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A Fröhlich Effect and Representational Gravity in Memory for Auditory Pitch

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Memory for the initial pitch of an auditory target that increased or decreased in auditory frequency was examined. Memory was displaced forward in the direction of pitch motion, and this is consistent with the Fröhlich effect previously observed for visual targets moving in visual physical space. The Fröhlich effect for pitch increased with faster target velocity and decreased if an auditory cue with the same pitch as the initial pitch of the target was presented before the target was presented. The Fröhlich effect was larger for descending pitch motion than for ascending pitch motion, and this is consistent with an influence of representational gravity. The data suggest that representation of auditory frequency space exhibits some of the same biases as representation of visual physical space, and implications for theories of attention in displacement and for crossmodal and multisensory representation of space are discussed.

Keywords: Fröhlich effect, representational gravity, pitch memory, auditory motion, displacement

The remembered initial location of a moving visual target is often displaced (i.e., shifted away) from the actual initial location of that target. This displacement can be in the direction of target motion or in the direction opposite of target motion, and these two types of displacement have been referred to as a *Fröhlich effect* (Fröhlich, 1923; for review, see Kerzel, 2010) or an *onset repulsion effect* (Thornton, 2002), respectively. Whether memory for the initial location of a visual target exhibits a Fröhlich effect or an onset repulsion effect has been a topic of investigation (e.g., Hubbard & Motes, 2005; Kerzel, 2002b; Kerzel & Gegenfurtner, 2004; Müsseler & Kerzel, 2004), but surprisingly, there has been relatively little investigation regarding whether memory for a moving auditory target exhibits a Fröhlich effect or an onset repulsion effect. The results of such an investigation would have important implications for theories of auditory processing and theories of spatial representation. In the experiments reported here, auditory targets that ascended or descended in frequency were presented, and whether a Fröhlich effect or an onset repulsion effect occurred in memory for the initial pitch of the target was examined. In addition, whether any displacement in memory for the initial pitch of the auditory target was influenced by the direction of pitch motion, velocity of the target, or cueing of the initial pitch of the auditory target was also examined.

Several explanations for the Fröhlich effect and for the onset repulsion effect have been proposed. Perhaps the most well-known explanation for the Fröhlich effect is that the appearance of a target triggers a shift of attention toward that target (Müsseler & Aschersleben, 1998). During this shift of attention, the target continues to move, and so the target will have traveled some distance before attention can reach the target. If the remembered initial location corresponds to the location of the target when attention reaches the target, then the remembered initial location will be shifted in the direction of target motion. Other explanations suggest that the Fröhlich effect results from (a) the time required to build up sensation (Fröhlich, 1923), (b) metacontrast masking of the original target position by subsequent target positions (Carbone & Ansorge, 2008; Kirschfeld & Kammer, 1999), (c) spreading activation across the retina in advance of a moving target (Müsseler, Stork, & Kerzel, 2002), (d) cumulative lateral inhibition (Geer & Schmidt, 2006), and (e) predictability of initial location (Müsseler & Kerzel, 2004). There has been less consideration of the onset repulsion effect, although Thornton (2002) proposed explanations involving the frame of reference, misestimation, and overcompensation for uncertainty (see also Hubbard & Ruppel, 2011). Some explanations appear limited to visual stimuli (e.g., patterns of retinal activation), but other explanations do not appear limited to visual stimuli (e.g., attention, masking), and so whether a Fröhlich effect or an onset repulsion effect occurs with auditory stimuli is theoretically important.

Only one published study explicitly examined whether a Fröhlich effect or an onset repulsion effect occurred in memory for the initial location of a moving auditory target. Getzmann (2005) presented participants who were in a dark and anechoic environment with an auditory target (a noise burst with lower and upper cutoff frequencies of 1 kHz and 3 kHz, respectively) that appeared to move from left to right or from right to left. Participants compared the remembered initial location of the target to a stationary illuminated visual reference stimulus that was subsequently presented slightly to the left or to the right of the initial

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auditory target position. The pattern of responses suggested that memory for the initial location of the target was displaced in the direction of auditory motion, and this displacement was larger if motion of the target began in a more peripheral location. Based on this, Getzmann suggested that a Fröhlich effect occurred in spatial hearing. Given that Getzmann's auditory targets moved in physical space, his data suggest that the Fröhlich effect reflects a general property of an amodal spatial representation rather than a specific property of visual or visuospatial representation. Also, Getzmann's findings of larger displacement if the initial target location was in a more peripheral location is consistent with findings that displacement of a visual target toward the fovea is increased with increases in target eccentricity (e.g., Mateeff & Gourevich, 1983; Müsseler, van der Heijden, Mahmud, Deubel, & Ertsey, 1999).

Getzmann's (2005) examination of memory for the initial spatial coordinates of a moving sound source suggests that a Fröhlich effect occurs in memory for an auditory target, but there is another type of auditory information that is often considered in spatial terms and that might also exhibit a Fröhlich effect. The perception of auditory frequency as pitch is often referred to in spatial terms with pitches resulting from faster or slower frequencies referred to as "higher" or "lower," respectively (Eitan & Granot, 2006; Spence, 2011). Indeed, the first dimension in geometric models of pitch representation is often referred to as "pitch height" (e.g., Krumhansl, 1990; Shepard, 1982), and there is a consistent mapping between higher locations in the picture plane in visual physical space and faster frequencies in auditory frequency space (e.g., Elkin & Leuthold, 2011; Melara & Marks, 1990; Rusconi, Kwan, Giordano, Umilta, & Butterworth, 2006). Whether a Fröhlich effect or an onset repulsion effect occurs in memory for the initial pitch of a target that is moving in auditory frequency space is not known. Whether phenomena related to the representation of visual physical space, such as the Fröhlich effect or the onset repulsion effect, would influence the representation of auditory frequency space, and whether the representation of auditory frequency space would exhibit the same biases as the representation of visual physical space, have implications for the understanding of spatial representation and the possibility of crossmodal or multisensory representation.

A common property of physical space that is encountered in everyday experience involves the asymmetrical direction of implied gravitational attraction (i.e., in everyday experience, the direction of gravitational attraction along the vertical is always downward and is never upward), and it could be predicted that such a common property of physical space would influence spatial representation. Hubbard and Bharucha (1988; Hubbard, 1990) found that memory for the final location of a horizontally moving visual target was displaced downward (in addition to a larger forward displacement in the direction of target motion) and that forward displacement for ascending visual targets was less than forward displacement for descending visual targets. Hubbard (1995, 1997) suggested this pattern was consistent with an influence of implied gravitational attraction on a moving target (as unpowered objects that move [a] horizontally descend along a parabola; [b] upward decelerate due to gravity; and [c] downward accelerate due to gravity), and this was referred to as *representational gravity*. Effects consistent with representational gravity were subsequently noted in memory for horizontally moving visual targets that exhibited an onset repulsion effect (Thornton, 2002), but whether representational gravity occurs in memory for targets that exhibited a Fröhlich effect or occurs with auditory targets moving in auditory frequency space has not been considered.

The extent to which implied gravitational attraction might influence the representation of an auditory target has important theoretical implications. A purely auditory target would not possess mass and so would not be influenced by gravitational attraction; thus, there would not be any a priori reason to predict an effect of implied gravitational attraction on memory for such a target. However, auditory information is usually generated by physical objects that possess mass and that are influenced by gravitational attraction. The representation of auditory information might contain information regarding the object that produced the sound or how that sound was produced (Godøy, 2001), and this might include information regarding any physical principles that might influence the source or production of that sound. Consistent with this, memory for the final location of a horizontally moving visual target exhibited larger downward displacement if accompanied by an auditory pitch that descended in frequency than if accompanied by an auditory pitch that ascended in frequency (Hubbard & Courtney, 2010). Just as auditory information influenced displacement of a visual target, perhaps top-down information regarding a source object or sound production might influence displacement of an auditory target. Similarly, if visual physical space and auditory frequency space are similar, then downward motion in auditory frequency space might result in the same types of biases in representation of an auditory target as downward motion in visual physical space in representation of a visual target.

In the experiments reported here, participants were presented with an auditory target that ascended or descended in auditory frequency space. Whether a Fröhlich effect, an onset repulsion effect, or representational gravity occurred in memory for the initial pitch of the target was examined. In Experiment 1, the pitch velocity of the target was varied. In Experiment 2, an auditory cue that indicated the initial pitch of the target was presented before the target was presented on half of the trials, and on the other half of the trials, no cue was presented. In Experiment 3, an auditory cue was presented on each trial; on 75% of the trials, the cue was valid (i.e., indicated the initial pitch of the target), and on 25% of the trials, the cue was invalid (i.e., indicated a pitch other than the initial pitch of the target). In all experiments, participants judged whether a subsequently presented auditory probe was the same pitch as the initial pitch of the target, and these judgments were used to estimate displacement in memory for the initial pitch of the target. If properties of spatial representation that result in the Fröhlich effect, onset repulsion effect, or representational gravity are not limited to visual targets, then memory for the initial pitch of an auditory target that ascended or descended in auditory frequency space might exhibit a Fröhlich effect or an onset repulsion effect, and any such effect might be modulated by representational gravity.

Experiment 1

A common finding in the literature on the Fröhlich effect for visual targets is that increases in target velocity result in larger forward displacement (e.g., Müsseler & Aschersleben, 1998; Müsseler & Kerzel, 2004). An increase in target velocity appears to result in larger backward displacement in the onset repulsion effect for visual targets, as well, but this is less clear (e.g., Thornton, 2002; Kerzel & Gegenfurtner, 2004). If a Fröhlich effect or an onset repulsion effect occurs in memory for the initial pitch of an auditory target, then faster pitch velocity should result in larger displacement. Also, if representational gravity influences memory for initial pitch, then forward displacement should be larger for descending motion than for ascending motion if a Fröhlich effect occurs (as a Fröhlich effect and representational gravity operate in the same direction for descending motion, but in opposite directions for ascending motion), whereas backward displacement should be larger for ascending motion than for descending motion if an onset repulsion effect occurs (as an onset repulsion effect and representational gravity operate in the same direction for ascending motion, but in opposite directions for descending motion). Accordingly, participants in Experiment 1 were presented with an auditory target that ascended or descended in auditory frequency space at a constant pitch velocity within each trial, and pitch velocity in auditory frequency space varied across trials.

Method

Participants. The participants were 14 undergraduates who received partial course credit for their participation and who were naive to the hypotheses.

Apparatus. The auditory stimuli were generated upon and the data collected with a Gateway desktop computer equipped with a 15-in. color monitor with a refresh rate of 60 Hz and a resolution of 1024 × 768 pixels. Auditory stimuli were presented over the speakers built into the desktop computer and at an approximate loudness of 55–57 dB sound pressure level, as determined by a Quest Model 1700 Precision Impulse Type I sound-level meter (Oconomowoc, WI) at a location corresponding to a participant's ear and directed at a right angle to the speakers.

Stimuli. The moving target and probe were auditory tones. As shown in Figure 1, on each trial there were five successive presentations of the target that implied consistent ascending motion of the target or consistent descending motion of the target in frequency space, and these successive presentations are referred to as *inducing stimuli*. Each inducing stimulus was presented for 250 ms, and there was a 250-ms interstimulus interval (ISI) between successive inducing stimuli. There were two directions of pitch motion, ascending (in which successive inducing stimuli exhibited faster frequencies) and descending (in which successive inducing stimuli exhibited slower frequencies). The initial frequency for ascending motion was 250 Hz, and the initial frequency for descending motion was 1265.63 Hz. There were three velocities of pitch motion (see Table 1). The frequency of each inducing stimulus differed from the frequency of the preceding inducing stimulus by 300, 500, or 700 cents for slow, medium, or fast velocities, respectively (100 cents = 1 semitone); in other words, there was a change of 20, 33, or 50% between frequencies of adjacent inducing stimuli in slow, medium, or fast velocities, respectively. The frequency ratio between pairs of adjacent inducing stimuli was 6:5, 4:3, or 3:2, for slow, medium, or fast velocities, respectively (and so the perceived interval size between adjacent inducing stimuli for slow, medium, or fast velocities was a minor third, perfect fourth, or perfect fifth, respectively).

The auditory probe was located at one of nine auditory frequencies relative to the initial frequency of the moving target (i.e., relative to the frequency of the first inducing stimulus): −80, −60, −40, −20, 0, +20, +40, +60, or + 80 cents (i.e., approximately 93.33, 95.00, 96.67, 98.33, 100.00, 101.67, 103.33, 105.00, and 106.67% of the frequency of the initial inducing stimulus for ascending targets, respectively, and approximately 106.67, 105.00, 103.33, 101.67, 100.00, 98.33, 96.67, 95.00, and 93.33% of the frequency of the initial inducing stimulus for descending targets, respectively). Probe positions denoted by a minus sign indicated that the probe was backward (i.e., the frequency of the probe was shifted in the direction opposite to target motion) from the initial frequency of the moving target by the indicated number of cents, and probe positions denoted by a plus sign indicated that the probe was forward (i.e., the frequency of the probe was shifted in the direction of target motion) from the initial frequency of the moving target by the indicated number of cents; the zero probe position was the same as the initial frequency of the auditory target. Each participant received 270 trials (3 velocities [slow, medium, fast] × 2 directions [ascending, descending] × 9 probes [−80, −60, −40,

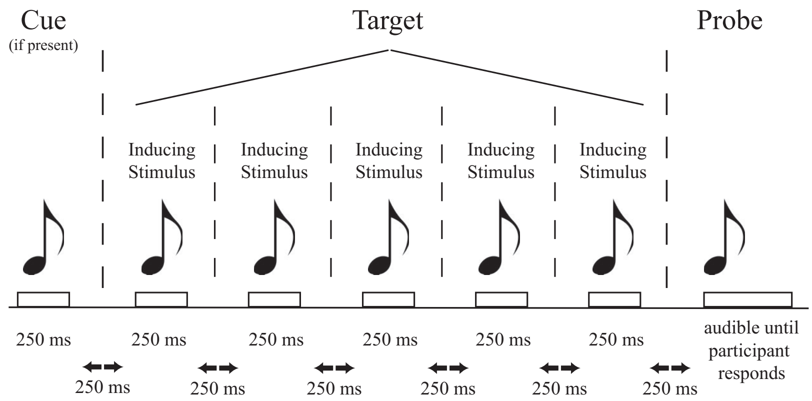

Figure 1. The structure of a trial in Experiments 1, 2, and 3. In Experiment 1, no cue was presented. In Experiments 2 and 3, the cue was an auditory tone. Also, if a cue was presented in Experiment 2, presentation of a visual cross preceded presentation of the cue.

Table 1
Target Velocities in Experiment 1

	Inducing Stimulus				
	1	2	3	4	5
Ascending					
Slow	250.00	300.00	360.00	432.00	518.40
Medium	250.00	332.50	442.23	588.16	782.25
Fast	250.00	375.00	562.50	843.75	1265.63
Descending					
Slow	1265.63	1054.70	878.91	732.42	610.35
Medium	1265.63	951.60	751.49	537.92	404.48
Fast	1265.63	843.75	562.50	375.00	250.00

Note. Values for each inducing stimuli are specified in Hertz.

−20, 0, +20, +40, +60, or + 80] × 5 replications) in a different random order.

Procedure. Participants were first given a practice session consisting of 10 practice trials that were randomly drawn from the experimental trials. Participants pressed a designated key to begin each trial. There was a 1-s pause, and the inducing stimuli were presented. After the final inducing stimulus ended, there was a retention interval of 250 ms before the probe was presented. After the probe was presented, participants pressed a key marked S or a key marked D (the M and C keys, respectively, of a standard keyboard) to indicate if the pitch of the probe was the same as or different from the initial pitch of the target. Participants then initiated the next trial.

Results

Probabilities of a *same* response for each probe position are shown in Figure 2. Two types of analysis were conducted: an examination of weighted mean estimates of displacement, and an examination of probabilities of *same* responses. A weighted mean significantly smaller than zero in a given condition would indicate that an onset repulsion effect occurred in that condition, and a weighted mean significantly larger than zero in a given condition would indicate that a Fröhlich effect occurred in that condition. Differences in the probabilities of *same* responses could indicate the relative uncertainty of participants regarding their responses.

Weighted means. Consistent with previous studies of displacement in memory for the spatial location of a visual target (e.g., Hayes & Freyd, 2002; Hubbard, Kumar, & Carp, 2009; Munger, Solberg, Horrocks, & Preston, 1999), estimates of the direction and magnitude of displacement were determined by calculating a weighted mean (the sum of the products of the distance of each probe from the location of the target, in cents, and the proportion of *same* responses to that probe, divided by the sum of the proportions of *same* responses) for each participant for each condition. The sign of a weighted mean indicated the direction of displacement (i.e., a minus sign indicated displacement in the direction opposite to target motion; a plus sign indicated displacement in the direction of target motion), and the absolute value of a weighted mean indicated the magnitude of displacement (i.e., a larger absolute value indicated a larger displacement).

In testing whether the weighted means in each condition differed from zero, the alpha value required for significance was adjusted by a Bonferroni correction (six comparisons: .05/6 = .0083 required for significance). If pitch velocity was slow, weighted means for ascending targets (M = 10.07, SE = 2.50), $t(13) = 4.03$, $p < .0014$, and for descending targets (M = 20.66, SE = 3.22), $t(13) = 6.42$, $p < .0001$, were significantly larger than zero. If pitch velocity was medium, weighted means for ascending targets (M = 12.07, SE = 2.66), $t(13) = 4.54$, $p < .0006$, and for descending targets (M = 22.34, SE = 2.84), $t(13) = 7.88$, $p < .0001$, were significantly larger than zero. If pitch velocity was

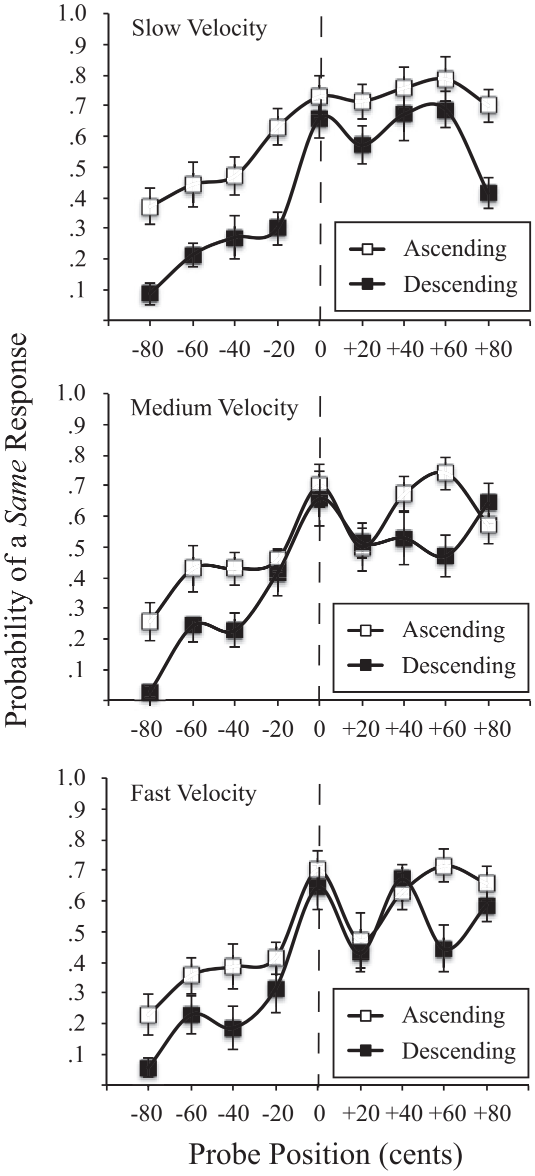

Figure 2. The probability of a *same* response as a function of probe position in Experiment 1. Data from the slow-velocity condition are shown in the upper panel; data from the medium-velocity condition are shown in the middle panel, and data from the fast-velocity condition are shown in the bottom panel. Data from ascending trials are plotted with open (white) squares, and data from descending trials are plotted with filled (black) squares. Error bars reflect standard error of the mean.

fast, weighted means for ascending targets ($M = 15.43$, $SE = 2.98$), $t(13) = 5.19$, $p < .0002$, and for descending targets ($M = 23.95$, $SE = 3.51$), $t(13) = 6.82$, $p < .0001$, were significantly larger than zero.

Weighted means were analyzed in a 3 (velocity) × 2 (direction) repeated-measures ANOVA. Velocity influenced displacement, $F(2, 26) = 3.56$, $MSE = 36.99$, $p < .05$, and pairwise comparisons of slow ($M = 15.37$, $SE = 2.24$), medium ($M = 17.21$, $SE = 2.15$), and fast ($M = 19.69$, $SE = 2.40$) targets revealed that displacement for slow targets was smaller than displacement for fast targets, and displacement for medium targets was not significantly different from displacement for slow targets or fast targets. Direction influenced displacement, $F(1, 13) = 12.30$, $MSE = 163.94$, $p < .05$, with ascending targets ($M = 12.52$, $SE = 1.57$) exhibiting a smaller Fröhlich effect than did descending targets ($M = 22.32$, $SE = 1.81$). Velocity × Direction did not approach significance, $F < 0.12$, $p > .89$.

Probabilities of *same* responses. Probabilities of *same* responses were analyzed in a 3 (velocity) × 2 (direction) × 9 (probe) repeated-measures ANOVA. Velocity influenced displacement, $F(2, 26) = 8.94$, $MSE = 0.04$, $p < .0011$, and interacted with direction, $F(2, 26) = 10.35$, $MSE = 0.03$, $p < .0003$. The probability of a *same* response decreased with increases in target velocity for slow ($M = .52$, $SE = .02$), medium ($M = .47$, $SE = .02$), and fast ($M = .45$, $SE = .02$) targets, and the rate of decrease was greater for ascending targets than for descending targets. Direction was significant, $F(1, 13) = 13.66$, $MSE = 0.31$, $p < .003$, with a lower probability of a *same* response for descending targets ($M = .41$, $SE = .02$) than for ascending targets ($M = .56$, $SE = .01$). As would be expected, probe was significant, $F(8, 104) = 36.04$, $MSE = 0.07$, $p < .0001$. A comparison of probabilities of *same* responses for negative probes and probabilities of *same* responses for positive probes was highly significant, $F(1) = 182.90$, $p < .0001$, with positive probes resulting in higher probabilities of *same* responses than negative probes. No other main effects or interactions approached significance, $Fs < 1.60$, $ps > .14$.

Discussion

Memory for the initial pitch exhibited a Fröhlich effect, and the Fröhlich effect was larger for fast targets than for slow targets. The effect of velocity on the Fröhlich effect for auditory targets in Experiment 1 is consistent with the effect of velocity on the Fröhlich effect for visual targets in Müsseler and Aschersleben (1998) and Müsseler and Kerzel (2004). Given that the initial pitch was constant across velocities for ascending targets and constant across velocities for descending targets, differences in the Fröhlich effect in memory for the initial pitch with different velocities cannot be attributed to differences in the initial pitch. Inspection of Figure 2 shows that participants were more likely to respond *same* to positive probes than to negative probes, and less obviously, that probability of a *same* response decreased slightly as velocity increased. The latter pattern might have been expected if velocity had been manipulated by varying tempo of movement through a constant pitch range, as a slow-pitch velocity would have involved a longer latency between the initial pitch and the probe, and resulted in more decay of the representation of the initial pitch. However, Experiment 1 manipulated velocity by varying pitch range and keeping tempo of movement constant, thus keeping latency between the initial pitch and the probe constant across velocities. Regardless, Experiment 1 revealed a Fröhlich effect for auditory targets that moved in frequency space, and this complements Getzmann's (2005) finding of a Fröhlich effect in spatial hearing.

The Fröhlich effect in memory for targets that descended in auditory frequency space was larger than the Fröhlich effect in memory for targets that ascended in auditory frequency space, and this is consistent with the influence of representational gravity. The apparent influence of representational gravity in Experiment 1 is an important finding, as gravitational attraction does not influence auditory frequency space per se (and purely auditory objects are not influenced by gravity). For descending motion, the Fröhlich effect and representational gravity operated in the same direction (downward), and so these effects summed and the resultant displacement was relatively larger. For ascending motion, the Fröhlich effect (upward) and representational gravity (downward) operated in opposite directions, and so these effects partially canceled out, and the resultant displacement was relatively smaller. Such a combination of effects in determining the ultimate displacement of a target (a) has been discussed for visual targets (e.g., Hubbard, 1995, 2005), but not yet considered for auditory targets, and (b) is more consistent with the possibility of a general displacement mechanism than with multiple modality-specific mechanisms. Along these lines, an influence of implied direction of gravitational attraction on memory for initial pitch is consistent with an amodal representation of space or with a crossmodal influence from the representation of visual physical space.

Two alternative hypotheses to account for the displacement in Experiment 1 can be ruled out. The first alternative is that representation of the initial pitch reflects an averaging in memory of the initial pitch with subsequent pitches. If an averaging of the initial pitch with subsequently presented pitches had been responsible for the displacement in memory for initial pitch, then displacement for ascending targets and displacement for descending targets should have been equal in magnitude. Although the strong effect of direction suggests that displacement is not due solely to averaging, it is nonetheless possible that averaging might still contribute to displacement (e.g., see Freyd & Johnson, 1987; Kerzel, 2002a). The second alternative is that ascending targets might have been perceived as moving toward participants, and descending targets might have been perceived as moving away from participants (e.g., see Ghazanfar & Maier, 2009; Neuhoff & McBeath, 1996). However, Neuhoff (2001) found that starting positions and stopping positions of approaching sounds, as well as starting positions and stopping positions of receding sounds, were each perceived as closer than their actual distance. If pitch motion in Experiment 1 was interpreted as approaching or receding, then Neuhoff's finding that starting positions of sounds are perceived as closer predicts ascending motion (perceived as approaching) would result in a Fröhlich effect and descending motion (perceived as receding) would result in an onset repulsion effect. Such a pattern did not occur.

Experiment 2

Müsseler and Aschersleben (1998) cued participants regarding the location at which a subsequently presented visual target would appear, and cues were in the form of parallel lines above and below the subsequent initial location of the target. The Fröhlich effect was decreased if the initial location of the target was cued. If the Fröhlich effect in memory for auditory pitch in Experiment 1 reflects general properties of spatial representation that are not unique to visual or visuospatial representation, then it could be predicted that a cue indicating the initial pitch of an auditory stimulus would decrease the Fröhlich effect in memory for initial pitch. Accordingly, in Experiment 2, participants were presented with auditory targets. On half of the trials, an auditory cue that indicated the pitch of the upcoming auditory target was presented prior to presentation of the target, and on the other half of the trials, no cue was presented. If the effect of an auditory cue on memory for initial auditory pitch is similar to the effect of a visual cue on memory for initial visual location, then the Fröhlich effect in memory for initial auditory pitch should be decreased by presentation of the cue. On trials when an auditory cue was presented, a visual signal was shown at the beginning of the trial. This visual signal informed participants that the first auditory stimulus would be the cue and not the target. On trials in which an auditory cue was not presented, no visual signal was presented.

Method

Participants. The participants were 17 undergraduates from the same participant pool as in Experiment 1, and none had participated in that experiment.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The auditory targets and probes were the same as in the fast-velocity conditions in Experiment 1. The auditory cue was the same frequency (250 Hz for ascending targets, 1265.63 Hz for descending targets) and duration (250 ms) as the first inducing stimulus on that trial. Given that participants would not have been able to determine if the first auditory stimulus on a given trial was the cue or the target at the time that stimulus was presented, trials in which an auditory cue was presented were preceded by a visual stimulus that was briefly presented in the center of the visual display, which was attached to the desktop computer. The visual stimulus was in the shape of a cross, and each horizontal and vertical arm of the cross was 10 pixels in length (the total width and height of the cross was 20 pixels) and 4 pixels in thickness. Each participant received 216 trials (2 cues (present, absent) × 2 directions (ascending, descending) × 9 probes (−80, −60, −40, −20, 0, +20, +40, +60, +80) × 6 replications) in a different random order.

Procedure. The procedure was the same as in Experiment 1, with the following exceptions: If a cue was presented in a trial, the visual cross immediately appeared and was visible for 250 ms before vanishing. There was a blank interval of 250 ms, and the auditory cue was presented for 250 ms. After the auditory cue was presented, there was a blank interval of 250 ms before the first inducing stimulus was presented. If a cue was not presented in a trial, there was a 1000-ms blank interval before the first inducing stimulus was presented. Thus, in the cue-present condition and in the cue-absent condition, the first inducing stimuli were presented 1000 ms after participants initiated the trial.

Results

Probabilities of a *same* response for each probe position are shown in Figure 3, and analyses of weighted mean estimates of displacement and of probabilities of *same* responses were conducted.

Weighted means. Weighted means were calculated as in Experiment 1. In testing whether the weighted means in each condition differed from zero, the alpha value required for significance was adjusted by a Bonferroni correction (four comparisons: .05/4 = .0125 required for significance). If the cue was present, weighted means for ascending targets (M = 7.46, SE = 2.62), $t(16) = 2.85$, $p < .012$, and for descending targets (M = 16.00, SE = 2.49), $t(16) = 6.41$, $p < .0001$, were significantly larger than zero. If the cue was absent, weighted means for ascending targets (M = 15.83, SE = 3.26), $t(16) = 4.86$, $p < .0002$, and for descending targets (M = 25.24, SE = 3.22), $t(16) = 7.84$, $p < .0001$, were significantly larger than zero.

Weighted means were analyzed in a 2 (cue) × 2 (direction) repeated-measures ANOVA. Cue influenced displacement, $F(1, 16) = 19.46$, MSE = 67.67, $p < .001$, and displacement was smaller if a cue was present (M = 11.73, SE = 1.93) than if a cue was absent (M = 20.54, SE = 2.40). Direction influenced displacement, $F(1, 16) = 8.62$, MSE = 158.86, $p < .01$, with ascending targets (M = 11.65, SE = 2.18) exhibiting a smaller Fröhlich effect than did descending targets (M = 20.62, SE = 2.16). Cue × Direction did not approach significance, $F < 0.07$, $p > .79$.

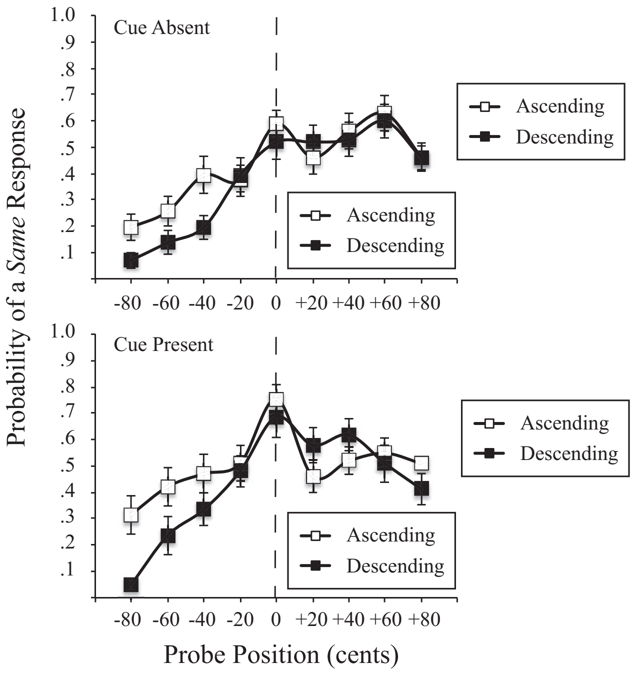

Figure 3. The probability of a *same* response as a function of probe position in Experiment 2. Data from the cue-absent condition are shown in the upper panel, and data from the cue-present condition are shown in the bottom panel. Data from ascending trials are plotted with open (white) squares, and data from descending trials are plotted with filled (black) squares. Error bars reflect standard error of the mean.

Probabilities of *same* responses. Probabilities of *same* responses were analyzed in a 2 (cue) × 2 (direction) × 9 (probe) repeated-measures ANOVA. Cue influenced displacement, $F(1, 16) = 9.28$, $MSE = 0.06$, $p < .008$, and interacted with probe, $F(8, 128) = 3.39$, $MSE = 0.03$, $p < .002$, such that the probability of a *same* response was higher if a cue was present ($M = .47$, $SE = .02$) than if a cue was absent ($M = .41$, $SE = .02$), and this difference was more pronounced for negative probes. Direction was marginally significant, $F(1, 16) = 3.22$, $MSE = 0.18$, $p < .10$, and interacted with probe, $F(8, 128) = 2.98$, $MSE = 0.05$, $p < .05$, such that the probability of a *same* response exhibited a trend to be higher for ascending targets ($M = .47$, $SE = .02$) than for descending targets ($M = .41$, $SE = .02$), and the probability of a *same* response was higher for negative probes if targets ascended than if targets descended. Probe was significant, $F(8, 128) = 25.30$, $MSE = 0.07$, $p < .0001$. A comparison of probabilities of *same* responses for negative probes and probabilities of *same* responses for positive probes was highly significant, $F(1) = 102.50$, $p < .0001$, with positive probes resulting in higher probabilities of *same* responses than did negative probes. No other main effects or interactions approached significance, $F\text{s} < 1.15$, $p\text{s} > .33$.

Discussion

Memory for the initial pitch exhibited a Fröhlich effect, and the Fröhlich effect was smaller if a cue was present than if a cue was absent and smaller for ascending targets than for descending targets. The decrease in the Fröhlich effect for an auditory target if an auditory cue that indicated the initial pitch of that target was presented in Experiment 2 is consistent with the (a) decrease in the Fröhlich effect for a visual target when a visual cue that indicated the initial location of that target was presented in Müsseler and Aschersleben (1998) and (b) effects of cueing on other types of displacement in memory for location of a visual target (onset repulsion effect, Hubbard & Ruppel, 2011; representational momentum, Hubbard et al., 2009). The larger Fröhlich effect for descending targets is consistent with the effect of direction in Experiment 1 and consistent with an influence of implied gravitational attraction on the representation of the initial pitch of the target. As shown in Figure 3, there was a larger difference in probabilities of *same* responses for negative probes than positive probes for descending targets, and the larger Fröhlich effect for descending targets might have made it easier to reject negative probes for descending targets. Also, presence of the cue increased overall probability of a *same* response, but the reason for this is not clear, as the cue should have decreased uncertainty (and thus decreased overall probability of a *same* response).

One possible explanation for the decreased Fröhlich effect when a cue had been presented is that the cue strengthened the representation of the initial pitch (as there were two presentations of the initial pitch and one presentation of each subsequent pitch). Presentation of the initial pitch in the cue and in the first inducing stimulus resulted in a representation of the initial pitch that was potentially more resistant to decay and less likely to be influenced by the representations of subsequent pitches that were each presented only once. However, and as noted in the discussion of Experiment 1, such an averaging could not account for the larger Fröhlich effect for descending targets than for ascending targets, and so cannot provide the sole explanation for the displacement pattern. Even so, whether or not memory averaging might contribute to displacement of the initial pitch of a target moving in auditory frequency space is not known. The effect of the cue in Experiment 2 is consistent with the suggestion in the discussion of Experiment 1 that the Fröhlich effect in memory for the initial pitch of the target does not result from changes in pitch being perceived as the target approaching or receding from the participant, because the auditory target (and the extent of motion through auditory frequency space) is the same regardless of whether the target is cued. Thus, any differences in the Fröhlich effect as a function of cueing cannot be due to perception of ascending targets or descending targets as approaching or receding, respectively.

Experiment 3

In Experiment 2, the cue was always presented at the same auditory frequency as the first inducing stimulus. If effects of the cue in Experiment 2 were due to specific pitch information regarding the target, then it could be predicted that the Fröhlich effect if the cue was valid (i.e., if the cue indicated the frequency at which the auditory target would be presented) should be smaller than the Fröhlich effect if the cue was invalid (i.e., if the cue indicated a frequency different from the frequency at which the auditory target would be presented). Alternatively, if the cue merely provided an alerting stimulus to participants regarding the impending presentation of the target, and pitch information provided by the cue was not used by participants, then it could be predicted that the Fröhlich effect should not be influenced by whether pitch information provided by the cue was valid or invalid. Accordingly, in Experiment 3, a cue was presented before the target appeared on each trial. On 75% of the trials, the cue was valid and indicated the initial pitch of the auditory target, and on 25% of the trials, the cue was invalid and indicated a pitch that was different from the initial pitch of the auditory target. Given that an auditory cue was presented on every trial, it was not necessary to present the visual cross to indicate that the first tone was an auditory cue; rather, participants were instructed that the first tone was always a cue.

Method

Participants. The participants were 16 undergraduates from the same participant pool as in Experiment 1, and none had participated in previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The auditory targets and probes were the same as in Experiment 2. The auditory cue was the same as in Experiment 2, with the following exceptions: The cue was presented on every trial. On 75% of the trials, valid cues were presented in which the frequency of the cue was the same as the frequency at which the target on that trial would be presented, and on 25% of the trials, invalid cues were presented in which the frequency of the cue was the same as the initial frequency of auditory targets that moved in the opposite direction (i.e., in invalid trials, if the first inducing stimulus was 250 Hz, then the cue was 1265.63 Hz, and if the first inducing stimulus was 1265.63 Hz, then the cue was 250 Hz). The visual cross was not presented. Each participant received 288 trials (2 cues [valid, invalid] × 2 directions [ascending, descending] × 9 probes [−80, −60, −40, −20, 0, +20, +40, +60, +80] × 8 replications [6 valid trials, 2 invalid trials]) in a different random order.

Procedure. The procedure was the same as that for trials in which the cue was presented in Experiment 2, with the following exceptions: The visual cross was not presented, and there was a 500-ms blank interval between when participants initiated a trial and when the auditory cue was presented.

Results

Probabilities of a *same* response for each probe position are shown in Figure 4, and analyses of weighted mean estimates of displacement and of probabilities of *same* responses were conducted.

Weighted means. Weighted means were calculated as in Experiment 1. In testing whether the weighted means in each condition differed from zero, the alpha value required for significance was adjusted by a Bonferroni correction (four comparisons: .05/4 = .0125 required for significance). If the cue was valid, weighted means for ascending targets ($M = 5.42$, $SE = 1.69$), $t(15) = 3.21$, $p < .006$, and for descending targets ($M = 17.59$, $SE = 2.80$), $t(15) = 6.29$, $p < .0001$, were significantly larger than zero. If the cue was invalid, weighted means for ascending targets ($M = 12.88$, $SE = 3.85$), $t(15) = 3.34$, $p < .005$, and for descending targets ($M = 22.83$, $SE = 3.64$), $t(15) = 6.28$, $p < .0001$, were significantly larger than zero.

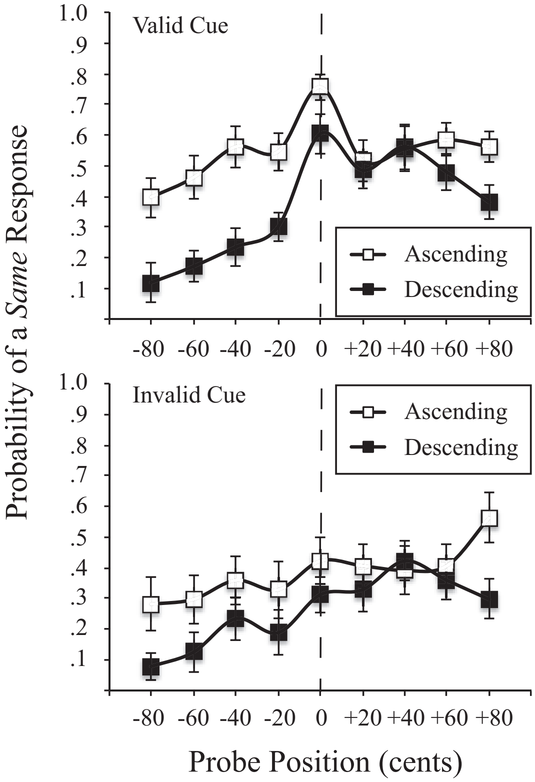

Figure 4. The probability of a *same* response as a function of probe position in Experiment 3. Data from the valid cue condition are shown in the upper panel, and data from the invalid cue condition are shown in the bottom panel. Data from ascending trials are plotted with open (white) squares, and data from descending trials are plotted with filled (black) squares. Error bars reflect standard error of the mean.

Weighted means were analyzed in a 2 (cue) × 2 (direction) repeated-measures ANOVA. Cue influenced displacement, $F(1,15) = 8.21$, $MSE = 78.65$, $p < .02$, and displacement was smaller if valid cues ($M = 11.50$, $SE = 1.94$) rather than invalid cues ($M = 17.86$, $SE = 2.75$) were presented. Direction influenced displacement, $F(1, 15) = 10.92$, $MSE = 179.39$, $p < .005$, with ascending targets ($M = 9.15$, $SE = 2.17$) exhibiting a smaller Fröhlich effect than did descending targets ($M = 20.21$, $SE = 2.31$). Cue × Direction did not approach significance, $F < 0.15$, $p > .70$.

Probabilities of *same* responses. Probabilities of *same* responses were analyzed in a 2 (cue) × 2 (direction) × 9 (probe) repeated-measures ANOVA. Cue influenced displacement, $F(1,15) = 31.27$, $MSE = 0.09$, $p < .0001$, and interacted with probe, $F(8, 128) = 3.39$, $MSE = 0.03$, $p < .002$, such that the probability of a *same* response was higher if valid cues ($M = .46$, $SE = .02$) rather than if invalid cues ($M = .32$, $SE = .02$) were presented, and the effect of probe position was more pronounced if valid cues rather than if invalid cues were presented. Direction was significant, $F(1, 15) = 7.87$, $MSE = 0.42$, $p < .02$, and interacted with probe, $F(8, 120) = 2.98$, $MSE = 0.05$, $p < .005$, such that the probability of a *same* response was higher for ascending targets ($M = .47$, $SE = .02$) than for descending targets ($M = .32$, $SE = .02$), and the probability of a *same* response was higher for negative probes if targets ascended than if targets descended. Probe was significant, $F(8, 120) = 14.70$, $MSE = 0.05$, $p < .0001$. A comparison of probabilities of *same* responses for negative probes and probabilities of *same* responses for positive probes was highly significant, $F(1) = 72.93$, $p < .0001$, with positive probes resulting in higher probabilities of *same* responses than negative probes. No other main effects or interactions approached significance, $Fs < 1.62$, $ps > .22$.

Discussion

Memory for the initial pitch exhibited a Fröhlich effect, and the Fröhlich effect was smaller when a valid cue was presented than when an invalid cue was presented and smaller for ascending targets than for descending targets. The smaller Fröhlich effect when a valid cue rather than an invalid cue was presented in Experiment 3, coupled with the smaller Fröhlich effect when the cue was present than when the cue was absent in Experiment 2, is consistent with previous findings that presentation of a valid cue or an invalid cue can facilitate or interfere with, respectively, a subsequent response (e.g., Posner, Nissen, & Ogden, 1977). Presentation of a valid cue in Experiment 3 did not eliminate the Fröhlich effect, and this is consistent with the significant Fröhlich effect that occurred when the cue was present in Experiment 2. Indeed, the valid cue condition in Experiment 3 and the cue-present condition in Experiment 2 presented identical cue and target stimuli, and the average weighted mean in the valid cue condition in Experiment 3 was nearly identical to the average weighted mean in the cue-present condition in Experiment 2. Similarly, the higher probability of a *same* response if a valid cue rather than an invalid cue was presented in Experiment 3 parallels the higher probability of a *same* response when a cue was present rather than absent in Experiment 2. As shown in Figure 4, the effect of direction on the probabilities of *same* responses was larger with negative probes than with positive probes, and this is consistent with Experiments 1 and 2.

A comparison of the functions in Figure 4 with the functions in Figures 2 and 3 shows that the functions in Figure 4 are generally flatter than the functions in Figures 2 and 3. This suggests that participants in Experiment 3 experienced greater uncertainty in their responses, and this uncertainty was particularly acute if an invalid cue was presented. If participants attended (even involuntarily) to an invalid cue, then they attended to an area of frequency space far from where the initial pitch was located, and so an increase in uncertainty regarding the initial pitch would be expected. The greater uncertainty in Experiment 3 is consistent with an attention-shifting account of the Fröhlich effect: If a participant attended to an invalid cue, then when the target was subsequently presented, that participant's attention traveled a greater distance through the representation of frequency space to reach the target than if the participant attended to a valid cue. If the velocity at which attention traveled through the representation of frequency space was constant, then a shift of attention through a greater distance in represented frequency space would result in attention reaching the target after the target had traveled a further distance; thus, the Fröhlich effect and uncertainty regarding the initial pitch of the target increased following an invalid cue. Also, the larger Fröhlich effect for descending targets than for ascending targets in Experiment 3 is consistent with Experiments 1 and 2 and with an influence of implied gravitational attraction on representation of the initial pitch of the target.

General Discussion

Memory for the initial pitch of an auditory target that ascended or descended in auditory frequency space was displaced in the direction of target motion. This displacement is an auditory equivalent of the Fröhlich effect, a displacement in memory previously observed for the initial location of a moving visual target in visual physical space. The Fröhlich effect in memory for the initial auditory pitch was larger if target velocity was faster, and this is consistent with previous findings regarding effects of target velocity on the Fröhlich effect for visual targets. An auditory cue presented before the target appeared, and which indicated the initial pitch of that auditory target, decreased but did not eliminate the Fröhlich effect in memory for initial auditory pitch, and this is consistent with previous findings regarding visual cueing of the initial location of a target on the Fröhlich effect for visual targets. The Fröhlich effect was larger when auditory targets descended than when auditory targets ascended, and this is consistent with representational gravity, a displacement in the direction of gravitational attraction that was previously observed for visual targets moving in visual physical space. The presence of a Fröhlich effect and of representational gravity in memory for initial pitch of an auditory target moving in auditory frequency space suggests that some aspects of spatial representation might be amodal, and that the representation of auditory frequency space shares crossmodal or multisensory properties with the representation of visual physical space.

A possible amodal spatial representation or a highly consistent mapping between representations of visual physical space and auditory frequency space is consistent with previous findings (e.g., Elkin & Leuthold, 2011; Melara & Marks, 1990; Rusconi et al., 2006). However, results of Experiments 1, 2, and 3 go beyond previous findings by demonstrating similarities, not just in static structural elements of representations of visual physical space and auditory frequency space, but in also demonstrating similarities in dynamics of motion within representations of visual physical space and auditory frequency space. Similarities in these representational spaces appear to involve at least some abstraction or top-down influence, as there is no strongly compelling a priori reason to associate a given auditory frequency with a given height in the picture plane (although Spence, 2011, provides some possibilities) or to represent sounds as if those sounds possessed properties (e.g., mass) of the sound sources. Regarding the latter point, Godøy (2001) suggested that auditory imagery involves visual information regarding the object that produced the sound, or kinesthetic information about how that sound was produced, and it is possible that such information might be involved in or activated during auditory perception (Hubbard, in press). Similarly, spatial representation might be a basic form of representation that can be used to represent nonspatial information, and in this case, properties of spatial representation influence the representation of nonspatial stimulus information.

Comparisons of effects of velocity and effects of the cue in Experiments 1, 2, and 3 were simplified by having a single initial auditory frequency for ascending targets and a single initial auditory frequency for descending targets. However, Müsseler and Kerzel (2004) suggested that a Fröhlich effect is more likely if participants can anticipate where a target will appear, and so it might be argued that use of a limited number of initial auditory frequencies in Experiments 1, 2, and 3 allowed participants to anticipate the initial auditory pitch, and so was responsible for the observed Fröhlich effect. However, such an argument can be rejected for three reasons. First, effects of a cue in Experiment 2 and of a valid cue in Experiment 3 show that the Fröhlich effect was actually diminished when participants were able to anticipate the initial auditory pitch. Second, even if the use of a limited number of initial auditory frequencies contributed to the Fröhlich effect observed in Experiments 1, 2, and 3, it is not clear how such an explanation could account for the effects of velocity in Experiment 1. Third, if there were any learning of the specific initial auditory pitches due to repetition of those frequencies across trials, then that learning would presumably have operated in the direction opposite a Fröhlich effect or an onset repulsion effect. In other words, any effect of learning the initial pitch should have decreased displacement away from that pitch. Overall, it is more parsimonious to attribute the results to a Fröhlich effect and representational gravity.

There are two other alternative hypotheses regarding displacement in memory for targets moving in auditory frequency space that can be ruled out. The first alternative is that displacement resulted from perception of a sound source moving toward or away from the participant rather than moving through frequency space. If pitch was taken to indicate location of a sound source relative to the participant, then Neuhoff's (2001) finding that the initial locations of approaching and receding sounds were judged to be closer than the actual initial locations would predict that an ascending (approaching) motion would result in a Fröhlich effect and a descending (receding) motion would result in an onset repulsion effect. This pattern is not consistent with the direction effect in Experiments 1, 2, and 3. The second alternative is that displacement resulted from an averaging of the initial pitch with subsequent pitches. Although this notion is consistent with the velocity effect in Experiment 1 and with reduction in the Fröhlich effect when a cue was presented in Experiment 2 and a valid cue was presented in Experiment 3, it is not consistent with the larger Fröhlich effect for descending targets than for ascending targets in Experiments 1, 2, and 3. Given that the same set of inducing stimuli (i.e., same pitch range) was used for ascending motion and for descending motion in Experiments 2 and 3, and for fast motion in Experiment 1, an averaging notion would predict that the Fröhlich effect for descending targets should not differ from the Fröhlich effect for ascending targets.

The findings of Experiments 1, 2, and 3 are relevant for theories of the Fröhlich effect. The presence of a Fröhlich effect in memory for the initial pitch of an auditory target that moved in auditory frequency space (as well as for auditory targets in spatial hearing in Getzmann, 2005) suggests that the Fröhlich effect is not limited to visual or visuospatial representation. Although it is possible the Fröhlich effect for visual targets moving in visual space and the Fröhlich effect for auditory targets moving in auditory frequency space each result from separate and distinct modality-specific mechanisms (e.g., retinal activation patterns), it seems more likely (and more parsimonious) that Fröhlich effects in different modalities might result from a single and more abstract or general mechanism that operates over different sensory modalities (e.g., attention, masking). Along these lines, the mapping of dynamics in the representation of auditory frequency space to the dynamics of the representation of visual physical space in Experiments 1, 2, and 3 is consistent with studies that found a mapping of dynamics of the representation of the final location of an auditory target to the representation of the final location of a visual target (e.g., Johnston & Jones, 2006). Such parallels suggest that an amodal representation of space, rather than a more specific sensory representation of space, might offer a more useful level of analysis and generalization in accounting for the Fröhlich effect (as well as in potentially accounting for other types of displacement).

An amodal representation of space suggests the Fröhlich effect reflects cognitive factors rather than perceptual factors, and this addresses Kerzel's (2010, p. 334) statement "future studies are needed to disentangle cognitive and perceptual components in the mislocalization of the initial position of a moving target." Indeed, there are several reasons for suggesting that the Fröhlich effect in Experiments 1, 2, and 3 was primarily due to cognitive factors rather than to perceptual factors. First, at probe judgment, the initial pitch was not available to perception and had to be retrieved from memory. Second, the latency between the end of the initial pitch and the beginning of the probe was longer than a percept would be expected to last (especially given intervening inducing stimuli). Third, if displacement was due to perceptual factors, then perception of the probe might have also been distorted. If representation of the probe was distorted in the same way as representation of the initial pitch, then use of probes would not detect distortion of the initial pitch (however, theories of the Fröhlich effect based on masking suggest that representation of the probe would not be distorted, because the probe is not followed by another stimulus). Even so, the current data do not allow perceptual factors to be ruled out (e.g., a distorted perception of the initial pitch might be encoded into memory, and during probe judgment, memory accurately reflects this distorted perception), and cognitive factors and perceptual factors might both contribute to displacement in memory for auditory pitch (cf. Hubbard, 2005, on displacement in memory for visual location).

Presentation of a cue before the target could decrease, but not eliminate, the Fröhlich effect in memory for initial pitch. This is consistent with the possibility that multiple mechanisms might contribute to the Fröhlich effect. At least one of these mechanisms was influenced by expectations regarding the target, and so expectations induced by a cue that indicated the correct initial pitch of the upcoming target could decrease the Fröhlich effect. However, at least one of these mechanisms was not influenced by expectations regarding the target, and so expectations induced by a cue that indicated the correct initial pitch of the upcoming target could not eliminate the Fröhlich effect. Just as it was earlier suggested that contributions of the Fröhlich effect and representational gravity influenced the overall displacement of the target, so too might the combined outputs of these different mechanisms of the Fröhlich effect influence the contribution of the Fröhlich effect to the overall displacement of the target. In other words, the Fröhlich effect involves multiple components, at least one of which is cognitively penetrable to expectations (i.e., is nonmodular), and at least one of which is cognitively impenetrable to expectations (i.e., is modular). A similar argument has been made for other types of displacement, such as representational momentum (Courtney & Hubbard, 2008; Hubbard et al., 2009; Ruppel, Fleming, & Hubbard, 2009) and the onset repulsion effect (Hubbard & Ruppel, 2011).

Memory for the final location of an auditory target moving in auditory frequency space exhibited a Fröhlich effect; that is, memory for the initial pitch was displaced in the direction of pitch motion. This displacement was larger with a faster velocity and larger for targets descending in frequency than for targets ascending in frequency, and this displacement was decreased but not eliminated when the initial pitch was cued prior to presentation of the target and participants could allocate more attention to the region of frequency space where the target would appear. Effects of velocity and cueing on the Fröhlich effect for auditory frequency were consistent with previous reports of effects of velocity and cueing on the Fröhlich effect for visual location, and effects of direction were consistent with previous reports of effects of representational gravity on memory for visual location. Suggestions that the representation of space is modality-specific do not offer compelling accounts why patterns of displacement observed for visual targets moving in visual physical space and attributable to characteristics of that space (e.g., asymmetric direction of gravitational attraction) should also occur for auditory targets moving in frequency space. Overall, patterns of displacement in memory for the initial pitch of auditory targets moving in auditory frequency space are consistent with patterns of displacement in memory for the initial location of visual targets moving in visual physical space, and these consistencies support the possibility of an amodal, crossmodal, or multisensory representation of space.

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