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Representational Momentum in Memory for Pitch

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When a visual pattern is displayed at successively different orientations such that a rotation or translation is implied, an observer's memory for the final position is displaced forward. This phenomenon of *representational momentum* shares some similarities with physical momentum. For instance, the amount of memory shift is proportional to the implied velocity of the inducing display; representational momentum is specifically proportional to the final, not the average, velocity; representational momentum follows a continuous stopping function for the first 250 ms or so of the retention interval. In a previous paper (Kelly & Freyd, 1987) we demonstrated a forward memory asymmetry using implied changes in pitch, for subjects without formal musical training. In the current paper we replicate our earlier finding and show that the forward memory asymmetry occurs for subjects with formal musical training as well (Experiment 1). We then show the structural similarity between representational momentum in memory for pitch with previous reports of parametric effects using visual stimuli. We report a velocity effect for auditory momentum (Experiment 2), we demonstrate specifically that the velocity effect depends on the implied acceleration (Experiment 3), and we show that the stopping function for auditory momentum is qualitatively the same as that for visual momentum (Experiment 4). We consider the implications of these results for theories of mental representation.

When a visual pattern is successively displayed at different orientations such that a rotation is implied, an observer's memory for the final orientations tends to be displaced forward (see Figure 1). Effects similar to those found for implied rotational motion (e.g., Cooper, Gibson, Mawafy, & Tataryn, 1987; Freyd & Finke, 1984, 1985; Freyd & Johnson, 1987; Kelly & Freyd, 1987) have been discovered for implied translational motion (e.g., Finke & Freyd, 1985; Finke, Freyd, & Shyi, 1986). When the transformation is subjectively continuous, the memory displacements are especially pronounced (e.g., Faust & Freyd, 1990; Hubbard & Bharucha, 1988; Hubbard, 1990).

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This phenomenon has been termed *representational momentum* (Freyd & Finke, 1984) because of its similarity to physical momentum, in which a physical object continues along its path of motion due to inertia. As with physical momentum, representational momentum is proportional to the implied velocity of motion (e.g., Freyd & Finke, 1985; Finke et al., 1986). In addition, the representational analogue of physical momentum also varies with the implied acceleration (and thus implied final velocity) of the pattern (Finke et al., 1986).

Representational momentum is not ubiquitous. Freyd and Finke (1984; also see Freyd & Johnson, 1987) found that, by reversing the order of the first two items in the inducing display and thereby disrupting the coherence of the implied transformation, the memory asymmetry disappears. Kelly and Freyd (1987) found that when the shapes of objects are radically altered from item to item in an implied rotation, momentum effects do not emerge. Also, when the inducing display ends with an implied final velocity of zero, the momentum disappears (Finke et al., 1986). Similarly, Kelly and Freyd (1987) found that an implied deformation of a rectangle into a perfect square produced no memory asymmetry, suggesting that when the inducing display ends with an item that is prototypical of a category, internal transformations may be halted.

The similarities between physical and representational momentum might be taken as evidence that the visual system has internalized knowledge of physical momentum in its operations. If this coupling is relatively tight, one might expect representational momentum to appear only with transformations to which physical momentum applies. Transformations that are not generally correlated with changes in the

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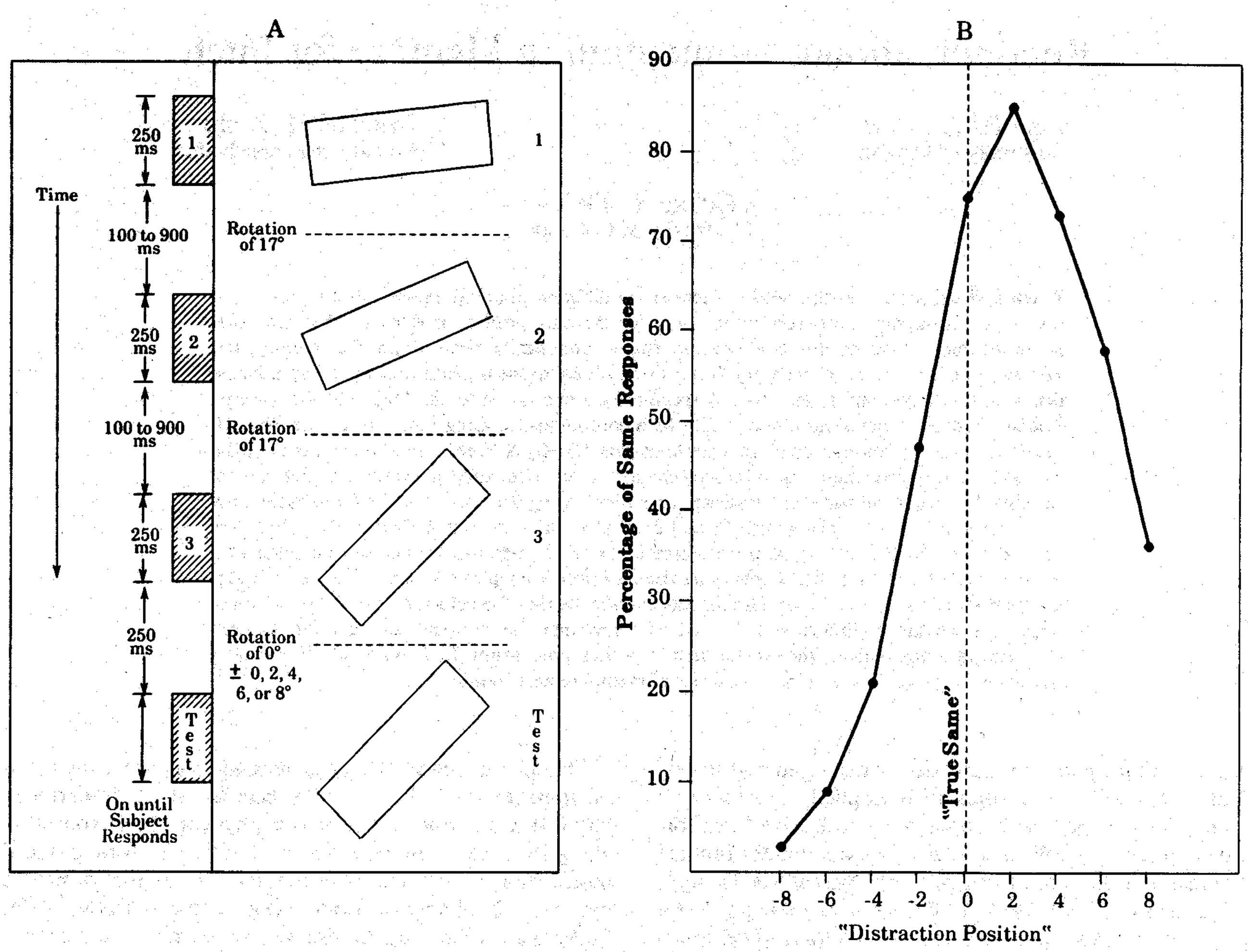

Figure 1. A. Example display sequence and test position used by Freyd and Finke (1985). B. Results from Freyd and Finke (1985) averaged across all subjects and conditions. Positive distractor positions represent forward displacements of the fourth rectangle; negative values, backward displacements.

spatial locations of an object might therefore not be expected to produce momentum.

An alternative view of why representational momentum exists was presented by Freyd (1987) in her theory of *dynamic mental representations.* Freyd suggested that representational momentum is a necessary characteristic of a representational system with spatiotemporal coherence, just as physical momentum is a property of objects embedded in a spatiotemporal world. Freyd thus predicts representational momentum effects for any dimension affording continuous transformation, including, in the visual domain: rotation, translation, change in illumination, plastic deformation of shape. From this perspective, it is the adaptive significance of time and anticipatory computations that necessarily results in representational momentum (Freyd, 1990), as opposed to the idea that representational momentum is directly useful. Thus, according to Freyd's argument, representational momentum should also exist for representations of nonvisual information, such as loudness or pitch.

Kelly & Freyd (1987) reported two instances of forward memory displacements for mental transformations that are not obviously analogous to physical transformations in which one would expect to find physical momentum. In Kelly & Freyd's Experiment 7 they discovered a significant forward shift in memory for the shape of a rectangle after an implied shrinking or fattening of the rectangle. In their eighth experiment they report a shift in memory for pitch after a sequence of tones rising or falling in pitch.

In the current paper we begin by considering Kelly & Freyd's (1987) report of auditory momentum. In our first experiment we replicate their finding, while also creating a control condition. The control condition is based on Freyd and Finke's (1984; Experiment 2) finding that, when the presentation order of the first two stimulus items is reversed, the memory asymmetry disappears. We thus compare trials in which the inducing tones are presented in strictly ascending or descending pitch with trials in which the presentation order of the first two tones is reversed. We predict representational momentum in the first case only. In our first experiment we also address a curiosity that Kelly and Freyd (1987) had reported from pilot data: that only subjects without musical training show a momentum effect for tones. Thus, in Experiment 1 we compare musically trained and untrained subjects.

In subsequent experiments we then ask how similar in structure the memory effect for tones is with what is known about representational momentum for visual stimuli. For instance, in Experiment 2 we ask whether the memory shift depends on implied velocity, and in Experiment 3 we look at the effects of implied acceleration. We also consider the stopping function for auditory momentum, based on the results Freyd & Johnson (1987) reported when they varied retention intervals for implied rotational motion.

Experiment 1

Kelly and Freyd (1987) found a momentum effect using ascending and descending changes in pitch. This suggests that representational momentum is not limited to visual stimuli. Our primary goal with Experiment 1 was to replicate Kelly and Freyd's Experiment 8 using different stimulus tones, different equipment for generating the tones, and a new group of subjects. As in Kelly and Freyd's experiment, the subject's task was to listen to three tones, remember the third, and then decide whether a fourth tone was the *same as* or *different from* the third tone. Also as in Kelly and Freyd, we blocked the Direction of the tonal sequence (ascending versus descending). Kelly and Freyd varied Direction of tonal sequence between subjects; in Experiment 1 we counterbalanced block order within subjects.

Beyond a simple replication, we hoped to validate the predicted finding of representational momentum for auditory stimuli, by including a condition in which we specifically did not predict representational momentum. We created such a condition based on Freyd and Finke's (1984; Experiment 2) finding for implied rotational motion, which found that by reversing the order of the first two items in the inducing sequence, no memory asymmetry is produced (also see Freyd & Johnson, 1987). We thus introduced the factor of Coherence, where coherent tonal sequences were strictly ascending or descending, and incoherent sequences were created by reversing the order of the first two tones. We predicted a representational momentum effect for coherent sequences of pitches, but not for incoherent sequences of pitches. Although the incoherent order could be compatible with a forward memory asymmetry based solely on the second and third inducing tones, we predict that the three tones as a pattern do not provide coherent evidence to the subjects about the path of pitch change, as previously found for visual momentum.

A second goal was to investigate a curious finding that Kelly and Freyd (1987) reported. In their pilot investigations, they only could measure a momentum effect for implied changes in pitch with non–musically trained subjects. The musically trained subjects made no errors, and thus showed no asymmetry for ability to distinguish between same pitches and higher or lower pitches. Kelly and Freyd therefore only used subjects without musical training in their Experiment 8. In the current experiment we varied Musical Training by using subjects with extensive musical training as well as subjects with essentially no formal training.

We predicted that the musically trained subjects would show a momentum effect if the task was of sufficient difficulty to lead them to make any errors at all. This explanation assumes that musically trained subjects are better able to discriminate pitches, and that the pitches presented to subjects were too dissimilar (Kelly and Freyd were limited by their equipment). Using more similar pitches we should be able to measure a momentum effect with musically trained subjects. Experiment 1 used a selection of tones with four times finer gradation of pitches than had been used by Kelly and Freyd.

In addition to Direction of tonal sequence, Coherence, and Musical Training, we included an additional factor of Stimulus Musicality (see Table 1). Stimulus Musicality was included out of curiosity about a possible role of "musicality" in auditory momentum. We varied the musicality of the inducing stimuli in Experiment 1 by creating two separate stimulus sets, one considered more musical than the other. Our curiosity arose from a theoretical issue suggested by the possibility that subjects with musical training might not show representational momentum. Perhaps musicality would influence the sort of transformation subjects use in moving from pitch to pitch, such that musical tones lead to discrete jumps along the pitch continuum, and nonmusical tones lead to continuous movements. Freyd (1987) has predicted that representational momentum will exist for any dimension of change the mind can represent continuously. We attempted to influence the musicality of a progression of tones by altering the number of half steps in the desired intervals. We verified our assumption of musicality with a forced-choice task in which subjects were asked to indicate the more musical of two tonal sequences (Experiment 1B), immediately after the replication of auditory momentum (Experiment 1A). We were interested in the possibility that we might see more momentum for the nonmusical stimuli due to a greater tendency to represent the pitches continuously than by categories of tones.

Table 1
Experiment 1A

	Stimulus Musicality			
	Musical		Nonmusical	
	Coherence			
Direction	Coherent	Incoherent	Coherent	Incoherent
Ascending	1261	1892	1103	1813
	1892	1261	1813	1103
	2523	2523	2523	2523
Descending	3785	3154	3943	3233
	3154	3785	3233	3943
	2523	2523	2523	2523

Note. Within each cell the three tones making up the inducing sequences for different trial types in Experiment 1A are given in presentation order from top to bottom. Stimulus Musicality was varied between subjects; Coherence and Direction were blocked and varied within subjects. An additional between-subject factor was Musical Training (see text). The nine test tones used for each trial type were 2443, 2463, 2483, 2503, 2523, 2543, 2563, 2583, 2603 Hz. All figures in table are Hz.

Method—1A

Subjects. Sixteen members of the Cornell University community were paid to participate. These subjects were solicited through posted advertisements on campus bulletin boards. Eight people with over five years of musical training and eight people with under one year of training were invited to participate in the experiment. These people were grouped in the "musical" and "nonmusical" conditions of Musical Training, respectively. The "musical" subjects had from 5.5 to 12 years of formal musical training, with an average of 9.31 years. The "nonmusical" subjects had from 0 to 1 years of formal musical training, with an average of 0.25 years.

Tone generation. Tones for these experiments were generated on an IBM PC-XT and were played through the computer's built-in speaker. The software used the microsecond timing capabilities of a TECMAR clock board to generate the desired frequencies. We used an HP oscilloscope to tune the computer's tone generation (+ rounding error of ± 0.5 Hz).

Stimulus construction. We programmed our computer to generate a sequence of five tones separated by equal Hertz intervals[1] for the musical stimuli, and five tones separated by equal Hertz intervals for the nonmusical stimuli, with the additional constraint that the middle tone be the same for the two sequences. Each five-tone sequence was designed so that the three highest tones could be used in experimental trials to induce a descending pitch sequence, and the three lowest tones could be used to induce an ascending sequence. Both descending and ascending sequences would thus end on the middle of the five tones. In this way every trial in the experiment would end on the same to-be-remembered tone (2523 Hz).

We attempted to influence the "musicality" of a progression on tones by altering the number of half steps in the desired intervals. We created a computer program to arrive at a sequence of five tones where the middle tone was given (2523 Hz, the middle tone used by Kelly & Freyd, 1987) and with the constraint that the intervals be separated by a constant number of Hertz. Musical sequences used an integral number of half steps, which corresponded to common musical intervals, whereas the nonmusical sequences used nonintegral numbers of half steps (actually halves of half steps). Using an iterative procedure that took as input the number of half-steps desired, the program arrived at the following two five-tone sequences (in Hz): 1261, 1892, 2523, 3154, 3785 for the musical stimuli, with intervals between them corresponding approximately to a 5th, 4th, major 3rd, and minor 3rd, respectively, and 1103, 1813, 2523, 3233, 3943 for the nonmusical stimuli.

Nine test tones were used, ranging from 2443 to 2603 Hz in 20-Hz steps. These tones are much closer to the actual third tone than were the test tones used by Kelly and Freyd. In fact, all of the test tones are within one half step of the third tone used in all trials of this experiment (2523 Hz). For data analysis, responses depending on test tone were collapsed to a single dependent measure of amount of memory shift (as described in Results).

Experimental design and block order. In this experiment four independent variables were used in a 2 × 2 × 2 × 2 design (see Table 1). Two factors were varied between subjects: Musical Training and Stimulus Musicality (musical versus nonmusical tone sequences), each as described in the sections above. The remaining two factors were varied within subjects: Direction of implied pitch change (ascending or descending); and Coherence (coherent versus incoherent) sequence.

The two between-subjects factors resulted in four groups of subjects, each group containing four individuals. Within-subjects factors were in blocked trials, resulting in four blocks of experimental trials. A Latin Square arrangement was used to determine four block orders. Each block order was used for one subject from each of the four between-subjects groups.

Procedure. Each subject completed four experimental blocks of trials, each block preceded by a practice block of the same sort of trials as used in the experimental block. Trials within a block all had identical inducing sequences, and only varied by the test tone, so that there were always nine trial types within a block. The first practice block had 36 trials, four repetitions of each trial type. The remaining practice blocks each had 18 trials, two repetitions of each trial type. Each of the four experimental blocks had 63 trials, seven repetitions of each trial type. The order of trials was randomized for each subject and within each block.

Interstimulus intervals (ISIs), the durations of the tones, and the retention interval were held constant at 250 ms. The test tones were played for 250 ms, or until the subject responded, whichever came first. The (extremely infrequent) response times of less than 250 ms or greater than 2,000 ms were not included in the data analyses for any of the experiments reported in this paper.

Before beginning the experiment, subjects were instructed to respond as rapidly and accurately as possible when presented with the fourth tone in a sequence. They were instructed to hit the "\" key on the IBM PC/XT keyboard if they thought the fourth tone was exactly the same in pitch as the third tone, and to hit the "/" key if the fourth tone was at all different. Subjects were also instructed that the percentage of same and different trials might not be evenly balanced, but that since the trials were in a random order each response should be independent of the previous responses.

Method—1B

Experiment 1B was run immediately after Experiment 1A for each of the 16 subjects (in the same sitting). Experiment 1B was intended only to verify the musicality manipulation. Subjects were presented with two three-tone sequences separated by a 1-second silence. There were no test tones. The ISIs and the durations were always 250 ms, just as in the first experiment, but no data were discarded on the basis of response time. The two series of tones contained in a given trial were always of the same direction (ascending versus descending) and order (coherent versus incoherent). Thus, a subject never had to compare series that differed in anything other than musicality. The subjects responded by pressing the "\" key if they thought the musical series came first, and by pressing the "/" key if they thought the musical series came second.

There were four independent variables: Musical Training (varied between subjects based on musical training as in Experiment 1A); Direction of pitch change within a sequence (ascending versus descending); Coherence (coherent versus incoherent); and Order of sequence (musical series first or nonmusical first). All eight combinations of the latter three variables were presented to each subject in a random order. Subjects completed a practice block of trials consist-

[1]The perception of equal pitch changes may correspond more closely to equal-cent intervals than equal-Hertz intervals. If so, our ascending sequences may imply a slight negative acceleration, and our descending sequences, a slight positive acceleration. Even so, the implied final velocities (expressed as change in cents over time) in the ascending and descending sequences that we used are very similar. Thus, we expect no main effects of direction of implied pitch change in the experiments reported in this paper. In Experiment 3, where effects of final velocity and acceleration are investigated by varying the temporal intervals of the inducing display, the positive and negative accelerations are of sufficient magnitude that they hold qualitatively whether the change in tones are analyzed in terms of equal-Hertz or equal-cent intervals.

ing of 16 trials (two repetitions of each type trial type), and then an experimental block of 56 trials (seven repetitions of each trial type).

Results—1B

We will consider the results from Experiment 1B first, because they inform our analysis of Experiment 1A. The first and most important question we addressed was whether the forced-choice task in Experiment 1B would indicate that subjects agree with us in their relative designation of musical versus nonmusical tone sequences. Our first analysis looked at the total percentage of matches (that is, identifying the "musical" sequence as musical) each subject made in the experimental block. We found that all 16 subjects matched over half (chance). The average (73%) across subjects was significantly different from chance: $t(15) = 8.10$; $p < .001$.

We also performed a three-way ANOVA on the data from Experiment 1B, in which the Musical Training (musical versus nonmusical) was a between-subject factor, Direction of tonal sequence (up or down) was a within-subject factor, and Coherence of tonal sequence (coherent or incoherent) was a within-subject factor. The ANOVA revealed two significant effects. Subjects with musical training had a higher percentage of matches (79%) than those without musical training (66%): $F(1, 14) = 8.78$; $p < .01$. The tonal sequences that ascended in pitch resulted in more matches (81%) than those that descended (64%): $F(1, 14) = 12.65$; $p < .01$. Coherence of tonal sequence (72% matches for coherent sequences versus 73% for incoherent sequences) had essentially no effect on judgments of musicality. There were no statistically significant interactions.

Both the simple t test and the ANOVA revealed highly interpretable results for Experiment 1B. Our manipulation of musicality did have the predicted effect on our subjects, in that they chose as more musical the tonal sequences we considered more musical. Further, the subjects with musical training showed their agreement with our designation of musical tones more strongly than did the subjects without musical training. These results indicate that we should look for an effect of musicality on the results of Experiment 1A. Also these results add validation to our subject variable of musically trained versus untrained individuals, in that the musically trained subjects were better able to identify the musical tonal sequences.

Results—1A

Results for each of the nine test tones (measured in Hz differences from the to-be-remembered tone) were reduced to a single dependent measure for each subject and condition by calculating a weighted mean using the number of same responses for each test tone. We will refer to these weighted means as shifts. A shift of 0.0 Hz would indicate no memory shift at all. A positive shift indicates a representational momentum effect (e.g., remembering the third tone as being lower in pitch than it actually was, given a descending inducing sequence); a negative shift indicates a memory failure in the other direction. We used weighted means to estimate shift for this experiment, as it currently seems the most reliable for analyzing individual subjects' results. In Experiments 2–4 we use quadratic regression for estimating shifts, so that our results are more comparable to the studies using visual stimuli. See Faust & Freyd (1990), for a discussion of various ways to estimate memory shift.

In our preliminary analysis we looked for an effect of Coherence of tonal sequence. We had predicted that there would be a greater forward memory shift for coherent tonal sequences than for incoherent sequences. This prediction was supported by the finding of significantly larger shifts for the coherent sequences than for the incoherent tonal sequences (See Table 2). In our subsequent analyses we consider only the data for trials with coherent sequences.

We next performed a three-way ANOVA with the two between-subjects factors of Musical Training (musical or not) and Stimulus Musicality (musical or not), and with the within-subjects factor of Direction of sequence (up or down). As Table 2 summarizes, this ANOVA revealed an overall representational momentum effect in that the memory shift of +3.31 Hz was significantly different from 0 Hz. Similarly, a one-sample t test using means for all coherent trials for each of the 16 subjects reveals $t(15) = 2.48$; $p < .05$. The hypothesis that musical subjects might show a smaller representational momentum effect was not supported by the data. There was no statistically significant main effect for Musical Training, and the trend was that musical subjects showed a greater memory shift than did nonmusical subjects. Although the trend for Stimulus Musicality was in the direction predicted, the difference did not reach statistical significance. There was no significant effect of Direction; the ascending and descend-

Table 2
Summary of Main Effects Tested in Experiment 1A

	Degrees of freedom	MS	F	p
Four-way ANOVA:				
Coherent (+3.31) vs. Incoherent (−0.32)	1,12	.5271/.0311	16.95	.001
Three-way ANOVA:				
Mean for Coherent trials (+3.31)	1,12	.8770/.1633	5.371	.039
Musical (+4.28) vs. Nonmusical (+2.34) subjects	1,12	.0753/.1633	0.461	.510
Musical (+2.12) vs. Nonmusical (+4.50) stimuli	1,12	.1135/.1633	0.695	.421
Ascending (+3.61) vs. Descending (+3.01) sequences	1,12	.0072/.0658	0.109	.747

Note. Condition means (in Hz) are given in parentheses. The four-way ANOVA revealed no other significant main effects or interactions. The three-way ANOVA (using results from Coherent trials only) revealed no significant interactions.

ing sequences led to very similar average shifts. None of the interactions were significant (and the three 2-way interactions each yielded $Fs < 1$).

The results from the 3-way ANOVA produced no evidence that subjects with musical training show a smaller representational momentum effect than do subjects without musical training, a possibility that was raised by Kelly & Freyd's (1987) results. However, to directly verify that subjects with musical training can be shown to have representational momentum in memory for pitch, we performed one final analysis looking only at those eight subjects. We found that the memory shift of +4.20 Hz was significantly greater than 0: $t(7) = 2.43$; $p < .05$.

Discussion

The primary goal of Experiment 1 was achieved; we replicated representational momentum for auditory memory. In addition we extended Kelly and Freyd's initial report of auditory momentum in a number of ways. First, we showed that the factor of Coherence of inducing sequence leads to the predicted effect; there is significantly greater momentum for coherent than incoherent sequences. Second, we demonstrated representational momentum using subjects with extensive musical training.

Experiment 1B verified our musicality manipulation, in that subjects were able to label as musical the sequence we coded as "musical." However, this factor did not have a statistically significant effect on the magnitude of representational momentum in Experiment 1A. Future investigations might attempt to make the difference in musicality of the tones even greater (perhaps the "musical" tonal sequence we used was not particularly musical, even if it was more musical than the other). Future studies should also correct one problem with the current manipulation of musicality—it is confounded with implied velocity. The musical stimuli we used have an implied velocity of 1.26 Hz/ms, and the nonmusical stimuli have an implied velocity of 1.42 Hz/ms, due to the greater tone ratios used in the nonmusical stimuli. Implied velocity and musicality could be varied somewhat independently by varying interstimulus intervals as well as pitch intervals.

Similarly, while we can interpret the positive finding of representational momentum for the musically trained subjects, we can not conclude much from the negative result of no effect of musical training. This is of course true of negative results in general, but it seems especially relevant in this experiment, where the role of formal musical training on music cognition may be relatively weak for subjects who have been exposed to extensive amounts of music informally (Bharucha & Stoeckig, 1986). In other words, it remains possible that representational momentum will be greater for subjects who are more inclined to treat pitches as just noise than for subjects who are inclined to categorize pitches into discrete tones. This possibility awaits future investigation. For the remainder of the current study we investigate the structural similarity between representational momentum for pitch and for visual stimuli.

Experiment 2

Freyd and Finke (1985) first reported a velocity effect for representational momentum (see Figure 2A). In their experiment they varied the implied rotational speed of a line-drawn rectangle using nine different ISIs. In our Experiment 2 we ask whether a qualitatively similar effect occurs when we vary the implied velocity for sequences of ascending or descending tones.

Method

Subjects. Ten subjects from the Cornell University community were recruited for their participation in a series of experiments, all using a standard memory task with auditory stimuli (including Experiments 2 and 4 reported in this paper). Subjects were paid at the completion of all the experiments, which were run in sequence, over the course of a few days, in three separate 1-hr blocks. Data from 1 of the 10 subjects was excluded from analysis due to error rates over two standard deviations higher than the mean. Error rates were analyzed separately from representational momentum shifts or other predicted effects.

Stimuli and apparatus. The tone-generating equipment was identical to that used in Experiment 1. The inducing tones used in this experiment were the same as those used in the nonmusical coherent series of Experiment 1A. The test tones were the same as in Experiment 1A except that only the middle seven tones were used (i.e., the highest and lowest tones were dropped).

Procedure. Individual trials were structured identically to trials in Experiment 1A. The stimulus durations and the retention interval remained constant at 250 ms. The ISIs were varied from 100 to 900 ms in 100-ms steps. Direction of tonal sequence (ascending or descending) was divided into two sets of blocks, and set order was counterbalanced across subjects.

Subjects completed two sets (differing only in Direction of tonal sequence) of three identical blocks of 189 experimental trials, each block preceded by a practice block of 21 trials. Each experimental block was composed of three identical sets of 63 trials. The 63 trials consisted of one of each of the nine ISI conditions × each of the seven test tones. For each practice block, 21 trials were chosen randomly from the entire set of 63 trials. Subjects were given the opportunity to rest between each block, and between each of the sets of 63 trials within the experimental blocks.

Results and Discussion

We analyzed the data in two separate ways. In our first analysis we attempted to make our results as comparable as possible with Freyd and Finke's (1985) results (see Figure 2A). Therefore we used their technique of estimating shifts by solving the quadratic regressions performed on the total number of same responses for each test tone for each velocity condition. Figure 2B displays the results from the current experiment analyzed in a way comparable to Freyd and Finke's (1985) analysis (Figure 2A). Although the correlation of 0.54 between estimated memory shift and implied velocity is not significantly different from zero, nor as great as Freyd and Finke's correlation of 0.90, at least the correlations are not significantly different from one another (see Hedges & Olkin, 1985; page 235): $Q = 2.2743$; $p > .10$.

Freyd and Finke (1985) used data from only seven of nine distractor positions because of the very low number of same responses for two positions; estimates of shift using quadratic

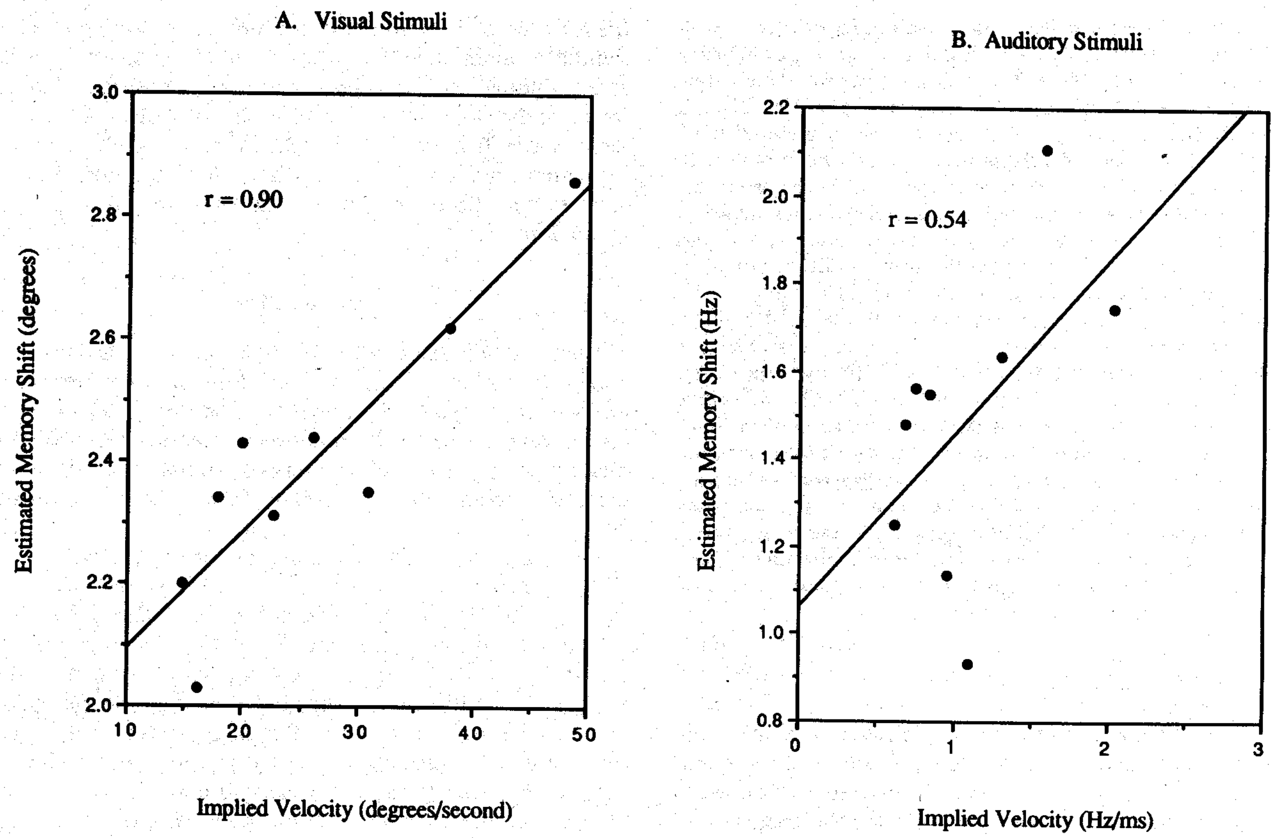

Figure 2. A. The velocity effect reported by Freyd and Finke (1985) for implied rotational momentum. B. An analogous velocity effect found in the current Experiment 2 for implied changes in pitch.

regressions are heavily influenced by departures from a good parabolic fit. We had a similar problem with our results in that each end of the distribution was flat; subjects committed false positive on only 7% of the trials for probe tones that differed from the third tone by 60 Hz. Furthermore, over 65% of these rare errors were produced by a single subject. This problem was evident in the relatively low R-squared values (average of 72%) compared with Freyd and Finke's (1985) R-squared values (average of 96%). However, with only seven test tones to start with we did not want to drop any of the data and still attempt quadratic regressions (as they use three degrees of freedom). Therefore, we used a more sensitive measure of the velocity effect by focusing solely on test tones that were closest in frequency to the standard tone (a similar analysis was performed by Freyd, Pantzer, & Cheng (1988, Experiment 4). For each ISI, we calculated the asymmetry in error rates between the forward and backward probe tones that differed from the third tone by 20 Hz. The size of this asymmetry was taken as an index of the size of the memory shift at each velocity. We predicted that a greater asymmetry should be found at higher velocities. This analysis reached a higher correlation, of $r = 0.78$ ($p < .05$), between estimated memory asymmetry and implied velocity.

The correlation between implied velocity and memory shift for auditory stimuli in Experiment 2 is smaller than the correlation found for visual stimuli by Freyd and Finke (1985). It is not clear whether the difference in the sizes of the correlation is due to the differences in sensory modalities, or if instead it is a function of something less interesting, like the range of stimulus items used on each dimension, or even the number or motivation of participating subjects. The meaningful finding is that the pattern for auditory stimuli replicates the visual velocity effect qualitatively.

Experiment 3

Finke et al. (1986) extended the velocity effect for representational momentum in the visual domain by showing that the implied final velocity, rather than the average velocity, is proportional to the magnitude of the memory shift. Finke et al. manipulated implied final velocity using a positive, negative, and zero acceleration condition, while holding average velocity constant for implied translatory movements of dots on a computer screen. Figure 3A displays the results Finke et al. reported.

In Experiment 3 we seek evidence that the magnitude of representational momentum will vary for the final velocity using implied accelerations of pitches, just as it does using implied acceleration of visual stimuli.

Method

Ten subjects, recruited from the Cornell community, were paid to participate in Experiment 3. The apparatus, stimuli, and procedure of Experiment 3 were identical to those used in Experiment 2, with the following exceptions: The individual trials contained six inducing tones followed by a test tone. The inducing tones were selected by taking the range of the five-tone musical sets used in Experiment 2 and dividing it into 10 equal-Hertz intervals. The durations of all the tones were 125 ms. The total elapsed time from the onset of the first tone to the onset of the sixth tone of the inducing sequence was always 1,420 ms. Thus the average velocity was held constant at 1.0 Hz/ms in all trials. Three acceleration conditions (positive, zero, and negative) were created by varying the ISIs within individual trials. In the zero acceleration condition the ISIs were all 159 ms. In the positive acceleration condition the ISIs were 510, 138, 77, 45, and 25 ms, for the five intervals respectively. In the negative acceleration condition the ISIs were 25, 45, 77, 138, and 510 ms, respectively. Retention interval was held constant at 500 ms. Visual reminders were presented on the computer screen upon the onset of the sixth tone "Remember this tone!" and upon the onset of the test tone "Same or Different?". Subjects completed two blocks of 189 experimental trials (nine repetitions of three acceleration conditions times seven test tones), each preceded by a block of 21 practice trials (one repetition of each trial type). The blocks differed in direction of tonal sequence; block order was counterbalanced across subjects. The order of trials was randomized for each block.

Results and Discussion

The data from one subject in the current experiment was excluded due to a very uncharacteristic pattern of responses in which he essentially responded "same" to tones low in pitch and "different" to tones high in pitch, independent of any other factor, such as direction of inducing sequence. The pattern of results we uncovered for the remaining nine subjects (see Figure 3B) is very similar to the results reported by Finke et al. for Experiment 3 (see Figure 3A). A two-way ANOVA using the individual shifts estimated from quadratic fits for each acceleration and direction condition revealed a significant main effect for Acceleration (analogous to Finke, et al.'s finding): $F(2, 16) = 6.744$; $p < .01$. Direction of tonal sequence did not produce a significant main effect, nor did it interact significantly with Acceleration. Thus, the current experiment replicates in the auditory domain Finke et al.'s acceleration effect for representational momentum in the visual domain.

Experiment 4

The final parametric effect from the visual domain that we hoped to replicate in the auditory domain is the retention interval effect reported by Freyd and Johnson (1987). Figure 4A displays the relationship between retention interval and memory shift, for retention intervals ranging from 10 to 90 ms (their Experiment 1) and 100 to 900 ms (their Experiment 2).

The sharply increasing function for retention interval Freyd and Johnson found for the small retention intervals is in keeping with the physical metaphor for representational momentum. In this metaphor retention interval is analogous to the time that has elapsed after the application of a stopping force (e.g., the time that has elapsed after engaging the brake of a car). Estimated memory shift is analogous to the distance traveled (e.g., the distance the car has traveled after the brake has been engaged). Physical models of stopping, and the extent to which an object travels due to inertia, despite a stopping force, predict a sharply increasing function that approaches an asymptotic stopping position.

At longer retention intervals Freyd and Johnson found that instead of reaching an asymptote, the memory shifts began to decline. They modelled the resulting U-shaped curve as a

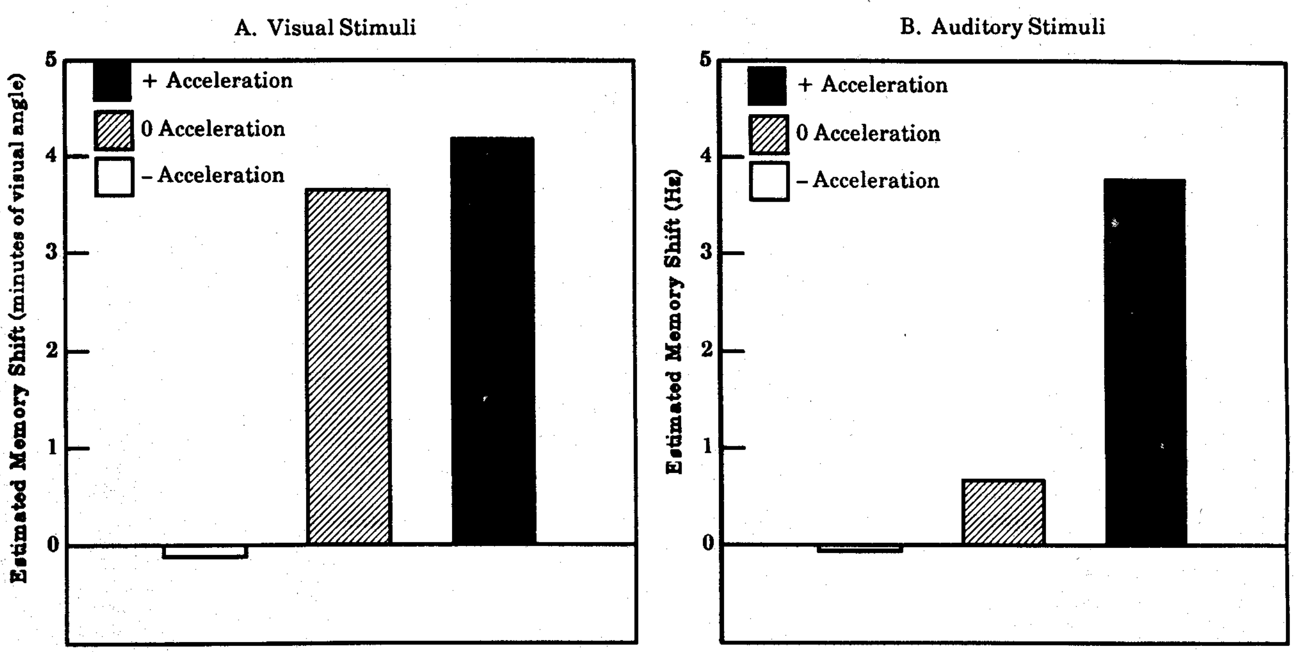

Figure 3. A. The acceleration results reported by Finke, Freyd, and Shyi (1986) for their Experiment 3 using an implied translatory motion of dots. B. An analogous acceleration effect found in the current Experiment 3 for implied changes in pitch.

result of two competing effects: a positive memory shift attributable to representational momentum, which dominates at short intervals, and a negative shift attributable to memory averaging effects, which dominates at longer intervals. Freyd and Johnson (1987, Experiments 3–5) collected data in support of their two-effect model in a series of additional experiments.

In the current Experiment 4 we use the same 18 retention intervals used by Freyd and Johnson in their Experiments 1 and 2 combined (that is, 10–90 ms in 10-ms steps, and 100–900 ms in 100-ms steps), with the inducing sequences of tones used in our Experiment 2. Because our inducing sequences are subjectively discrete (in that three distinct tones can be heard) we predict a qualitatively similar pattern to Freyd and Johnson for both short and long retention intervals.

Method

The subjects who previously participated in Experiment 2 returned to the laboratory on a separate day to participate in the current experiment. The apparatus, stimuli, and procedure were similar to Experiment 2. The same three-tone inducing sequences were used as in Experiment 2, and the same seven test tones were used. Stimulus durations and ISIs were held constant at 250 ms. Subjects first completed four blocks of trials in which the retention intervals ranged between 100 and 900 ms in 100-ms steps. There were two blocks of 189 experimental trials (three repetitions of nine retention intervals times seven test tones), each preceded by a block of 21 practice trials. They then completed six experimental and six practice blocks of trials, in which the retention intervals ranged between 10 and 90 ms in 10-ms steps. We will only consider the two experimental blocks in which the ISI was 250 ms. Two of the experimental blocks had ISIs of 0 ms and two had ISIs of 750 ms. The experimental blocks had 189 trials, each preceded by a practice block of 21 trials.

Results

Figure 4B displays the estimated shifts for the 18 retention intervals. We found essentially the same results using either weighted means (as in Experiment 1) or shifts calculated from quadratic regression (as in Experiment 3). Our prediction that the memory shifts would first increase with retention interval and then decrease with longer retention intervals was confirmed by a significance test using a quadratic regression in which the estimated memory shift (expressed in Hz) was predicted from retention interval (expressed in seconds) and retention interval–squared: $Hz = 2.82\ s - 4.58\ s^2$; $F(2, 15) = 3.75$; $p < .05$. Further, a linear regression predicting memory shift from retention interval is not statistically significant: $p > .10$. Although the results are not as tidy as Freyd & Johnson found (perhaps due to the range of tones used, the number of subjects, or something intrinsic to differences between visual and auditory stimuli), we again replicate in the auditory domain an effect found initially using visual stimuli.

General Discussion

The four experiments reported here demonstrate representational momentum in memory for pitch. Quantitative regularities previously discovered for representational momentum in the visual domain are also found using implied changes in pitch. One implication of this finding is that it makes it highly unlikely that representational momentum is a product of tacit knowledge of physical momentum, for changes in pitch in the world do not usually exhibit momentum-like properties (Finke and Freyd, 1989).

Auditory Momentum and Music

In Experiment 1 we looked for effects of musicality on representational momentum, but failed to find any. One

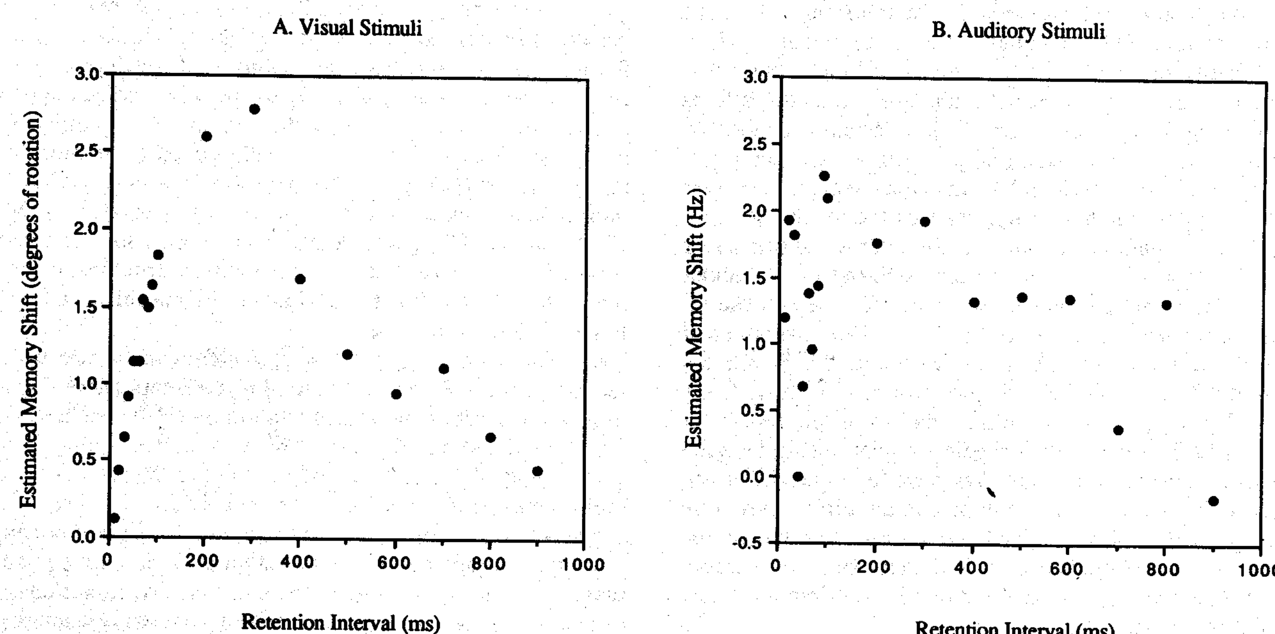

Figure 4. The stopping function reported by Freyd and Johnson (1987) for implied rotational momentum (results from their Experiments 1 and 2 are plotted together). B. An analogous set of results found in the current Experiment 4 for implied changes in pitch.

manipulation was Musical Training; we compared subjects with and without extensive formal training. We considered the possibility that more musical subjects might show less momentum because of a tendency to treat tones categorically instead of as continuous variations on a pitch scale. If anything, however, the trend in our data suggests that subjects with formal musical training show larger momentum effects. Perhaps musical training is irrelevant in the face of everyday exposure to music; Bharucha & Stoeckig (1986) have suggested that most members of our culture are so heavily exposed to Western music that formal training makes little difference for perceptual organization.

We also looked for evidence of a musicality effect by varying how "musical" were the inducing sequences, and while the trend was in the predicted direction, the result was not statistically significant. Although we verified our manipulation through subject ratings of musicality, we may nonetheless be comparing two conditions that barely differed. Neither our musical nor nonmusical sequences were very musical at all.

It may be instructive to compare our results and approach with that of Jones (e.g., 1976; Jones, Maser, & Kid, 1978) who has considered the role of time in music perception. Jones et al. (1978), for example, argues a point with which we agree enthusiastically: "As we listen to a music-like sequence unfold, we generate certain expectancies about future pitch and time relations" (p. 246). In addition, Jones considers pitch velocity a crucial parameter; we concur. However, in detail, our approach differs, perhaps fundamentally, from that of Jones et al. Jones et al. investigated memory for musical patterns whereas we investigated memory for individual tones. Furthermore, Jones et al. looked at memory accuracy after longer intervals than our fractions-of-a-second retention intervals. Perhaps most significantly, Jones et al. used stimulus patterns that are much more musical than the ones we used.

These differences may explain some inconsistencies between our results and predictions that follow from Jones's expectancy model (1976; Jones et al., 1978). For instance, a prediction from Jones's model is that constant velocity patterns produce more accurate pattern memory than do patterns with varying velocity. Thus, one could interpret her model to predict higher accuracy for the coherent versus incoherent conditions of our Experiment 1, since the coherent condition implies constant pitch velocity, whereas the incoherent condition implies highly variable velocities. Although our initial predictions were not about accuracy itself, but instead about accuracy asymmetries depending on the direction of the inducing sequence, we reanalyzed our data using overall error rates. We found absolutely no evidence that the incoherent condition led to greater errors; the error rates were virtually identical. We performed a similar analysis on the results for Experiment 2. Jones' model predicts a relationship between velocity and overall error rate. Again we found absolutely no evidence for such a relationship; overall error rates were virtually constant across velocity conditions. In contrast, the momentum model predicts a particular kind of error: memory asymmetries that depend on the direction and implied velocity of the inducing sequence.

Although our results do not support Jones' expectancy model, we do not believe our results challenge the model either. This is because of the very different levels to which the two approaches apply. Representational momentum makes quantitative predictions about representational dynamics occurring in fractions of a second. Jones' model makes predictions about memory for musical patterns that are built up over longer periods. Both models address the fundamental importance of expectancy for human perception and cognition, a function of the mind that is presumably so important it characterizes a wide range of different perceptual and cognitive mechanisms.

Why Auditory Momentum?

That representational momentum in vision and audition share a number of similarities also suggests that the connection between physical and representational momentum is not likely to be very tight, given that changes in pitch are not generally correlated with physical motion. This is not to say that perception of pitch change is unimportant to us, quite the contrary, but that pitch change does not seem predictive of motions that have real-world momentum. A detailed analysis of the correlation between pitch and motion in human perception remains to be performed. In the meantime, however, it appears that for humans the predictive value of pitch change for inertial motions is quite low compared with the predictive value of visual position changes for inertial motions. In contrast, for some animals, such as echo-locating bats, the correspondence between pitch change and object motion may be crucial. Effects like the doppler shift, however, do not seem nearly so prevalent in the human perceptual environment. We can thus speculate on two possible accounts of the relation between representational and physical momentum:

Neural espionage. Perhaps representational momentum originated in the visual system as an internalization of physical momentum. This process might than have been confiscated by other systems to permit predictions of the future course of perceived events. Such a process might be similar to Paul Rozin's (1976) claim that the evolution of intelligence proceeds by increasing general access to cognitive and perceptual procedures that were originally domain specific or similar to the theory that insect wings originally served a thermoregulatory function (Kingsolver & Koehl, 1985). Analogous to the morphological examples of "expectations" (see also Gould, 1977; Mayr, 1982), psychological mechanisms such as those supporting language ability might include structural details that reflect older functions (Piattelli-Palmarini, 1989; cf. Pinker & Bloom, in press).

Momentum as a property of spatiotemporal systems. A second, perhaps simpler, account of representational momentum would attribute no causal relation between physical and representational momentum. The two domains might be similar in an abstract, structural manner, yet representational momentum might not be an internalization of a specific physical law. Perhaps rate of change is an intrinsic component of event perception and memory (Jones, 1976), with perceptual systems using this rate change, or velocity, in automatically calculating future positions in a coherently changing event. If so, momentum effects should be found for any dimension of continuous change. Along similar lines, Freyd (1987, 1990) has proposed that momentum may be a property of a representational system in which time is a fully integrated dimension, just as physical momentum is a property of a world with spatiotemporal coherence.

Momentum and Psychophysics

A phenomenon reported by S. S. Stevens (1957) anticipates some of the current momentum work. In one series of experiments, Stevens asked his subjects to adjust the loudness of five tones so that they are separated by perceived equal intervals. The relevant feature of this experiment concerns the starting tone. Some subjects started with the tone of lowest intensity and moved to higher intensities, whereas other subjects began with the tone of highest intensity and moved lower. Let us concentrate on the placement of the third tone. When the subjects went up the scale, they placed the third tone at a higher intensity than when they went down the scale. This phenomenon seems similar to representational momentum in that the subject's memory for tone intensity in Steven's experiments may shift further along the direction of change. As a result, the intensity of currently perceived tones must be increased further along the direction of change to preserve equal intensity intervals between tones.

The phenomenon reported by Stevens pertains to loudness, whereas that reported here concerns pitch. Stevens argued that these two dimensions belong to qualitatively different sensory categories, and that one basis for his belief is that the apparent momentum phenomenon was found for loudness but not pitch. Nonetheless, Stevens reports some evidence for the effect with pitch, but was unsure he believed it. Stevens did not have an explanation for this unanticipated momentum-like finding. Perhaps the same phenomenon was being detected in Stevens' experiments that we have described in this paper. Perhaps the phenomenon reflects something very deep about the relation between the mental and physical worlds, such as the internalization of physical laws. Instead, we propose that the finding of a memory shift for implied changes in pitch indicates that representational momentum might be more profitably construed as resulting from a set of mental laws about perception and representation (see Freyd, 1987), processes that may be useful in predicting the future course of perceived events, but which may not reflect a tight isomorphism between psyche and physics.

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