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Direct Learning in Auditory Perception: An Information-Space Analysis of Auditory Perceptual Learning of Object Length

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The theory of direct learning characterizes perception of a given property as occupying a locus in an information space and characterizes perceptual learning as continuous movement in that information space toward a more optimal locus. Three experiments investigated whether such an information-based account of learning could be applied to perceptual learning in audition. The results of Experiment 1 showed that perception of length by audition could be characterized as occupying a locus in an information space consisting of inertial variables that constrain perception of length by dynamic or effortful touch. Experiments 2 and 3 showed that feedback about length led to predictable movements across the information space from less optimal to more optimal loci. Such results provide additional support for the theory of direct learning and suggest that convergence information may be modality independent.

From the ecological perspective on perception and action, objects and events structure patterned energy distributions such that this structure is specific to (i.e., is lawfully related to) its source (Turvey & Shaw, 1999). Such higher order

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stimulation patterns that specify environmental properties to a perceiver are known as information, and perception is a single-valued function of information (Gibson, 1979/1986). In this view, perception is direct in that it is specific to information. Consequently, the theory of direct perception is an information-based theory of perception.

When perceivers become more skilled at perceiving a given property, they often change what informational variable(s) they are exploiting and/or how they are exploiting those variables (Runeson, Juslin, & Olsson, 2000; Wagman, Shockley, Riley, & Turvey, 2001; Withagen & Michaels, 2005). Specifically, perceivers often shift attention from less optimal informational variables to more optimal informational variables—a process known as the *education of attention* or *attunement* (Gibson, 1966). Proposed as a complement to the theory of direct perception, the theory of direct learning (Jacobs & Michaels, 2007) describes learning as movement across an information space—a manifold that represents the totality of informational variables of relevance to perceiving a given property. It is important to note that movement across this space is also a single-valued function of information (see later in the article). By this theory, perceptual learning is direct in that it is (also) specific to information. Consequently, the theory of direct learning is an information-based theory of perceptual learning.

The theory of direct learning has been applied to improvements in perception of length of a wielded object. In doing so, researchers have developed an information space consisting of informational variables that have been implicated in research on perception of length by dynamic of effortful touch (see Michaels, Arzamarski, Isenhower, & Jacobs, 2008; Michaels & Isenhower, 2011). We investigate whether the theory of direct learning can also be applied to (improvements in) perception of length by audition. Moreover, motivated by both ecological theory and empirical findings, we investigate whether the very same information space that has been developed for (improvements in) perception of length by dynamic or effortful touch can be applied to (improvements in) perception of length by audition. In what follows, we outline (a) the theory of direct learning, (b) how this theory has been applied to learning to perceive length by dynamic touch, and (c) the motivation for applying this analysis (using the same information space) to learning to perceive length by audition.

THE THEORY OF DIRECT LEARNING AND INFORMATION SPACES

A key concept of the theory of direct learning is that of information space. An information space is a low-dimensional manifold, where each point (or locus) in that manifold represents an informational variable of potential relevance to perceiving a given property (Jacobs & Michaels, 2007). Each possible locus in the space has a particular degree of usefulness to the perceiver given the correlation between the values of the property specified by that locus and the measured metrical values of that property. Although the usefulness of particular loci in the space may be limited to a particular set of experimental stimuli, the space will invariably consist of some loci that are more optimal than others for perceiving the intended property. The optimal locus in the space represents the informational variable that yields perceptual reports with the highest correlation with the to-be-perceived property (Jacobs & Michaels, 2007).

The key claim of the theory of direct learning is that learning is movement across an information space from a less optimal locus to a more optimal locus, often as a result of feedback about performance. The distance between the currently occupied locus and the optimal locus can be represented by a vector, and learning is represented as the reduction in the length of this vector over trials or over blocks of trials. As feedback is provided over this span, systematic relationships between perceived and metrical values of the to-be-perceived property provide *convergence information* to a perceiver. Convergence information can be represented as a vector field that "pushes" a perceiver toward the optimal locus (see Jacobs & Michaels, 2007). In the theory of direct learning, learning is a single-valued function of this convergence information. Just as a given environmental property is specified by information, so too are the changes required to improve perception of that environmental property.

Representing information by means of an information space allows for a clear hypothesis regarding the continuous nature of perceptual learning. When a perceiver uses a less optimal informational variable to perceive a given property, there will be a larger distance between the locus occupied by that perceiver and the end point of the vector that represents the (or an) informational variable that would allow for optimal performance. Learning occurs when the perceiver moves toward the optimal locus in information space and subsequently reduces the length of this vector.

Constructing an appropriate information space requires choosing candidate variables that specify the property to be perceived. For the purposes of the three experiments reported here, this property is the length of a homogeneous wooden rod. As a result, we turn now to a discussion of the informational variables of relevance for perceiving this property by dynamic or effortful touch.

THE INFORMATION (SPACE) FOR PERCEPTION OF LENGTH BY DYNAMIC TOUCH

Dynamic or effortful touch is the kind of touch used when objects are hefted and wielded by means of muscular effort (Gibson, 1966). A large body of research has shown that many geometric and functional properties of wielded objects—including length—can be perceived in this manner (see Turvey & Carello, 2011, for a review). Manipulating any object requires generating and controlling muscular forces sufficient to overcome the object's resistance to being rotated about a joint such as the wrist. Although a number of mechanical variables have been proposed as possible informational variables for perception of length by dynamic touch (see Kingma, Beek, & van Dieën, 2002; Kingma, van de Langenberg, & Beek, 2004), our analysis focuses on the first and third principal moments of inertia—I_1 and I_3. These variables describe the resistance to rotational acceleration about the short and long symmetry axes of the hand-object system, respectively. We focus on these two variables for a number of reasons.

First, such variables are explicitly relevant to the control of movements about joints and thus influence the patterns of deformation in the bodily tissues that serve as the medium for haptic perception (Turvey & Carello, 2011; Turvey & Fonseca, 2014). Accordingly, these variables account for nearly all of the variance in perception of length of freely wielded objects (Fitzpatrick Carello, Schmidt, & Corey, 1994). Moreover, feedback about the length and width of a wielded object tunes participants to I_1 and I_3, respectively (Wagman et al., 2001).

Second, previous research has validated the use of an information space composed of these variables in describing (improvements in) perception of length by dynamic or effortful touch (Michaels et al., 2008). Third, as discussed in more detail in the next section, these variables have also been implicated in perception of length by audition (Carello, Anderson, & Kunkler-Peck, 1998; Wagman & Abney, 2012, 2013; Wagman, Carello, Schmidt, & Turvey, 2009).

THE INFORMATION (SPACE) FOR PERCEPTION OF LENGTH BY AUDITION

The ecological proposal that objects and events structure patterned energy distributions such that this structure is lawfully related to its source is accompanied by a corollary proposal that structure in a given energy distribution is lawfully related to structure in other energy distributions (Gibson, 1966; Wagman & Abney, 2012, 2013). By this corollary proposal, objects and events simultaneously structure multiple patterned energy distributions such that structure in any one of these arrays is specific to its source. That is, the information for perception is (or at least could be) modality independent (but see Stoffregen & Bardy, 2001). Accordingly, I_1 and I_3 not only influence the patterns of muscular deformation that occur when an object is freely wielded but they also influence the pattern of vibrations that occur when an unsupported object strikes a support surface (Carello et al., 1998). Thus, in this context, these variables lawfully structure a higher order pattern of stimulation in the medium for auditory perception. I_1 and I_3 account for nearly all of the variance in perception of length by audition (Carello et al., 1998). Moreover, feedback about the length of a dropped object tunes participants to I_1 (see Wagman et al., 2009). In addition, recalibration of perception of length by dynamic touch transfers to perception by length by audition, and vice versa (Wagman & Abney, 2012, 2013).

Given (a) the likelihood that the information for perception of length is modality independent and (b) the empirical findings that I_1 and I_3 account for nearly all of the variance in both perception of length by dynamic touch and perception of length by audition, we investigate whether the theory of direct learning can also be applied to learning to perceive length by audition. Specifically, we investigate whether the very same information space developed to characterize information-based improvements in perception of length by dynamic or effortful touch can also be used to characterize information-based improvements in perception of length by audition.

In following Michaels et al. (2008), we constructed a one-dimensional information space with I_1 and I_3 as informational variables. A one-dimensional information space (an information line) for a particular rod set can be generated with Equation 1:

$$E_\alpha = (1 - |\alpha|)\ln(I_1) + \alpha \ln(I_3) \tag{1}$$

Each point on the information line corresponds to a locus value of α. Theoretically, an infinite set of loci can be computed. However, we computed an information space with α ranging from -1.0 to $+1.0$ in steps of 0.05 (cf. Michaels et al., 2008). The usefulness of each E_α differs and is determined by the squared correlation between E_α and the to-be-perceived property, rod length. The usefulness of each locus in the information space can be depicted in a usefulness curve in a graph with E_α on the *x*-axis and the squared correlation coefficient on the *y*-axis[1] (Michaels et al., 2008; see Figure 1).

To identify where a perceiver is located in information space, a similar computation is performed. Instead of correlating E_α values with rod length, E_α values are correlated with the perceptual reports of the intended property by a given perceiver for each block of trials. The locus value with the highest correlation is used as the perceiver's locus for that particular block of trials and can be plotted as the α on the x-axis and the corresponding squared correlation coefficient on the *y*-axis.

EXPERIMENT 1

In Experiment 1, we investigated whether an information space developed for perception of length by dynamic or effortful touch can be also applied to

[1]Given that E_α is calculated using $\ln(I_1)$ and $\ln(I_3)$, rod length values were ln transformed before the squared correlation at each locus was calculated. This is the case for the usefulness curves depicted in Figures 1, 4, and 7.

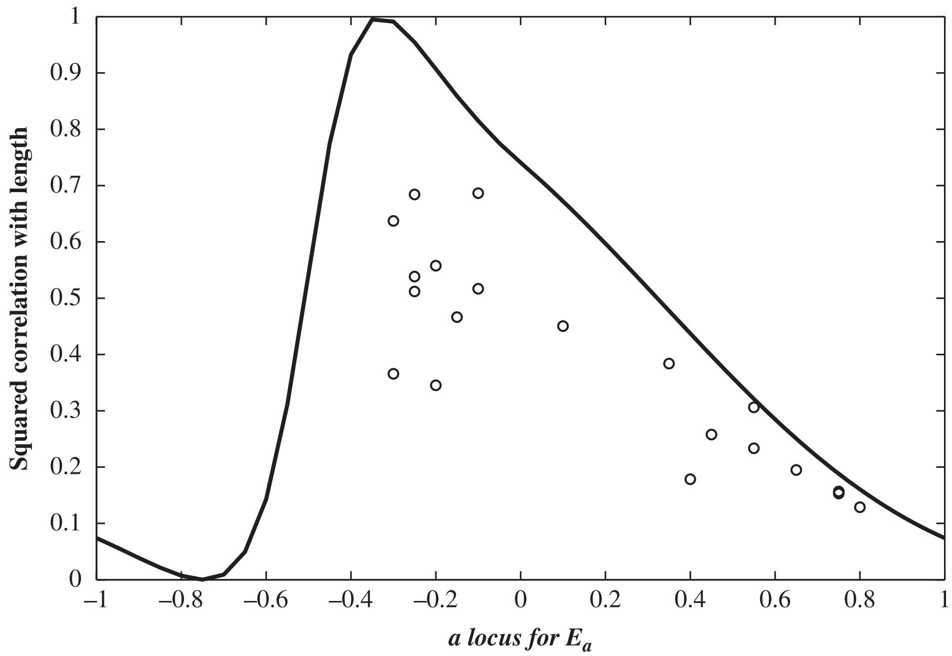

FIGURE 1 The information space for Experiment 1. The x-axis represents the information space. The y-axis is the squared correlation coefficient between rod length and each E_α on the information curve. The solid line represents usefulness of each locus in the space. The small open circles represent the loci occupied by each of the individual participants.

perception of length by audition. Following Michaels et al. (2008), we constructed a one-dimensional information space using I_1 and I_3 as described earlier. Previous research has shown that perception of length by audition is constrained by both I_1 and I_3, with a larger positive contribution of I_1 and a smaller negative contribution of I_3 (Carello et al., 1998). Therefore, it is expected that perceivers will tend to occupy loci in the information space between $\alpha = 0$ (corresponding to a positive contribution of I_1 only) and $\alpha = +1$ (corresponding to a negative contribution of I_3 only) but closer to $\alpha = 0$ than to $\alpha = +1$.

Method

Participants

Twenty undergraduate students (5 men and 15 women) from Illinois State University participated in this experiment for extra credit in a psychology course. The protocol for this and all other experiments was approved by the Institutional Review Board at Illinois State University in accordance with the Declaration of Helsinki. Written informed consent was obtained from each participant prior to participation.

Materials and Apparatus

Twenty wooden rods were used as stimuli in this experiment. Rods were five different lengths (20 cm to 100 cm in 20 cm increments) at each of four diameters (0.32 cm, 0.64 cm, 0.95 cm, 1.27 cm; see Table 1). The report apparatus consisted of an adjustable horizontal marker along a 240-cm wooden track at a height of 70 cm. Participants adjusted the distance of the marker toward or away from themselves using a pulley system such that the distance between the marker and the zero point of the apparatus corresponded to the perceived length of the rod. A tape measure secured to a wooden board on the floor allowed the experimenter to read reports of perceived length but was not visible to participants. Rods were rolled from the edge of a (23 cm tall × 29 cm deep × 44 cm wide) cardboard box and on to a large flat wooden surface on the laboratory floor.

Procedure

On each trial, the experimenter rolled one of the rods off the box and on to the wooden surface. The rod was centered with the edge of the box before being rolled and was rolled with the minimum force required to cause it to fall to the

TABLE 1
Stimulus Set Characteristics

Actual Length (cm)	*Perceived Length (cm)*	*Radius (cm)*	I_1	I_3
20	17.08 (1.22)	0.318	110.08	0.17
20	19.1 (1.97)	0.635	501.51	3.02
20	25.88 (3.47)	0.953	949.76	12.85
20	34.05 (5.97)	1.270	1720.56	41.13
40	21.28 (1.85)	0.318	1013.52	0.38
40	31.25 (3.59)	0.635	3375.88	5.1
40	44.26 (5.80)	0.953	7826.64	26.61
40	50.35 (8.80)	1.270	13681.25	82.5
60	28.95 (2.91)	0.318	3300.28	0.55
60	40.63 (4.59)	0.635	11493.86	7.72
60	50.03 (7.04)	0.953	25999.66	39.33
60	53.55 (6.69)	1.270	45451.01	122.02
80	31.98 (3.02)	0.318	7093.67	0.67
80	49.90 (6.40)	0.635	33926.41	12.82
80	61.68 (6.70)	0.953	60825.88	51.77
80	68.95 (7.58)	1.270	109949.73	166.13
100	46.15 (6.45)	0.318	13333.74	0.81
100	55.25 (7.42)	0.635	67174.79	16.25
100	72.10 (8.34)	0.953	121366.39	66.12
100	66.95 (9.39)	1.270	232445.75	224.84

surface (cf. Wagman & Abney, 2012, 2013). The participant listened to the rod strike the surface and then reported the perceived length of that rod as described earlier. Each rod was presented once per participant, and the order of presentation of rods was randomized across participants. On each trial, a participant could listen to a given rod as many times as necessary to achieve an impression of length, and he or she could continually adjust the report apparatus until satisfied with the perceptual report. After reporting perceived length on a given trial, the participant returned the marker to the zero point of the apparatus.

Results and Discussion

As a first pass in investigating calibration of perceived length to actual length (or lack thereof), we conducted a number of preliminary analyses. First, we conducted a 5 (Length) × 4 (Radius) analysis of variance (ANOVA) on perceived length. Main effects of Length ($F[4, 76] = 44.50$, $p < .001$, $\eta_p^2 = .14$) and Radius ($F[3, 57] = 16.41$, $p < .001$, $\eta_p^2 = .46$) were superseded by an interaction of these factors, $F(12, 228) = 1.95$, $p < .05$, $\eta_p^2 = .09$ In general, perceived length increased as actual length increased, especially for rods of larger diameter.

Second, for each participant, we computed regression lines with perceived length as the dependent variable and actual length as the independent variable. On average, actual length accounted for 35% of the variance in perceived length ($r^2 = .35$). The average slope of the regression lines was .44. Third, we conducted two multiple regressions at the level of the mean data.

The first multiple regression revealed that, together, length and width accounted for 94% of the variance in perceived length ($r^2 = .94$, $p < .001$). Perceived length increased with both variables, and length ($\beta = .76$) accounted for more variance in perceived length variance than did width ($\beta = .60$). The second multiple regression found that, together, log I_1 and log I_3 accounted for 96% of the variance in log perceived length ($r^2 = .96$, $p < .001$). Log perceived length increased with both variables; log I_1 ($\beta = .84$) accounted for more of the variance than log I_3 ($\beta = .18$).

Information-Space Analyses

Figure 1 shows the information space for the rod set used in Experiment 1, the usefulness of each locus in that space, and the loci occupied by each of the individual participants in Experiment 1. The occupied loci ranged from $\alpha = -.30$ to $\alpha = +.80$, with an average locus value of $\alpha = +.16$ ($SE = .09$). Given that a locus of $\alpha = 0$ reflects a positive contribution of I_1 only and a locus of $\alpha = +1$ reflects a positive contribution of I_3 only, a mean locus of $\alpha = +.16$

suggests that, on average, perceived length increased with both variables but that I_1 was more influential than I_3. Such results are consistent with the results of the multiple regression analysis described in the previous paragraph and with previous research (Carello et al., 1998).

The optimal locus for this set of rods is $\alpha = -.35$ (see Figure 1). This locus accounts for the largest portion of variance in rod length and includes a larger positive contribution from I_1 and a smaller negative contribution from I_3. We computed the absolute α_{observed}-to-α_{optimum} distance for each participant. A value of zero would indicate that the observed locus was equal to the optimal locus and increasing values from zero would indicate a larger distance between the optimal locus and observed loci. Averaged across participants, the average absolute α_{observed}-to-α_{optimum} distance was $\alpha = .51$ ($SE = .09$; see Figure 1).

Together, the analyses show that, without explicit feedback, perceivers use both I_1 and I_3 to perceive length by audition. Consistent with previous research (Carello et al., 1998), averaged across participants, these candidate informational variables accounted for almost all of the variance in perceived length. It is possible that a portion of the variance of perceived length in individual perceptual reports would be accounted for by informational variables in the acoustics of each rod dropped on a given trial (but see Carello et al., 1998).

The results from Experiment 1 provide further evidence for the modality independence of perception of length (Wagman & Abney, 2012). However, the results also show that perceivers did not direct attention to an optimal informational variable in perceiving length by audition. As described earlier, the theory of direct learning predicts that, with feedback, perceivers will move across the information space from a less optimal locus to a more optimal locus. We test this hypothesis with respect to perception of length by audition in Experiment 2.

EXPERIMENT 2

Experiment 1 established that perception of length by audition can be characterized as occupying a locus in an information space. Experiment 2 investigated whether improvements in perception of this property by this modality can be characterized as movement across that space from a less optimal to a more optimal locus. Experiment 2 consisted of a pretest, two practice sessions, and a posttest. During the practice sessions, half of the participants were provided with feedback corresponding to the actual lengths of each rod (i.e., the length specified by the optimal locus in information space, $\alpha = -.35$). The other half of the participants did not receive any feedback. Our general prediction was that participants who were provided with feedback would move toward the optimal locus in the information space.

Method

Participants

Thirty-eight undergraduate students (5 men and 33 women) from Illinois State University participated in this experiment for extra credit in a psychology course. Participants were randomly assigned to either the Feedback condition ($n = 19$) or the No Feedback condition ($n = 19$).

Materials and Apparatus

The 15 wooden rods used as stimuli in this experiment were a subset of those used in Experiment 1. The five rods with the largest diameter (1.27 cm) from Experiment 1 were not used in Experiment 2 (see Table 1). This particular subset of 15 rods was used in this experiment to keep the length of the experiment (and the number of trials) from becoming burdensome. The apparatus was the same as in Experiment 1.

Procedure

The experiment consisted of four blocks of trials: a pretest, two practice Sessions (Practice_1 and Practice_2), and a posttest.

Pretest. The procedure for the pretest was identical to that used in Experiment 1.

Practice$_1$. Following the pretest, each participant completed two practice sessions. Trials in the practice sessions were identical to those in the pretest except that participants in the Feedback condition received feedback after every trial. In this condition, after a participant reported perceived length of a given rod, the experimenter repositioned the marker such that the distance between the marker and the zero point corresponded to actual length (i.e., the length specified by the optimal locus for this set of rods, $\alpha = -.35$). Participants in the No Feedback condition did not receive feedback after reporting perceived length of the rod on a given trial.

Practice$_2$. The procedure for Practice_2 was identical to that for Practice_1.

Posttest. The procedure for the posttest was identical to that of the pretest.

Results and Discussion

Regression Analyses

As in Experiment 1, we computed regression lines with perceived length as the dependent variable and actual length as the independent variable for each participant in each condition for both the pretest and the posttest. To investigate changes in calibration of perceived length to actual length in the two feedback conditions, we conducted a 2 (Test: pretest vs. posttest) × 2 (Feedback Type: Feedback vs. No Feedback) ANOVA on the slopes of the regression lines. Main effects of Test, (F[1, 36] = 9.53, $p < .01$, $\eta^2_p = .21$), and Feedback type, (F[1, 36] = 10.20, $p < .01$, $\eta^2_p = .89$), were qualified by an interaction of these factors, $F(1, 36) = 5.89$, $p < .05$, $\eta^2_p = .14$. Follow up t tests were conducted to investigate this interaction. Such analyses showed that slopes increased from pretest ($M = .39$) to posttest ($M = .58$) in the Feedback condition (t[19] = 3.79, $p < .01$) but did not change from pretest ($M = .33$) to posttest ($M = .35$) in the No Feedback condition $t(19) = .48$, $p = .63$ (see Figure 2).

A multiple regression of log I_1 and log I_3 on log perceived length found that, in the pretest, these variables accounted for nearly all of the variance in log perceived length for participants in the Feedback ($r^2 = .94$, $p < .001$) and No Feedback conditions ($r^2 = .96$, $p < .001$). For both sets of participants, log I_1 accounted for more variance than log I_3, and log perceived length increased with both log I_1 (Feedback: $\beta = +.89$; No Feedback: $\beta = +.72$) and log I_3 (Feedback: $\beta = +.11$; No Feedback: $\beta = +.33$).

In the posttest, log I_1 and log I_3 again accounted for nearly all of the variance in log perceived length for both conditions (Feedback: $r^2 = .98$, $p < .001$; No Feedback: $r^2 = .97$, $p < .001$), with log I_1 accounting for more variance than log I_3. However, *how* these variables influenced perceived length changed (relative to the pretest) for participants in the Feedback condition but not for participants in the No Feedback condition. For participants in the Feedback condition, log perceived length increased with log I_1 ($\beta = +1.04$) and *decreased* with log I_3 ($\beta = -.64$). For participants in the No Feedback condition, log perceived length increased with both variables (log I_1: $\beta = +.48$; log I_3: $\beta = +.59$).

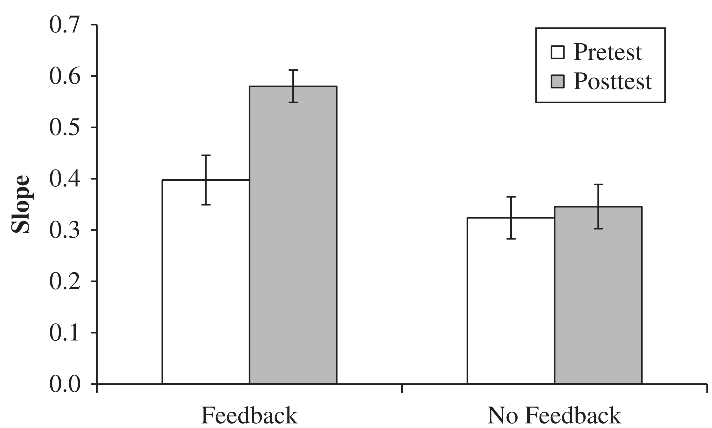

FIGURE 2 Slope values for pretest and posttest for Feedback and No Feedback conditions in Experiment 2.

Information-Space Analyses

To determine if participants moved toward the optimal locus in the information space ($\alpha = -.35$) as a result of feedback, we calculated the usefulness of each α value on the manifold and then determined each participant's locus in the information space during each of the four blocks of trials. To determine if participants moved toward the feedback locus ($\alpha = -.35$) in the information space after feedback, we computed the $\alpha_{observed}$-to-$\alpha_{optimum}$ distance for the four blocks. We first performed a 4 (Blocks: 1st, 2nd, 3rd, 4th) $\times$ 2 (Feedback vs. No Feedback) mixed-measures ANOVA on the $\alpha_{observed}$-to-$\alpha_{optimum}$ distance. There were no significant effects (all $ps > .1$).

However, inspection of the $\alpha_{observed}$-to-$\alpha_{optimum}$ distances across the blocks suggested potential conditional differences from pre- to posttest only (see Figures 3 and 4). Therefore, a 2 (Test: Pre vs. Post) $\times$ 2 (feedback: Feedback vs. No Feedback) mixed-measures ANOVA was performed on $\alpha_{observed}$-to-$\alpha_{optimum}$ distance. A main effect of Feedback ($F[1, 36] = 2.07$, $p < .05$, $\eta_p^2 = .12$) showed that, on average, $\alpha_{observed}$-to-$\alpha_{optimum}$ distance was smaller in the Feedback condition ($M = .43$, $SE = .06$) than in the No Feedback condition ($M = .61$, $SE = .06$). All other effects were not significant, $ps > .15$.

In addition, to determine if the $\alpha_{observed}$-to-$\alpha_{optimum}$ distances differed in the posttest, for participants in Feedback and No Feedback conditions, we compared these values directly. A t test showed that the $\alpha_{observed}$-to-$\alpha_{optimum}$ distance in the posttest was smaller for participants in the Feedback condition ($M = .35$, $SE = .26$) than for participants in the No Feedback condition ($M = .62$, $SE = .30$), $t(18) = -2.98$, $p < .01$.

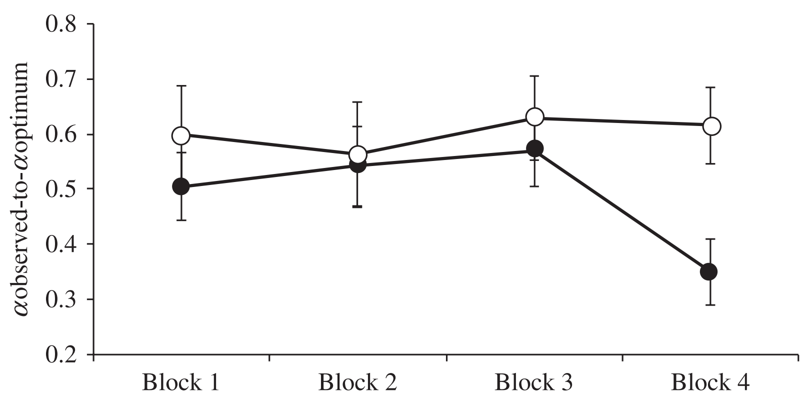

FIGURE 3 $\alpha_{observed}$-to-$\alpha_{optimum}$ distance values for the four blocks for Feedback and No Feedback conditions. Open circles correspond with the No Feedback condition and solid circles correspond with the Feedback condition.

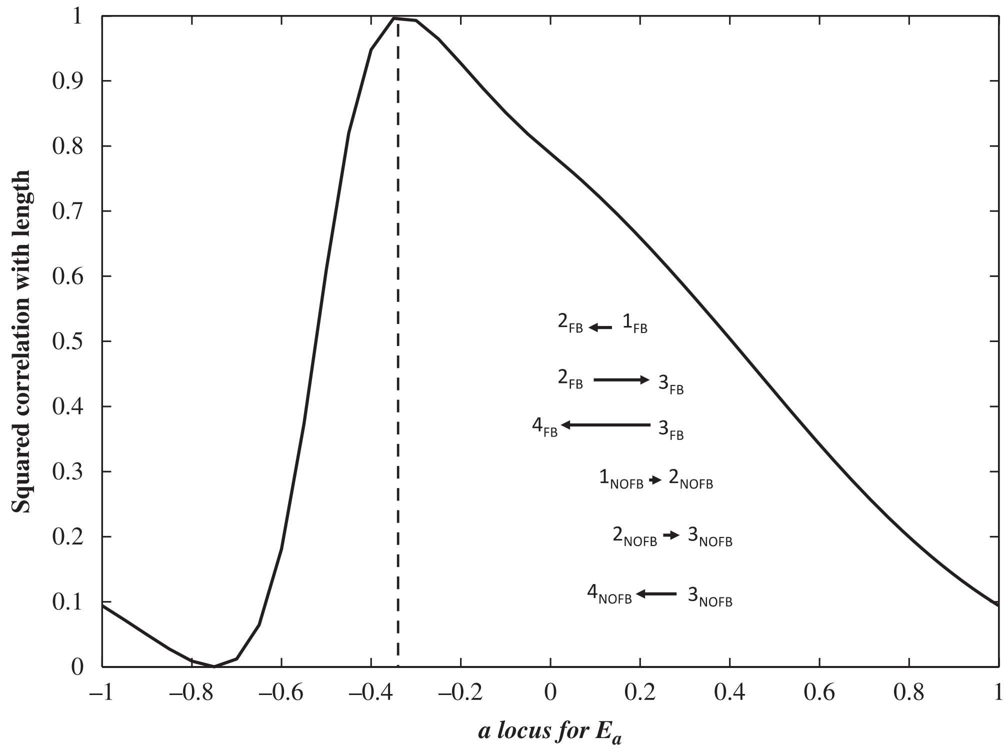

FIGURE 4 The information space for Experiment 2 and the average movement vectors for the Feedback (FB) and No Feedback (NOFB) conditions across the four blocks. Dashed vertical line corresponds to the optimal locus.

To test whether observed movement paths in the information space were correlated with the direction and distance from the observed locus to the optimal locus for each participant, we calculated the squared correlation coefficients between (a) the movements through the space (i.e., the signed change in locus on successive blocks) and (b) the relative distance (the optimal movement) to the optimal locus. This analysis included data for all blocks (cf. Michaels et al., 2008). We found that observed movements were in the direction of the expected movements for participants in the Feedback condition ($r = .24$, $p = .035$) but not for participants in the No Feedback condition ($r = .08$, $p = .472$).

The results of Experiment 2 suggest that following feedback, perceived length was better calibrated to actual length, and participants moved toward the optimal locus in the information space. This provides a preliminary demonstration that improvements in auditory perception of length as a result of feedback can be described as movements through an information space. Experiment 3 implements a two-step feedback procedure to provide a stronger test of this hypothesis (cf. Michaels et al. 2008).

EXPERIMENT 3

Experiment 2 provided preliminary evidence that improvements in auditory perception of length as a result of feedback can be described as movements through an information space. Experiment 3 provided a stronger test of this hypothesis by implementing a two-step feedback procedure in which participants were pushed toward and then away from a particular locus in information space. This two-step procedure creates a greater opportunity for learning and provides a potential for larger movements across the information space (cf. Michaels et al., 2008). In the first step, feedback was based on actual length (i.e., the length specified by the optimal locus, $\alpha = -.35$), reflecting a stronger positive contribution of I_1 and a weaker negative contribution of I_3. In the second step, feedback was based on the length specified by I_1 only ($\alpha = 0$), reflecting a strong positive contribution of I_1 and no contribution of I_3.

Method

Participants

Thirty-six undergraduate students (9 men and 27 women) from Illinois State University participated in this experiment for extra credit in a psychology course.

Materials and Apparatus

The 10 wooden rods used as stimuli in this experiment were a subset of those used in Experiment 2. The five .64-cm diameter rods used in Experiment 2 were not used in Experiment 2 (see Table 1). As in Experiment 2, a subset of rods was used to keep the length of the experiment from becoming burdensome. The apparatus was the same as in Experiments 1 and 2.

Procedure

We used a two-step feedback procedure (cf. Michaels et al., 2008) that consisted of seven blocks of trials: Step One pretest, Step One Practice Session, Step One Practice Session, Step One posttest/Step Two pretest, Step Two Practice Session, Step Two Practice Session, and Step Two posttest. The Step One posttest/Step Two pretest served as both the posttest for Step One and the pretest for Step Two. The procedure for each phase of the experiment was identical to corresponding phases in Experiment 2 except that all participants received feedback during the practice sessions. Feedback given during the Step One Practice sessions was based on the length specified by the optimal locus ($\alpha = -.35$), and feedback given during the Step Two Practice Sessions was based on the length specified by a locus of $\alpha = 0$, reflecting a contribution of I_1 only (cf. Michaels et al., 2008; see Table 2).

TABLE 2
Feedback for Rods in Experiment 3 as a Function of the Locus Values

Length (cm)	*Radius (cm)*	*$\alpha = -.35$ (cm)*	*$\alpha = 0$ (cm)*
20	0.318	20	20
20	0.953	20	33
40	0.318	40	34
40	0.953	40	55
60	0.318	60	45
60	0.953	60	74
80	0.318	80	54
80	0.953	80	90
100	0.318	100	63
100	0.953	100	107

Results and Discussion

Regression Analyses

We computed regression lines with perceived length as the dependent variable and feedback length (actual length, specified by locus $\alpha = -.35$) as the independent variable for each participant in pretest One and posttest One. We computed regression lines with perceived length as the dependent variable and feedback length (specified by locus $\alpha = 0$) as the independent variable for each participant in pretest Two and posttest Two.

To investigate changes in calibration of perceived length to actual length from pretest to posttest in the two feedback steps, we conducted a 2 (Test: pretest vs. posttest) × 2 (Feedback Step: One vs. Two) ANOVA on the slopes of the regression lines. A main effect of Test, ($F[1, 35] = 202.34$, $p < .001$, $\eta_p^2 = .85$), showed that slope values were larger in the posttest blocks ($M = .48$) than in the pretest blocks ($M = .36$). A main effect of Feedback Step ($F[1, 35] = 15.40$, $p < .001$, $\eta_p^2 = .09$) showed that, overall, slope values were larger in Step Two ($M = .67$) than in Step One ($M = .17$). The interaction of these variables was marginally significant, $F(1, 35) = 3.77$, $p = .06$, $\eta_p^2 = .09$ (see Figure 5).

A multiple regression of log I_1 and log I_3 on log perceived length found that, in Step One pretest, these variables accounted for nearly all of the variance in log perceived length ($r^2 = .90$, $p < .001$). Log I_1 accounted for more variance than log I_3, and log perceived length increased with both log I_1 ($\beta = +.90$) and log I_3 ($\beta = +.13$). In Step One posttest/Step Two pretest, these variables again accounted for nearly all of the variance in log perceived length ($r^2 = .97$, $p < .001$), with log I_1 accounting for more variance than log I_3 and log perceived length increasing with both log I_1 ($\beta = +.94$) and log I_3 ($\beta = +.06$). In Step Two posttest, these variables continued to account for nearly all of the variance in

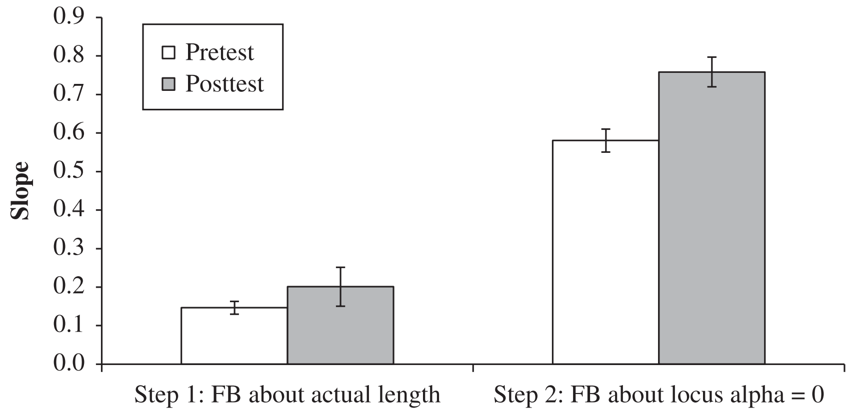

FIGURE 5 Slope values for pretest and posttest for Step One and Step Two in Experiment 3. FB = Feedback.

log perceived length ($r^2 = .98$, $p < .001$). Log I_1 accounted for more variance than log I_3, and log perceived length increased with both log I_1 ($\beta = +.88$) and log I_3 ($\beta = +.14$).

Information-Space Analyses

To determine if participants moved toward the locus in the information space specified by feedback provided at Step One ($\alpha = -.35$) and Step Two ($\alpha = 0$), we computed the α_{observed}-to-α_{optimum} distance for the pretest and posttest for Steps One and Two. To determine if participants moved toward the locus in information space, for each phase we performed a Welch two-sample *t* test on the pre- and posttest α_{observed}-to-α_{optimum} distances for each of the two feedback steps. For Step One, there was a reliable decrease in α_{observed}-to-α_{optimum} distances from pretest ($M = .49$, $SE = .01$) to posttest ($M = .23$, $SE = .01$), $t(69.53) = -2.22$, $p < .05$. For Step Two, there was a reliable decrease in α_{observed}-to-α_{optimum} distances from pretest ($M = -.12$, $SE = .01$) to posttest ($M = .14$, $SE = .01$), $t(67.12) = -2.34$, $p < .05$ (see Figures 6 and 7). To determine if the amount of movement toward the two optima differed for each step, we recalculated the α_{observed}-to-α_{optimum} distances to be the absolute difference between α_{observed} and α_{optimum}. A 2 (Test: Pre vs. Post) $\times$ 2 (Feedback Step: One vs. Two) ANOVA was performed on the absolute α_{observed}-to-α_{optimum} distances. A main effect of Test suggested that α_{observed}-to-α_{optimum} distances for Step One ($M_{\text{pre}} = .56$, $SE_{\text{pre}} = .06$; $M_{\text{post}} = .44$, $SE_{\text{post}} = .05$) and Step Two ($M_{\text{pre}} = .44$, $SE_{\text{pre}} = .06$; $M_{\text{post}} = .34$, $SE_{\text{post}} = .05$) each decreased after feedback, $F(1, 70) = 6.63$, $p < .05$.

As in Experiment 2, we determined if observed movements through the information space were correlated with the relative distance to the optimal

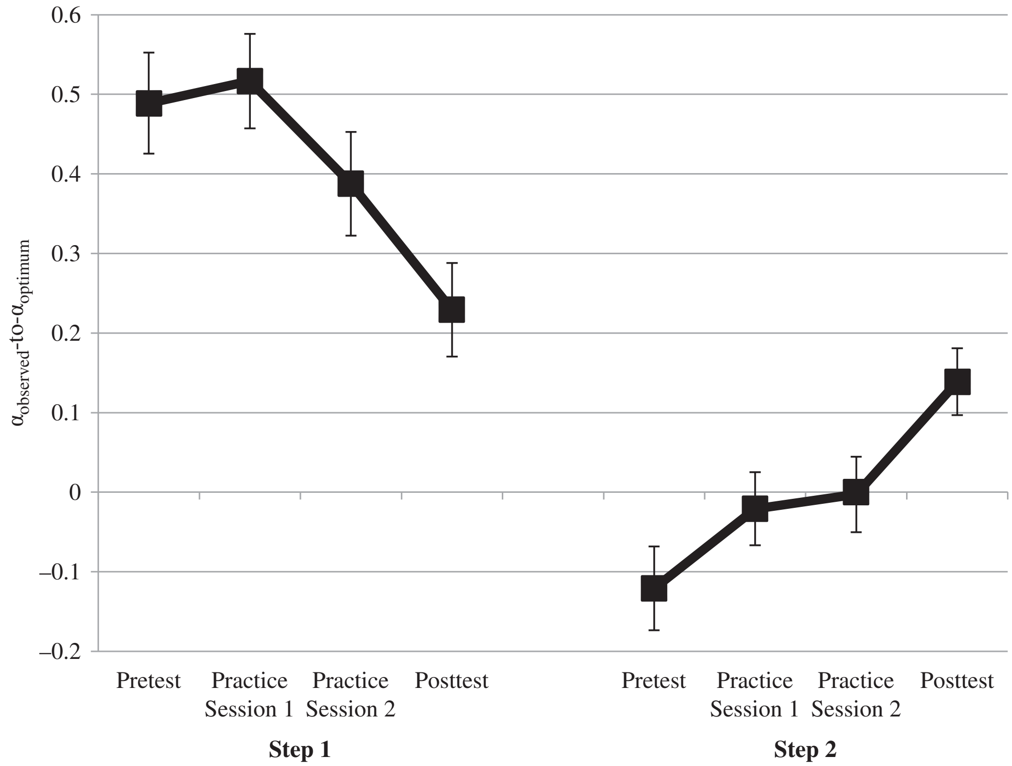

FIGURE 6 $\alpha_{observed}$-to-$\alpha_{optimum}$ distance values for the four blocks for Step One and Step Two.

movements. Across both phases, we found that the observed movements were in the direction of the optimal movements, $r = .63$, $p < 001$.[2]

GENERAL DISCUSSION

In the theory of direct perception, objects and events structure patterned energy distributions such that this structure is lawfully related to its source. That is, perception is specific to information. Moreover, to the extent that (a) a given object or event simultaneously structures multiple energy distributions and (b) there are lawful relationships among those patterns, the information for perception is (or at least could be) modality independent. To this end, previous research has shown that the information for perception of length by dynamic or effortful touch is analogous (if not identical) to the information for perception of length by audition (see Carello et al., 1998; Fitzpatrick et al., 1994).

[2]Step 1: $r = .67$, $p < 001$; Step 2: $r = .65$, $p < 001$.

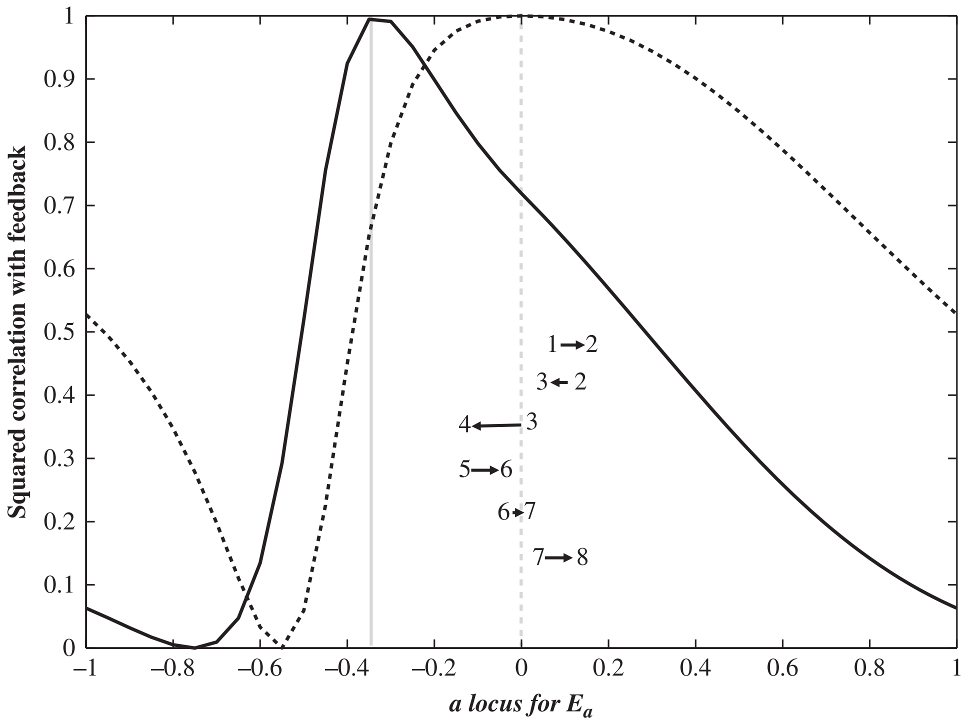

FIGURE 7 Average movement vectors in the information spaces in Experiment 3. For Step One (Blocks 1 through 4) the information space is shown with solid lines and a solid vertical line indicates the locus of the first feedback variable ($\alpha = -.35$). For Step Two (Blocks 5 through 8) the information space is shown with dashed lines and a dashed vertical line indicates the locus of the second feedback variable ($\alpha = 0$). Average movement vectors do not correspond with the average squared correlation with length.

In the theory of direct learning, learning is specific to convergence information (provided via feedback) that pushes a perceiver from less optimal to more optimal loci in an information space. Previous research has applied the theory of direct learning to characterize learning to perceive object length by dynamic or effortful touch in this manner (Michaels et al., 2008). Given the likelihood that the information for perception of this property is modality independent, we investigated whether the information space developed to characterize (improvements in) perception of length by dynamic or effortful touch could also be used for (improvements in) perception of length by audition. In short, we investigated whether such convergence information for this property might also be modality independent (see Wagman & Abney, 2012, 2013).

Experiment 1 was a preliminary investigation of whether the information space developed for perception of length by dynamic or effortful touch could be applied to perception of length by audition. In other words, it investigated whether perception of length by audition could be characterized as occupying a locus in an information space comprised of the first and third principal moments of inertia—I_1 and I_3 (see Michaels et al., 2008). Both the multiple regression and information-space analyses suggested that perceivers used both I_1 and I_3 to perceive length by audition (but relied on I_1 more than I_3), a finding that is consistent with previous work on perception of length by audition (Carello et al., 1998; Wagman et al., 2009). Experiment 1, therefore, validated the use of the information space developed in the context of perception of length by dynamic touch for use in the context of perception of length by audition. Perception of length by audition can also be described as occupying a locus in analogous (if not identical) information space.

The main proposal for the theory of direct learning is that learning is an information-based phenomenon. Feedback about performance provides convergence information that pushes a perceiver across the information space from a less optimal locus to a more optimal locus. Experiments 2 and 3 were designed to explicitly investigate this hypothesis with respect to learning to perceive length by audition.

In Experiment 2, we used a four-block (pretest, practice$_1$, practice$_2$, posttest) design where half of the perceivers received feedback about actual length (locus, $\alpha = -.35$) during the practice blocks, and the other half did not receive any feedback. In the posttest, participants who received feedback during the practice blocks moved toward the optimal locus; participants who did not receive feedback during the practice blocks did not do so.

The design of Experiment 3 provided a stronger test that convergence information pushes perceivers through specific paths toward particular loci in information space. In Step One, perceivers received feedback about actual length (locus, $\alpha = -.35$). In Step Two, they received feedback about the length specified by I_1 only ($\alpha = 0$). The general pattern of results of Experiment 3 mirrored those of Experiment 2—participants moved toward the locus in information space specified by feedback. Moreover, such movements were predicted by the direction and length of the information vectors providing convergence information. Such results provided further support for the theory of direct learning in that the learning process is information based.

Convergence Information Is Modality Independent

An object's inertial properties (particularly I_1 and I_3) lawfully constrain both patterns of deformation in bodily tissue when that object is freely wielded and patterns of vibrations in air when that object strikes a support surface. Accordingly, together, these variables account for nearly all of the variance of perception of object length by dynamic touch and audition, respectively (Carello et al., 1998; Fitzpatrick et al., 1994; Withagen & Michaels, 2005). In each case, perceived length is a single-valued function of these variables. An information-space analysis provides a topological model for investigating how perceivers increasingly learn to exploit such variables following feedback.

This study found that an information space constructed using I_1 and I_3 that was initially developed for investigating improvements in perception of length by dynamic touch (Michaels et al., 2008) can be used for investigating improvements in perception of length by audition. Feedback about the length specified by a locus in the information space provided convergence information for perception by each modality and produced similar patterns of movement through information space in each case. Such results provide additional support for the generality of the theory of direct learning (Jacobs & Michaels, 2007; see Jacobs, Vaz, & Michaels, 2012).

The findings also provide support for the ecological proposal that objects and events simultaneously structure multiple patterned energy distributions such that structure in any one of these arrays is specific to its source. That is, the results provide support for the proposal that information for perception is (or at least could be) modality independent. Deformation in bodily tissue as a result of wielding a rod and deformation in air as a result of that rod colliding with a support surface are likely not identical. However, this does not prevent these two stimulation patterns from being lawfully related to each other as well as to their respective sources. Such lawful relationships between patterns across energy media is the *information for transfer* across modalities (Wagman & Abney, 2012, 2013).

Jacobs and Michaels (2007) proposed that direct learning is the change of variable use of higher order properties of ambient energy arrays. Our study provides evidence for the notion that convergence information—a singled-valued informational variable—is (or could be) modality independent.

CONCLUSION

Three experiments tested whether the theory of direct learning could be applied to perception of length by audition. The results showed that feedback led to predictable movements across an information space from less optimal to more optimal loci. Such results support Jacobs and Michaels' (2007) theory of direct learning and the notion that convergence information guides learning. Moreover, the results are also consistent with the proposal that convergence information is modality independent.

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