number of questions concerning representational momentum (and auditory representational momentum in particular) remain unanswered, however. One question concerns how the nature of the stimulus influences whether or not representational momentum occurs. Freyd (1993) predicts that the occurrence of representational momentum is a function of whether the stimuli are drawn from a continuous or a discrete dimension: Continuous dimensions such as length, orientation, and presumably auditory frequency should exhibit representational momentum, whereas discrete dimensions such as integers should not exhibit representational momentum. For visual stimuli, robust representational momentum has been found for the continuous dimensions of orientation and location using both discrete implied rotation (Freyd & Finke, 1984) and continuous apparent linear

motion (Hubbard, 1990), but the magnitudes of the memory shifts from discrete and continuous forms of the same underlying stimulus dimension have not been directly compared. It seems possible, however, that the "surface form" of the stimulus (i.e., whether the stimuli are presented in a discrete or continuous form) might nonetheless influence the magnitude (or even occurrence) of representational momentum, regardless of whether those stimuli are drawn from a dimension that is relatively more continuous or relatively more discrete. Smooth continuous motion might induce a more vivid sense of motion, in which case we might expect stronger representational momentum. Discrete motion might not induce the same level of vividness of motion, in which case we might expect weaker representational momentum. If differences in displacement attributable to the surface form can be found, then the role or importance of the underlying stimulus dimension in the determination of representational momentum becomes less clear.

A second question concerns the nature of velocity and direction effects in auditory representational momentum. In Freyd et al. (1990) no effect of direction was found, but a velocity effect consistent with previously reported velocity effects for visual representational momentum (e.g., Freyd & Finke, 1985) was found. The stimuli used by Freyd et al. (1990) confounded direction with velocity, however, and so conclusions concerning the relative contributions of these factors cannot yet be drawn. In both ascending and descending trials in the musical condition in Freyd et al. the frequency distance between the first and third inducing tones was equal to 1262 Hz. This poses a problem because even though the total change in frequency was equal, the perceived change in pitch was not equal, as the ascending sequence covered approximately one octave (ratio of 2:1 between first and third inducing stimuli) and the descending sequence covered approximately a fifth (ratio of 3:2 between first and third inducing stimuli). Thus, the descending sequence actually covered less of a total perceived pitch distance than did the ascending sequence, and because the durations of the inducing stimuli and the interstimulus interval (ISI) between stimuli were equal, the perceived pitch velocity for descending sequences (which covered a smaller pitch interval) should have been slower and more decelerating than the perceived pitch velocity for ascending sequences (which covered a larger pitch interval). A similar direction and velocity confound existed in the nonmusical stimuli. Given that direction was not significant in the Freyd et al. data, it could be predicted that if perceived pitch distance were equated for ascending and descending trials, then descending sequences would exhibit larger memory shifts than ascending sequences. Such an asym-

metry would also be consistent with the finding that descending visual motion leads to larger forward displacements than does ascending visual motion (e.g., Hubbard, 1990; Hubbard & Bharucha, 1988).

EXPERIMENT 1

In this experiment, the effect of the surface form of the stimulus on representational momentum for pitch was examined. Freyd (1993) suggested that a critical factor in determining whether or not a given stimulus dimension exhibits representational momentum is the nature of the underlying stimulus; specifically, movement along a stimulus dimension that is relatively continuous (e.g., spatial orientation, auditory frequency) should produce representational momentum, whereas movement along a stimulus dimension that is relatively discrete (e.g., integers) should not produce representational momentum. However, it is possible that the surface form of a given stimulus, rather than the underlying discrete or continuous nature of that stimulus dimension, determines whether or not representational momentum occurs. In this experiment, subjects were presented with two types of stimuli: smooth frequency glides and series of discrete tones. If the surface form of the stimulus does not influence whether representational momentum occurs, then similar patterns and magnitudes of displacements for both glides and discrete tones should be obtained. If, however, the surface form of the stimulus does influence whether representational momentum occurs, then different patterns or magnitudes of displacement for glides and discrete tones should be obtained.

METHOD

Subjects

The subjects were recruited from members of the summer community at the University of Oregon by posting notices on bulletin boards. Subjects were paid a small fee for participating in the experiment. Thirteen subjects participated in the current experiment, and data from an additional 2 subjects were discarded because of subjects' failure to follow instructions.

Apparatus

Stimuli were generated by an Apple Macintosh IIcx microcomputer and were presented to subjects over a pair of Pioneer headphones (#SE-2) connected directly to the computer. Subjects' responses were recorded by the microcomputer.

Stimuli

All auditory stimuli consisted of simple sine waves generated by the microcomputer. The sound chip within the microcomputer was connected to an RFI filter to eliminate onset transients and ensure that the pure tone stimuli were not contaminated by other frequencies. An auditory mask consisting of 16 tones, each of which lasted 125 ms, was generated at the beginning of each trial, and the purpose of the mask was to remove any lingering echoic memories from the previous trials that might confound subjects' responses. The frequencies of each tone in the mask were randomly determined for each trial. The entire mask lasted 2 s, with no pauses between notes. There were four types of trials: ascending discrete, descending discrete, ascending glide, descending glide. In discrete trials, subjects heard three discrete inducing stimulus tones that were followed by a probe; in glide trials, subjects heard a continuous frequency glide that was followed by a probe.

The distance between each of the inducing stimuli in the discrete trials was based on an equal-tempered tuning such that the distance between the first and second inducing stimuli was 600 cents and the distance between the second and third inducing stimuli was 600 cents. The duration of each inducing stimulus was 500 ms and the duration of each ISI was 500 ms. Glides were created by a loop which increased the frequency by a factor of 1.0135 each time through the loop for ascending glides and decreased the frequency by a factor of 0.9865 each time through the loop for descending glides. The frequency distance between the first and third inducing stimuli in the discrete trials matched the frequency distance covered by the glide in the glide trials. The duration from the onset of the first inducing stimulus to the offset of the third inducing stimulus in the discrete trials equaled the duration of the glide in the glide trials. In both discrete and glide trials, probes were equally spaced in 25-cent increments, with the lowest probe 100 cents below the frequency of the third inducing tone or glide ending and the highest probe 100 cents above the frequency of the third inducing tone or glide ending. For ascending trials, the starting frequency was either 500, 1000, or 2000 Hz; for descending trials, the starting frequency was either 1000, 2000, or 4000 Hz. Auditory intensity was constant across and within trials. Although perceived loudness might have differed slightly across trials (because stimuli ranged across three octaves), loudness did not change significantly within a trial (because stimuli ranged across only one octave), and any changes in perceived loudness would have differed across starting pitches and would not have systematically biased subjects. There were 324 trials (2 directions \times 2 surface forms \times 9 probes \times 3 starting frequencies \times 3 replications) which each subject received in a different random order.

Procedure

Subjects were tested individually, and initiated each trial by pressing a designated key. The auditory mask was presented for 2 s, there was a 1-s pause, and then either a series of discrete inducing stimuli or a glide was

presented. After the end of either the third inducing stimulus or the glide, there was a 500-ms pause and then the probe was presented. Subjects were instructed to respond as quickly but as accurately as possible as soon as the probe began playing, and responded by pressing either a key marked *S* (for *same*) or a key marked *D* (for *different*). Subjects were given 12 practice trials at the beginning of the session, and more practice was given if they requested it or appeared confused in any way. Practice trials were drawn randomly from the experimental trials. The entire session took approximately 50 min.

RESULTS AND DISCUSSION

On each trial, the nine possible frequencies that the probe could have had ranged in 25-cent increments from 100 cents below the final frequency of the inducing sequence to 100 cents above the final frequency of the inducing sequence. Were subjects responding accurately, we would have observed 0% *same* responses on the probes -100, -75, -50, -25, +25, +50, +75, and +100 cents from the final frequency of the inducing sequence and 100% *same* responses on the probe 0 cents from (i.e., identical to) the final frequency of the inducing sequence. Two types of analyses were conducted: analysis of variance (ANOVA) using estimates of the degree of memory shift, and direct comparison of the predicted asymmetries in the *same* responses of probes immediately above and below the final frequency of the inducing sequence. Estimates of the degree of memory shift were determined by calculating the weighted mean for each subject for each condition (i.e., by taking the sum of the products of the proportion of *same* responses to each probe and that probe's distance [in cents] from the final frequency of the inducing sequence and dividing by the sum of the proportion of *same* responses). All analyses were collapsed over starting frequency.

The proportion of *same* responses for each of the trial types is shown in Figure 1. Surface form did not influence the degree of memory shift, $F(1, 12) = 0.312$, $MSE = 107.19$, $p = .59$, although there was a trend in the predicted direction with glide trials ($M = 2.12$) producing a slightly greater forward shift than discrete trials ($M = 0.51$). Direction was not significant, $F(1, 12) = 1.28$, $MSE = 180.97$, $p = .28$, although the Surface Form \times Direction interaction was marginally significant, $F(1, 12) = 3.69$, $MSE = 137.08$, $p = .08$. Inspection of Figure 1 suggests that representational momentum was found only in descending discrete trials, but t tests using a Bonferroni correction ($.05/4 = .013$) revealed that none of the comparisons between the fourth and sixth probes in either the ascending glide, descending glide, ascending discrete, or descending discrete trials were significant.

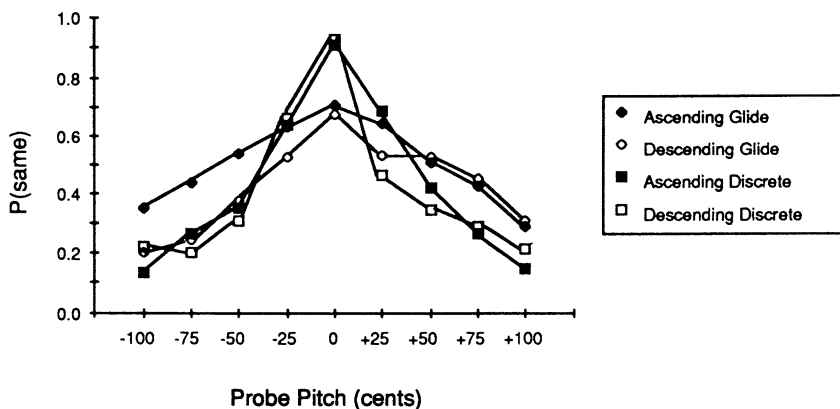


Figure 1. Probability of a *same* response as a function of probe pitch in Experiment 1

Although clear differences in the overall response distributions between glide and discrete trials were observed, little evidence for representational momentum with auditory stimuli was seen in any of the analyses. There was a trend toward a forward shift in the downward discrete trials, but the other conditions did not exhibit representational momentum. Although the response distributions were flatter for glide trials than for discrete trials, the distributions did not seem to be consistently shifted as a function of direction. The flatter distributions produced by glide trials may have been due to noise resulting from difficulty in encoding or perceiving the final perceived pitch of each glide, thus obscuring any effects of representational momentum.

EXPERIMENT 2

Failure to obtain representational momentum in Experiment 1 may be due to the duration of the final pitch-to-be-remembered. The final frequency of the inducing series was presented for a relatively longer time in the discrete trials (500 ms) than in the glide trials (approximately 50 ms), and the clearer trend toward representational momentum in the discrete trials (especially the descending trials) might be based on the longer presentation of the final frequency rather than on any differences in surface form per se. In this experiment, similar discrete and glide sequences were presented, but in glide trials the final frequency of the glide was held for a duration equal to the duration of the final discrete inducing stimulus.

METHOD

Subjects

Twelve subjects were drawn from the same pool used in Experiment 1. None of the subjects had participated in the previous experiment.

Apparatus

The apparatus was the same as in Experiment 1.

Stimuli

The stimuli were the same as in Experiment 1 with the following exceptions: The duration of each inducing stimulus in the discrete trials and the duration of each ISI were increased from 500 ms to 630 ms. The final frequency of the glide was held for an additional 630 ms. The duration of the glide + final frequency in the glide trials matched the duration from the onset of the first inducing stimulus to the offset of the third inducing stimulus in the discrete trials. Each subject received 324 trials (2 directions \times 2 surface forms \times 9 probes \times 3 starting frequencies \times 3 replications) in a different random order.

Procedure

The procedure was the same as in Experiment 1.

RESULTS AND DISCUSSION

Data were analyzed as in Experiment 1. Surface form did not influence shift magnitude, $F(1, 11) = 0.66$, $MSE = 39.74$, $p = .43$, although as in Experiment 1 there was a trend for glide trials ($M = 4.18$) to exhibit slightly greater forward shift than discrete trials ($M = 2.70$). As shown in Figure 2, direction significantly influenced shift, $F(1, 11) = 9.29$, $MSE = 108.96$, $p = .01$, such that memory for the final pitch of the ascending sequences was shifted forward more than memory for the final pitch of the descending sequences. The Surface Form \times Direction interaction was not significant, $F(1, 11) = 0.02$, $MSE = 76.58$, $p = .88$. Using a Bonferroni correction ($.05/4 = .013$), the asymmetries between the fourth and sixth probes were significant in the predicted direction for ascending glide, $t(11) = -3.49$; ascending discrete, $t(11) = -3.69$; and descending discrete trials, $t(11) = 3.09$; and marginally significant for descending glide trials, $t(11) = 2.92$.

There were virtually no differences between the response patterns found in the glide trials and the response patterns found in the discrete trials, and clear representational momentum patterns were observed in each condition. When the duration of the final frequency was

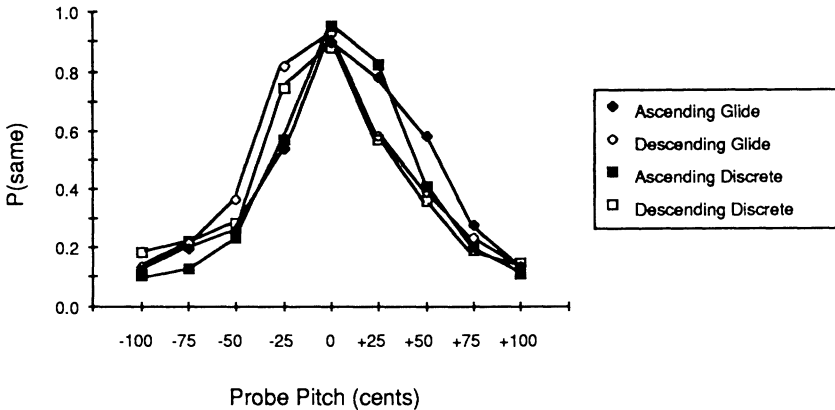


Figure 2. Probability of a *same* response as a function of probe pitch in Experiment 2

extended, the surface form of the stimulus did not significantly influence displacement. The only difference between the glide trials in Experiments 1 and 2 was that the final frequency was held constant for a longer duration in Experiment 2; similarly, the only difference between the discrete trials in Experiments 1 and 2 was the duration of each inducing stimulus. This pattern suggests that the representational momentum mechanism may require a stimulus of some minimum duration. Whereas the durations of the final frequencies in Experiment 1 were below that threshold, the durations of the final frequencies in Experiment 2 were above that threshold. When the final frequencies of the inducing sequences were lengthened in Experiment 2 though, virtually no differences were found between representational momentum in the glide and discrete trials.

It is still possible that the glide stimuli did, in fact, lead to more overshooting. By sustaining the final frequency of the glide, it is possible that subjects perceived not a constant velocity, but a deceleration. Thus, the glide stimuli may have been perceived as decelerating, whereas the discrete stimuli may have been perceived as having a constant velocity. Previous research using visual stimuli has shown that faster implied or apparent velocities lead to increased magnitudes of forward shift (Freyd & Finke, 1985; Hubbard & Bharucha, 1988) and that implied decelerations lead to decreased magnitudes of forward shift (Finke et al., 1986); therefore, in Experiment 2 it is possible that a larger shift initially caused by the glide was then reduced due to a perceived deceleration.

EXPERIMENT 3

This experiment further examined the possibility that the pattern found in Experiment 2 resulted from holding the final frequencies of the glide and the discrete sequences for equal periods of time. Both glide and discrete trials were presented, and as in Experiment 1, the glide stimuli ended without sustaining the final frequency of the glide. The duration of the third inducing tone in the discrete stimuli, however, was shortened so that it approximated the duration of the final frequency of the glide. Thus, the endings of the inducing sequences were again equal in duration, but now the glide should not be perceived as decelerating (although the discrete step may be perceived as accelerating). Additionally, sustaining the final frequencies of the glide and discrete stimuli by an equal but shorter time allows further examination of the hypothesis of whether lengthening the duration of the final frequencies can account for the differences in the displacement patterns between Experiments 1 and 2.

METHOD

Subjects

The subjects were recruited from an introductory psychology class at Eastern Oregon State College and received partial course credit for participating. Thirteen subjects participated in the current experiment, and data from an additional 2 subjects were discarded because of failure to follow instructions.

Apparatus

The apparatus was the same as in Experiment 1.

Stimuli

The stimuli were the same as in Experiment 1 with the following exceptions: The duration of the first and second inducing stimuli in the discrete trials was increased to 630 ms, and the duration of the third inducing stimulus was decreased to 50 ms. The duration from the onset of the first inducing stimulus to the offset of the third inducing stimulus matched the duration of the glide. Each subject received 324 trials (2 directions \times 2 surface forms \times 9 probes \times 3 starting pitches \times 3 replications) in a different random order.

Procedure

The procedure was the same as in Experiment 1.

RESULTS AND DISCUSSION

The data were analyzed as in Experiment 1. Neither the surface form, $F(1, 12) = 0.08$, $MSE = 35.64$, $p = .78$, nor direction, $F(1, 12)$

= 2.52, $MSE = 136.98$, $p = .14$, influenced the magnitude of the memory shift. The Surface Form \times Direction interaction approached significance, $F(1, 12) = 3.29$, $MSE = 140.52$, $p = .09$, and as shown in Figure 3, is driven by larger differences in glide trials than in discrete trials. As found in Experiment 1, the distribution for discrete trials is more peaked than the distribution for glide trials. As also found in Experiment 1, descending discrete trials demonstrate the clearest trend toward representational momentum, and little evidence is seen for representational momentum in other conditions. When the predicted asymmetries between the fourth and sixth probes were examined using a Bonferroni correction ($.05/4 = .013$), only the asymmetry in descending discrete trials approached significance, $t(12) = 2.33$, $p = .04$. As shown in Figure 3, there appear to be more *same* responses in Experiment 3 than in previous experiments, a pattern that may be attributable to confusion concerning the final pitch of the inducing sequence; specifically, the final frequency of the inducing sequence may have been presented too briefly to allow a full encoding of the pitch, and so subjects may have been more likely to be confused by probes with similar frequencies and thus more likely to respond *same*. Overall, with very short durations of the final frequency little evidence for representational momentum is seen.

What can the differences in the patterns of *same* responses in Experiments 1, 2, and 3 tell us about the nature of representational momentum? One difficulty in comparing the glide and discrete trials across the experiments is that velocity and duration appear hopelessly confounded. When glide trials are directly compared with discrete trials (Exp. 1), the durations of the final frequencies are unequal. When these durations are made equal by extending the duration of the final frequency of the glide (Exp. 2), velocities are unequal because glide stimuli may be interpreted as slowing in velocity whereas discrete stimuli may be interpreted as maintaining a constant velocity. When the duration of the final inducing stimulus in discrete trials is shortened to match the duration of the final frequency of the glide, discrete stimuli may be perceived as accelerating whereas glide stimuli may be perceived as maintaining a constant velocity (Exp. 3). It is not clear how these factors can be orthogonally manipulated (see Faust & Freyd, 1991, for further discussion of this issue).

Despite these caveats, some tentative suggestions may still be advanced. When the duration of the final frequency was lengthened, stronger representational momentum was found in both glide and discrete trials. Indeed, in Experiment 2 there was very little difference in the distributions of *same* responses between glide and discrete trials. When the durations of the final frequencies of the glide and the final

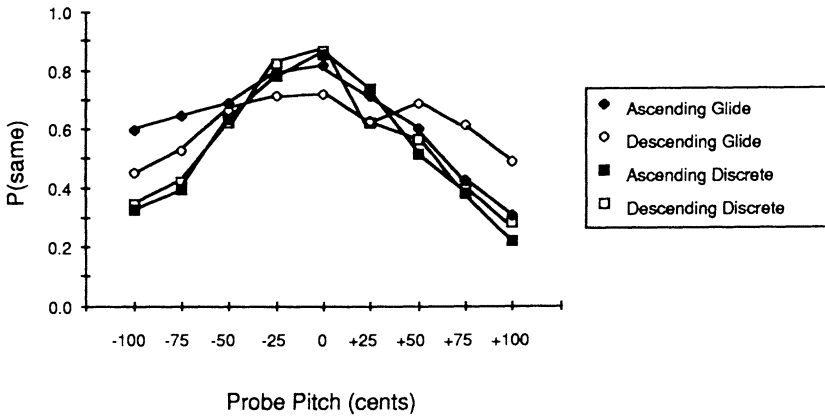


Figure 3. Probability of a *same* response as a function of probe pitch in Experiment 3

inducing stimulus were shortened, representational momentum was greatly diminished or eliminated. One possible explanation for this pattern is that the final frequency of the inducing sequence must be present for some minimum time for representational momentum to occur. Given that consistently strong visual representational momentum for implied rotation has been found with durations of 250 ms for each inducing stimulus (e.g., Freyd & Finke, 1984) and that strong visual representational momentum has been found for apparent motion in which the target is not held constant at its final location before vanishing (e.g., Hubbard & Bharucha, 1988), the minimum threshold seems to be higher for auditory representational momentum than for visual representational momentum. Perhaps auditory representational momentum requires an integration over longer periods of time than does visual representational momentum. If the stimulus is present for a shorter time, auditory representational momentum would not yet have had the opportunity to build up, and representational momentum would not be observed. Such a suggestion, although admittedly quite speculative, is also consistent with observations that the auditory modality is primarily temporal whereas the visual modality is primarily spatial, and with findings that auditory echoic memory may have a longer duration than visual iconic memory (e.g., Crowder, 1982; Darwin, Turvey, & Crowder, 1972).

If, as suggested earlier, representational momentum is a function (at least in part) of the surface form of the stimulus, then the strength of representational momentum would be a function of how successful the stimulus is in conveying a sense of motion to the subject; smooth

continuous glides would be predicted to convey a better sense of motion and hence result in larger magnitudes of representational momentum. Differences in shift magnitude between glide and discrete trials never attained significance, however, and thus representational momentum does not appear to be driven by how smooth (e.g., continuous) the motion of the stimulus itself appears to be. The obtained patterns are consistent with Freyd's (1993) hypothesis that representational momentum is determined primarily by the underlying nature of the stimulus and not by the surface form of presentation.

EXPERIMENT 4

One of the more robust findings in the literature on representational momentum and displacement with visual stimuli is that the amount of forward shift is related to target velocity; specifically, faster implied or apparent velocities lead to larger shifts. Freyd et al. (1990) reported an experiment in which implied velocity was manipulated by varying the ISI between the inducing stimuli. In general, as velocity increased, the size of the estimated memory shift also increased, although the correlation between velocity and memory shift was not as strong for auditory stimuli as had been previously reported for visual stimuli. One possible reason why the correlation might not have been as strong is the confound between direction and velocity discussed earlier, because the equal frequency separation should have resulted in ascending sequences being perceived as slower and more decelerating and descending sequences being perceived as faster and more accelerating. Alternatively, velocity effects may simply be weaker with auditory stimuli. This experiment examined whether the direction of target motion influences the velocity effect in auditory representational momentum.

METHOD

Subjects

Thirteen subjects were drawn from the same pool used in Experiment 3. None of the subjects had participated in the previous experiment.

Apparatus

The apparatus was the same as in Experiment 1.

Stimuli

The auditory mask was the same as that used in Experiment 1. There were six types of discrete trials: ascending fast velocity, ascending medium velocity, ascending slow velocity, descending fast velocity, descending medium

velocity, and descending slow velocity. For fast, medium, and slow velocity trials, the duration of each inducing stimulus and ISI was 250, 500, and 750 ms, respectively. The distance between each of the inducing stimuli was 600 cents (based on an equal-tempered tuning). Probes were spaced in 25-cent increments, with the lowest probe 75 cents below the third inducing stimulus and the highest probe 75 cents above the third inducing stimulus. For ascending trials, the starting frequency was either 500, 1000, or 2000 Hz; for descending trials, the starting frequency was either 1000, 2000, or 4000 Hz. There were 378 trials (2 directions \times 3 velocities \times 7 probes \times 3 starting frequencies \times 3 replications) which each subject received in a different random order.

Procedure

The procedure was the same as in Experiment 1.

RESULTS AND DISCUSSION

Weighted means were calculated as in Experiment 1 and analyzed in a 2 (Direction) \times 3 (Velocity) ANOVA. As shown in Figure 4, direction was not significant, $F(1, 12) = 2.37$, $MSE = 284.26$, $p = .15$, although, as predicted, memory for the final pitch was shifted above the final frequency for ascending sequences and below the final frequency for descending sequences. Velocity did not significantly affect the magnitude of the memory shifts, $F(2, 24) = 1.14$, $MSE = 55.63$, $p = .35$, nor was the Direction \times Velocity interaction significant, $F(2, 24) = 0.67$, $MSE = 54.21$, $p = .52$. Using a Bonferroni correction ($.05/6 = .008$), the asymmetry between the third and fifth probes was significant in descending fast trials, $t(12) = 4.55$, and was marginally significant in descending medium, $t(12) = 1.91$, and descending slow, $t(12) = 1.92$, trials. The asymmetries between the third and fifth probes for the ascending trials did not reach significance, however.

The support for a velocity effect in representational momentum for auditory stimuli in the current experiment is mixed. For descending motion, subjects were more likely to respond *same* to probes slightly below the frequency of the third inducing stimulus than to probes slightly above the frequency of the third inducing stimulus, and the magnitude of this asymmetry increased with increasing velocity. For ascending motion, subjects were more likely to respond *same* to probes slightly above the frequency of the third inducing stimulus than to probes slightly below the frequency of the third inducing stimulus, but these trends did not reach significance. This stronger effect with descending motion is consistent with the data in Experiments 1 and 3 in which descending discrete trials produced

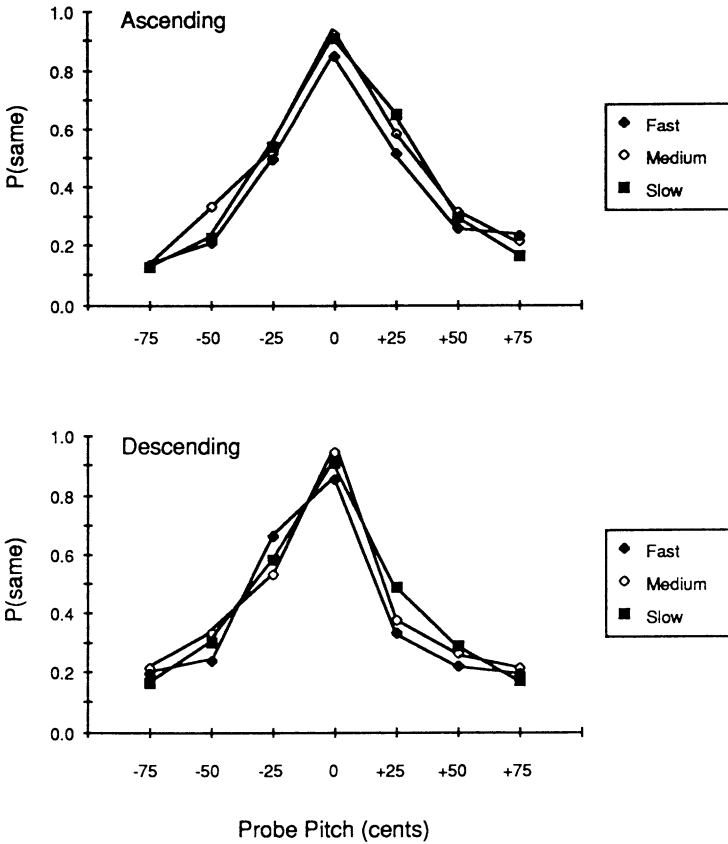


Figure 4. Probability of a *same* response as a function of probe pitch in Experiment 4 (data for the ascending trials are displayed in the upper panel; data for the descending trials are displayed in the lower panel)

data most consistent with a standard representational momentum pattern. Consistent with Freyd et al. (1990), the effect of velocity on auditory representational momentum in the current experiments seems relatively weak when compared with the robust effect of velocity on visual representational momentum.

GENERAL DISCUSSION

Experiments 1, 2, and 3 suggest that the surface form of the stimulus per se does not influence the magnitude of auditory representational momentum. What seems to be more critical, rather, is the duration of the final frequency. When the duration of the final frequency is

short, representational momentum is not observed, but when the duration of the final frequency is longer, representational momentum is observed. When the durations of the final frequencies of glide and discrete stimuli are equated and sufficiently long, there do not seem to be any differences in the magnitude of the memory shifts. Such a result is consistent with Freyd's (1987, 1993) hypotheses concerning the dynamic nature of mental representation in that auditory frequency, a relatively continuous stimulus dimension, exhibits representational momentum regardless of whether the actual stimulus sequences are composed of discrete or continuous exemplars. These conclusions, however, must be tempered by an acknowledgment of the difficulties of disentangling duration and velocity, because sustaining the final frequency of a glide or shortening the length of the final discrete inducing tone seems to inevitably introduce confounds of duration with velocity.

The results of Experiments 1 and 2 suggest that the minimum length of time that the final frequency must be presented if representational momentum is to be obtained is between 500–630 ms. Freyd et al. (1990), however, obtained representational momentum using discrete auditory stimuli that were presented for only 250 ms each. One possible reason for this apparent discrepancy is that the stimuli in the current experiments may have been perceived as more musical than the stimuli used by Freyd et al. In the current experiments the interval between the first and third inducing stimuli and between the beginning and ending of the glide was an octave (1200 cents), and it is possible that representational momentum may have been overwhelmed or diminished because of schematic effects of the octave interval (see Hubbard, 1993a). If such musical schemata were initially evoked, however, their influence should have been reduced (at least in the discrete groups) by the placement of the second inducing stimulus; specifically, because the second inducing stimulus was in a tritone relationship to the first and third inducing stimuli (i.e., 600 cents higher or lower), any expectancies due to evocation of musical key should have been diminished. Nonetheless, it is possible that subjects may treat an auditory sequence differently if that sequence is perceived to be musical.

A second possible reason for the apparent discrepancy between the current experiments and Freyd et al. (1990) is the range of possible final frequencies. Freyd et al.'s inducing stimuli spanned only one octave (although the ascending inducing stimuli spanned a lower set of frequencies than the descending stimuli), whereas the inducing stimuli in the current data spanned three octaves. It may be that representational momentum with auditory stimuli is found only within

the range of frequencies examined by Freyd et al. and is not as strong when a larger frequency range is considered. Perhaps more important, the final inducing stimulus was the same for both ascending and descending sequences in Freyd et al., and the repeated presentation of that frequency over the course of an experiment may have focused relatively more activation in the representation corresponding to that frequency and thus lowered its threshold for activation; in essence, the representation for that final frequency was continually primed after the first few trials, and this residual activation lowered the threshold and allowed representational momentum. Without such priming, the threshold might have been too high and representational momentum not obtained. The current experiments avoided this risk of priming by using a range of final frequencies and by employing the auditory mask at the beginning of each trial.

One particularly interesting aspect of the data is that even with relatively short durations of the final frequency, trends toward representational momentum could be seen with descending motion. The discrete trials of Experiments 1 and 3, as well as the data in Experiment 4, all suggest that representational momentum is greater or more likely with descending motion than with ascending motion. The representational momentum patterns for descending motion occurred consistently, even though the analogous patterns for ascending motion were weak or inconsistent. Why should descending motion be more likely to exhibit representational momentum or exhibit larger representational momentum than ascending motion? One possibility involves the auditory equivalent of a "gravity effect." Hubbard (1990, 1995) noted that subjects' judgments of the position of a visually moving target, in addition to being displaced in the direction of anticipated motion, were also displaced in a direction consistent with an "internalized gravitational influence." Visual targets moving horizontally were also displaced downward, and descending visual targets were displaced forward more than ascending visual targets, patterns consistent with the idea that rising objects (that do not achieve orbital or escape velocity) decelerate (and then begin to fall) and that falling objects accelerate. Subjects may associate a descending auditory sequence with a descending object and an ascending auditory sequence with an ascending object; in fact, some subjects spontaneously reported just these sorts of associations (e.g., the descending glide sounded like a bomb dropping). If there is such an association, and given the stronger forward displacements found for descending visual targets, it would not be surprising to find greater sensitivity to or effects of representational momentum with descending auditory motion.

The effect of velocity on representational momentum for descend-

ing auditory motion is perfectly consistent with the effect of velocity on representational momentum for visual implied rotation (e.g., Freyd & Finke, 1985) and apparent linear motion (e.g., Hubbard & Bharucha, 1988), but the effect of velocity on representational momentum for ascending auditory motion is not consistent with the effect of velocity on representational momentum for visual stimuli. Effects of auditory velocity in the current experiments are much weaker than effects of visual velocity in Freyd and Finke (1985) and in Hubbard and Bharucha (1988). Consistent with this conclusion, Freyd et al. (1990) also report much lower correlations for memory shift and velocity for auditory stimuli than for visual stimuli. Stimulus velocity may not thus be as critical a component in determining auditory representational momentum as it is in determining visual representational momentum.

In conclusion, representational momentum can be found with auditory stimuli, and thus representational momentum is not solely a visual phenomenon or dependent upon the visual properties of a stimulus. Consistent with predictions from Freyd's (1987, 1993) theory, auditory representational momentum does not seem to depend on the surface form of a stimulus, and can be found when stimuli from a continuous dimension are presented in either a relatively continuous form or a relatively discrete form. With descending sequences, patterns consistent with visual representational momentum and effects of velocity on visual representational momentum are observed; with ascending sequences, patterns are not quite as consistent as those seen with visual representational momentum. Overall, the magnitude of auditory representational momentum is influenced by the direction of pitch motion, the velocity of pitch motion, and the duration of the final part of the inducing stimulus, but not by whether the stimuli are presented in a continuous or discrete form.

Notes

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