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Transfer of Recalibration From Audition to Touch: Modality Independence as a Special Case of Anatomical Independence

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An important step in developing a theory of calibration is establishing what it is that participants become calibrated to as a result of feedback. Three experiments used a transfer of calibration paradigm to investigate this issue. In particular, these experiments investigated whether recalibration of perception of length transferred from audition to dynamic (i.e., kinesthetic) touch when objects were grasped at one end (Experiment 1), when objects were grasped at one end and when they were grasped at a different location (i.e., the middle) (Experiment 2), and when false (i.e., inflated) feedback was provided about object length (Experiment 3). In all three experiments, there was a transfer of recalibration of perception of length from audition to dynamic touch when feedback was provided on perception by audition. Such results suggest that calibration is not specific to a particular perceptual modality and are also consistent with previous research that perception of object length by audition and dynamic touch are each constrained by the object's mechanical properties.

Keywords: calibration, transfer, haptic perception, auditory perception

Successfully performing everyday behaviors requires that both perception and behavior are scaled to environmental properties—a process known as calibration (Bhalla & Proffitt, 1999; Reiser, Pick, Ashmead, & Garing, 1995). Calibration provides the link between behavior and perception in that it establishes and maintains an appropriate relationship between an informative stimulation pattern and perception of an environmental property or performance of a behavioral task. A large body of research has shown that calibration requires experiences over and above the perceptual task itself (such as feedback in some form or another) (E. Gibson, 1969; Withagen & Michaels, 2005; Wagman, McBride, & Trefzger, 2008). An important step in developing a theory of calibration of perception and behavior is establishing the *object of calibration*—the "entity, process or disposition to which calibration applies" (Withagen & Michaels, 2004, p. 1282). Doing so requires establishing what it is that participants become calibrated to as a result of feedback (Reiser et al., 1995; Withagen & Michaels, 2007). One method of investigating this is by using a transfer of recalibration paradigm. The circumstances under which calibration transfers from one context to another are expected to reveal how calibration is organized and thus shed light on what participants become calibrated to as a result of feedback (see Redding & Wallace, 1997; Schmidt & Lee, 2005, for reviews).

Recently, hypotheses about transfer of recalibration of behavior have been motivated by the observation that the performance of most (if not all) behaviors seems to exhibit task-specificity and anatomical independence. That is, in general, behavior is organized not in terms of the anatomical structures involved but rather in terms of the purpose of the behavior or goal to be achieved (Reed, 1982). To this end, performing a given behavior requires flexibly and temporarily recruiting a collection of potentially independent anatomical structures into a task-specific device capable of performing the intended behavior (Bingham, 1988; Kugler & Turvey, 1987). Moreover, to a large extent, a given behavior can be performed by means of different anatomical components (and different behaviors can be performed by means of the same anatomical components). For example, locomoting from one place to another over a ground surface can be performed by walking, crawling, or hopping—each of which uses different (or a different coordination of the same) anatomical components. The anatomical independence of behavior suggests that calibration of a particular behavior may also be anatomically independent. If so, recalibration of performance of a particular behavior by a given effector (or set of effectors) would be expected to transfer to performance of that behavior by a different effector (or set of effectors). A number of studies have shown this to be the case. For example, recalibration of walking (distance) transfers to other locomotory behaviors such as sidestepping (Reiser et al., 1995) and crawling (Withagen & Michaels, 2002) but does not transfer to nonlocomotory behaviors such as turning in place, kicking, or throwing (Bruggeman, Pick, & Reiser, 2005; Bruggeman & Warren, 2010; Reiser et al., 1995).

Perception of most (if not all) environmental properties also seems to exhibit task-specificity and anatomical independence. That is, in general, perception is organized not in terms of the

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anatomical structures involved but rather in terms of the environmental property being perceived (J. Gibson, 1966). To this end, perceiving a given environmental property also requires flexibly and temporarily recruiting a collection of potentially independent anatomical structures into a perceptual device capable of perceiving the intended property (Runeson, 1977). Moreover, to a large extent, perception of a given environmental property can occur by means of different anatomical components, and the same anatomical components can be used to perceive different environmental properties. For example, the length of an occluded object can be perceived when that object is wielded by one hand, both hands, or one hand and one knee (Carello, Fitzpatrick, Domaniewicz, Chan, & Turvey, 1992) as well as when that object is wielded by a foot (Hajnal, Kinsella-Shaw, Fonseca, Carello, & Harrison, 2007) or by the entire torso (Palatinus, Carello, & Turvey, 2011). As in behavior, such anatomical independence of perception suggests that calibration of perception of a given environmental property may also be anatomically independent. If so, recalibration of perception of a given environmental property by a given effector (or set of effectors) would be expected to transfer to perception of that property by means of a different effector (or set of effectors). A number of studies have shown this to be the case as well. For example, recalibration of perception of length of an occluded wielded rod transfers from one hand to the other (Withagen & Michaels, 2004) as well as from hand to foot (and vice versa) (Stephen & Hajnal, 2011).

Just as perception of a given environmental property can occur by means of different effectors within a given perceptual modality (such as in perception of properties of wielded objects), perception of a given environmental property can also occur by means of different perceptual modalities. For example, geometric properties such as length and shape can be perceived with a comparable degree of accuracy by vision, touch, and audition (Carello, Anderson, & Kunkler-Peck, 1998; Wagman, Carello, Schmidt, & Turvey, 2009), and functional properties such as whether an inclined surface affords standing on can be perceived with a comparable degree of accuracy by vision and touch (Fitzpatrick, Carello, Schmidt, & Corey, 1994; Malek & Wagman, 2008; Regia-Corte & Wagman, 2008). Given that different perceptual modalities generally consist of different anatomical pieces, the modality independence of perception seems to be a special case of the anatomical independence of perception. That is, anatomical independence seems to apply not only within a given perceptual modality but also across different perceptual modalities (Wagman et al., 2009). If so, then calibration of perception of a given environmental property may be independent of a given perceptual modality. A necessary condition of the modality independence of calibration is that recalibration of perception of a given environmental property transfers from one perceptual modality to another (i.e., that calibration is not specific to a particular perceptual modality). The three experiments reported here investigate whether this is the case.

Experiment 1

Experiment 1 investigated whether recalibration of perception of a given environmental property transfers from one perceptual modality to another. Specifically, Experiment 1 investigated whether recalibration of perception of object length transferred from audition to dynamic touch. Dynamic touch is the subsystem of touch used when objects are grasped and wielded by means of muscular effort (see Carello & Turvey, 2004; Carello & Wagman, 2009 for reviews). We chose this property and these perceptual systems for a number of reasons. First, previous research has shown perceivers have definite impressions of object length when objects are perceived by audition (i.e., when unsupported occluded objects are dropped to the floor) and when objects are perceived by dynamic touch (i.e., when occluded objects are grasped and wielded). Moreover, in each case, perceived length is systematically related to actual length (Carello et al., 1998; Wagman et al., 2009). This systematic relationship allows for an analysis of both the calibration of perceived length to actual length and the transfer of recalibration using regression statistics (Cabe & Wagman, 2010; Wagman & Van Norman, 2011; Withagen & Michaels, 2004; see Jacobs & Michaels, 2006).

Second, despite a number of anatomical, physiological, and functional differences between audition and touch, there is evidence to suggest that perception of object length by audition and dynamic touch might be constrained by the same (or similar) physical variables. In particular, in each case, perception of length seems to be constrained by the object's mechanical properties (including mass, static moment, and moment of inertia) (Carello et al., 1998; Kingma, Beek & van Dieën, 2002; Withagen & van Wermeskerken, 2009). Such properties have the potential to influence both patterns of muscular deformations when the object is wielded and patterns of vibrations when the object strikes a surface and are thus potentially informative about object length in each perceptual modality.[1]

Third, a number of recent studies have investigated transfer of calibration within the perceptual subsystem of dynamic touch. Such studies have shown that transfer of calibration in dynamic touch is anatomically independent—that is, recalibration transfers from one hand to the other (Withagen & Michaels, 2004) and from hand to foot (and vice versa) (Stephen & Hajnal, 2011). The three experiments reported here build on and extend this work by investigating whether such anatomical independence might also apply *across* perceptual systems (when one of those perceptual systems is dynamic touch).

Experiment 1 consisted of a pretest, training session, and posttest. In the pretest and posttest, participants judged the length of a set of occluded wooden rods while (1) wielding those rods about

[1] Carello et al., (1998) investigated whether a set of candidate acoustic variables might provide information about the length of dropped rods. They found that duration, amplitude, and frequency centroid of recordings of the rods striking the floor each accounted for less variance in perceived length than did the actual length of the rod. Given that length is a geometric property, it cannot directly affect acoustic structure or muscular deformation. An object's mechanical properties, on the other hand, can affect *both* acoustic structure and muscular deformation and can therefore be informative about length in both audition and touch. Along these lines, Carello et al. (1998) found that the maximum and minimal principal moments of inertia accounted for 97% of the variance in perceived length. Given that our goal is to determine whether recalibration of perception of length transfers from audition to touch, and that such transfer would reveal "common ground" between these perceptual systems (Stephen & Hajnal, 2011), we focus on variables that might be potentially informative about object length in both perceptual modalities.

their wrist and (2) after listening to those rods fall on to a wooden surface (on separate blocks of trials). In the training session, participants judged the length of a sub set of the rods after listening to those rods fall on a wooden surface. Participants in the feedback condition received feedback after each attempt in the training session. Participants in the no-feedback condition did not.

A large body of research has shown that calibration requires experiences over and above the perceptual task itself (such as feedback in some form or another) (E. Gibson, 1969; Stephen & Arzamarski, 2009; Wagman, Shockley, Riley, & Turvey, 2001; Wagman, McBride, & Trefzger, 2008; Wagman & Van Norman, 2011; Withagen & Michaels, 2004, 2005). As a result, we expect that auditory perception of length will recalibrate only when participants are provided with feedback during training. Moreover, if calibration of perception of length is not specific to a particular modality, then recalibration should transfer from audition to touch. Alternatively, if calibration of perception of length is specific to a given perceptual modality, then there should be no such transfer of recalibration.

Method

Participants

Twenty-six right-handed undergraduate students (five men and 21 women) from Illinois State University participated in this experiment.[2] All participants received extra credit in their psychology courses in exchange for their participation. Participants were assigned to either the feedback condition ($n = 15$) or the no-feedback condition ($n = 12$). One participant in the feedback condition was excluded from data analysis because of failure to follow instructions.

Materials and Apparatus

Ten wooden rods (1.2 cm diameter) ranging in length from 30 cm to 120 cm in 10-cm increments were used as stimuli in this experiment. Participants sat in a right-handed student desk and placed their right forearm on the desk. They slid their right hand through a curtain, which occluded both hand and rod. 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 the floor allowed the experimenter to read reports of perceived length (in cm measured from the wrist of the participant). The tape measure was not visible to the participant.

Procedure

The experiment consisted of three sets of trials: a pretest, a training session, and a posttest.

Pretest. Each participant was seated and placed his or her right arm on the armrest. The participant then placed his or her right hand through the curtain such that the wrist was aligned with the zero point of the report apparatus.

The pretest consisted of two different conditions—touch and audition. On a trial in the touch condition, the participant was handed one of the rods by the experimenter such that one end of the rod was flush with the bottom of the hand (i.e., so that all but the portion of the rod in the hand extended from the "thumb side" of the fist) and attempted to perceive the length of the rod by wielding it about the wrist. Wielding was not restricted in any way except that the participant was instructed to refrain from lifting his or her forearm off the desk and from touching the occlusion curtain with the wielded object. The participant then reported the perceived length of the rod as described above. A participant could wield each rod as long as necessary to achieve an impression of length and was allowed to continually adjust the report apparatus until he or she was satisfied with the perceptual report. After reporting perceived length, the participant returned the marker to the zero point of the apparatus.

On a trial in the audition condition, the experimenter rolled one of the rods from the edge of a (23 cm tall × 29 cm deep × 44 cm wide) cardboard box and on to a large wooden surface. Each rod was centered with the box before being rolled and was rolled with the minimum force necessary to cause it to fall to the surface. On a given trial, the participant listened to a rod strike the wooden surface and reported the perceived length of the rod in the same manner as in the touch condition. A participant could listen to each rod as many times as necessary to achieve an impression of length and was allowed to continually adjust the report apparatus until he or she was satisfied with the perceptual report. (Typically, a participant did not ask to hear a given rod more than once or twice on a given trial). After reporting perceived length, the participant returned the marker to the zero point of the apparatus.

Each participant reported perceived length once for each rod in each modality condition. Blocks of five trials in the touch condition were alternated with blocks of five trials in the audition condition. The participant was not informed that the same rod set was used in both modality conditions. The order of modality conditions was randomized across participants, and the order of rod lengths was randomized within a given modality condition. The procedure for the pretest was the same for participants in both feedback conditions.

Training session. After the pretest, each participant completed a training session. The training session consisted of six audition trials using a subset of rods from the pretest in the following order: 30 cm, 100 cm, 120 cm, 50 cm, 40 cm, and 110 cm (cf. Withagen & Michaels, 2004, 2007). These trials were identical to trials in the audition condition described above except that participants in the feedback condition received feedback after each trial. In this condition, after a participant reported perceived length on a given trial, the experimenter repositioned the marker such that the distance between the marker and zero point corresponded to the actual length of the rod. Participants in the no-feedback condition did not receive any feedback after reporting perceived length of the rod. The participant was not informed that the rod set used in the training session was a subset of the rod set used in the pretest.

[2] No sex differences are to be expected in perception of length by audition or dynamic touch.

Posttest. The procedure for the posttest was identical to the procedure of the pretest. As in the pretest, the order of modality conditions was randomized across participants, and the order of rod lengths was randomized within a modality condition. The participant was not informed that the rod set used in the posttest was identical to that used in the pretest or that it was a superset of the rod set used in the training session.

Results

To investigate recalibration (and transfer of recalibration) of perceived length, we computed regression lines with perceived length as the dependent variable and actual length as the independent variable for each perceptual modality in the pretest and the posttest.[3] The slopes of these regression lines can be used to quantify scaling error (i.e., the error in the mapping between changes in perceived length and changes in actual length), and the intercepts can be used to quantify offset error (i.e., error attributable to a consistent tendency to over- or underestimate actual lengths by a constant amount) (Cabe & Wagman, 2010). As recalibration occurs, slopes should approach 1.0 and intercepts may or may not approach 0.0 (Cabe & Wagman, 2010; Wagman & Van Norman, 2011).

A large body of research has shown that lengths of occluded wielded rods are typically underestimated (especially for longer rods), and such underestimation is attributable to a miscalibration of the scaling of perceived length to actual length (e.g., Carello et al., 1992; Hajnal et al., 2007; Solomon & Turvey, 1988; Wagman et al., 2009). As a result, we expect that recalibration will be observed in increases in slope values from pretest to posttest (Wagman & Van Norman, 2011; Withagen & Michaels, 2004).

Figure 1 shows the regression plots at the level of the aggregate data in Experiment 1 for both modality and feedback conditions in the pretest and posttest. In the touch condition, the r^2 values for the fit between actual length and mean perceived length were approximately .99 in both the pretest and in the posttest. In the audition condition, the r^2 values ranged between .79 and .90 in the pretest and between .91 and .93 in the posttest (all ps $< .001$). Such results confirm that perceived length is systematically (and linearly) related to actual length in the pretest and posttest of both perceptual modalities.

A 2 (Modality: Audition vs. Touch) × 2 (Test: Pre vs. Post) × 2 (Feedback vs. No Feedback) mixed design analysis of variance (ANOVA) was performed on the slopes of the regression lines of the individual participants. A main effect of Modality, $F(1, 24) = 139.08$, $p < .001$, $\eta_p^2 = .85$, showed that slopes were larger when rod lengths were perceived by touch ($M = 0.77$) than when they were perceived by audition ($M = 0.38$).[4] A main effect of Test, $F(1, 24) = 22.79$, $p < .001$, $\eta_p^2 = .49$, showed that slopes increased from pretest ($M = 0.50$) to posttest ($M = 0.66$). An interaction of Test and Feedback, $F(1, 24) = 5.24$, $p < .05$, $\eta_p^2 = .18$, showed that changes in slope from pretest to posttest depended on feedback (see Figure 2, top). The ANOVA showed no other significant main effects or interactions (all other ps $> .11$).

Follow-up tests were conducted to further investigate the Test × Feedback interaction revealed by the ANOVA. First, we compared pretest to posttest changes in slope with and without feedback in both perceptual modality conditions. t tests with Bonferroni corrections showed that when feedback was provided, slopes increased from pretest to posttest both in the touch condition (pretest: 0.72 vs. posttest: 0.90), $t(13) = 5.79$, $p < .001$, and in the audition condition (pretest: 0.33 vs. posttest: 0.64), $t(13) = 3.06$, $p < .01$. When feedback was not provided, there was no change in slope from pretest to post test in either perceptual modality condition (both ps $> .20$) (see Figure 2, top). Second, to determine whether there were any differences in pretest to posttest changes in slope in the two perceptual modalities when feedback was provided, we calculated difference scores by subtracting pretest slope values from posttest slope values in each of the two modalities. A t test showed that these difference scores did not differ from each other. These results suggest that, in general, perception of length shows less scaling error in touch than in audition. This finding is consistent with previous research (see Wagman et al., 2009). In addition, scaling error decreased (i.e., slopes increased) from pretest to posttest in both touch and audition but only when feedback (on perception of length by audition) was provided during the training session. Thus, the results show a transfer of recalibration of perception of length from audition to touch.

A 2 (Modality: Audition vs. Touch) × 2 (Test: Pre vs. Post) × 2 (Feedback vs. No Feedback) mixed design ANOVA was also performed on the intercepts of the regression lines of the individual

[3] Given that the objects used in this (and all) experiments were homogenous uniformly cylindrical wooden rods that varied only in length, candidate mechanical variables that might provide information about length (e.g., mass, static moment, and moment of inertia) were perfectly correlated with each other as well as with length itself. Such features of the stimuli preclude an investigation of whether participants are more or less calibrated to a particular mechanical variable in perceiving length by audition or by dynamic touch because they make an analysis of how perceived length relates to candidate mechanical variables no more informative than how perceived length relates to actual length. However, such features circumvent the problems of (1) determining what mechanical variable(s) a given participant might be using to perceive length and (2) determining what variable(s) to provide feedback about during training—providing feedback about length during training provides information about how all such candidate variables relate to actual length (see Withagen & Michaels, 2004, 2007). Therefore, such features of the stimuli do not preclude an investigation of the main hypotheses of the experiments reported here—that is, whether recalibration of perception of length (to actual length) transfers from audition to touch, and hence whether calibration of perception of length (to actual length) is specific to a given perceptual modality. As a result, our analyses focus on calibration of perceived length to actual length rather than of calibration of perceived length to (any or all of) these candidate mechanical variables.

[4] Although the r^2 values in the audition conditions of the experiments reported here are comparable to those reported by Carello et al. (1998, Experiment 1), the slope values reported here are smaller. Such differences are likely attributable a number of methodological differences between the two studies. For example, in the experiments by Carello et al. (1998), each rod was dropped five times from a height of 71.8 cm onto a linoleum surface, and in the current set of experiments rods were dropped once (or twice) from a height of 23 cm onto a wooden surface. Together, it is likely that such differences in height, surface, and number of drops per trial allowed for a more accurate scaling of perceived length to actual length by participants in Carello et al. (1998) than by participants in the current experiments. Therefore, the difference in performance across these experiments does not preclude the possibility that the stimulation patterns that support perception of object length by audition and dynamic touch are each anchored in the object's mechanical properties.

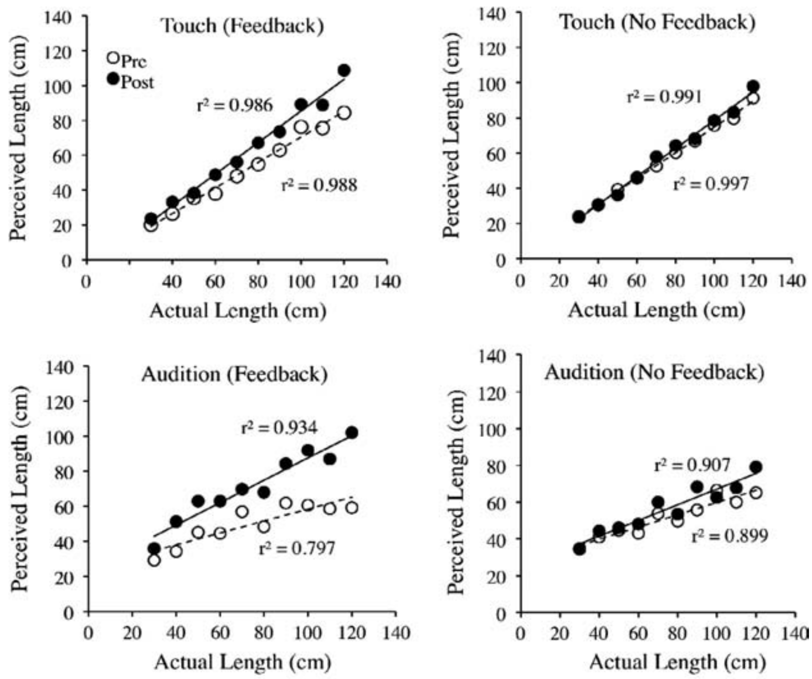

Figure 1. Regression plots for mean perceived length versus actual length in the pretest and posttest for both modality and feedback conditions in Experiment 1.

participants. A main effect of Modality, $F(1, 24) = 183.03$, $p < .001$, $\eta_p^2 = .88$, showed that intercepts were smaller in touch ($M = -1.5$ cm) than in audition, ($M = 26.2$ cm) (see Figure 2, bottom). There were no other significant main effects or interactions (all other $ps > .23$). These results suggest that, in general, perception of length showed less offset error in touch than in audition. This finding is also consistent with previous research (see Wagman et al., 2009). However, there were no changes in offset error from pretest to posttest in either perceptual modality (with or without feedback).

It is possible that the changes in perceived length from pretest to posttest in both perceptual modalities as a result of feedback during auditory training were attributable not to a rescaling of perceived length to actual length but rather to a post hoc decision on the part of the participant to adjust posttest perceptual reports by a constant amount. Such a change in perceptual reports might suggest that rather than learning a specific mapping between a detectable stimulation pattern and an environmental property, participants are learning a nonspecific rule about their pretest perceptual reports (i.e., "too short" or "too long"). Ruling out this possibility requires demonstrating that feedback resulted in a specific rescaling of perceived length to actual length (rather than in a nonspecific shifting of perceived lengths by a constant). The finding that feedback resulted in recalibration of slope (scaling error) but not intercept (offset error) provides preliminary evidence that this is the case (Wagman & Van Norman, 2011; Withagen & Michaels, 2004). However, providing stronger evidence for this claim requires explicitly demonstrating that in the feedback condition (1) changes in perceived length from pretest to posttest differed for different rods (i.e., such changes were not the result of a nonspecific shifting of perceived lengths by a constant amount) and (2) the amount of change in perceived length from pretest to posttest for a given rod is predicted by the amount of error in the pretest for that rod (i.e., feedback resulted in a specific rescaling of perceived length to actual length based on the amount of error on that rod in the pretest).

To investigate (1), we calculated difference scores by subtracting perceived length in the pretest from perceived length in the posttest for each rod length in both modality conditions for participants in the feedback condition. A 2 (Modality: Audition vs. Touch) × 10 (Rod Length) ANOVA was then conducted on these values. A significant main effect of length, $F(9, 117) = 4.73$, $p < .001$, $\eta_p^2 = .28$, shows that changes in perceived length as a result of feedback depended on rod length. Thus, such changes differed for different rods and were not merely attributable to a shifting of perceived lengths by a constant amount from pretest to posttest.

To investigate (2), we calculated two sets of difference scores. First, we calculated pretest error scores by subtracting mean perceived length in the pretest from actual length for each rod length in both modality conditions for participants in the feedback condition. Second, we calculated perceptual change scores by subtracting mean perceived length in the pretest from mean perceived length in the posttest for each rod length in both modality conditions for participants in the feedback condition. In both modality conditions, there were significant positive correlations between changes in perceived length from pretest to posttest on a given rod and the amount of error in the pretest on that rod (touch: $r = .87$, $p < .001$; audition: $r = .91$, $p < .001$). Such results show that the amount of change in perceived length for a given rod as a result of feedback is predicted by the amount of error in the pretest for that rod. Thus, feedback resulted in a specific rescaling of perceived length to actual length.

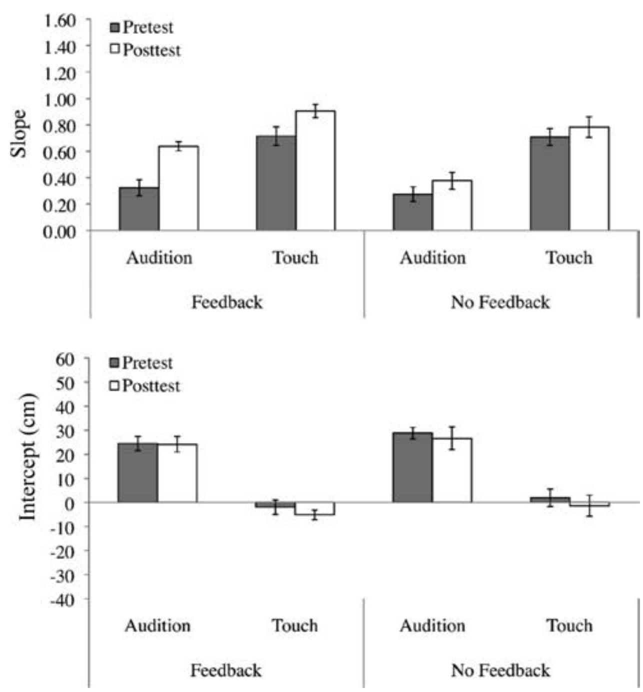

Figure 2. Average regression line slopes (top) and intercepts (bottom) for perception of length in the Audition and Touch conditions with and without feedback in the pretest and posttest of Experiment 1. The error bars indicate standard error.

Taken together, these results suggest that the changes in perceived length from pretest to posttest as a result of feedback were attributable to a specific rescaling of perceived length to actual length (that was based on the amount of error for a given rod in the pretest) and not a nonspecific shifting of posttest perceptual reports on all rods by a constant amount.

It is also possible that changes in perceptual reports after training with feedback were merely attributable to the participants fitting posttest perceptual reports into the range of object lengths experienced after feedback during (auditory) training. Surely, the range of objects experienced during feedback influenced the posttest perceptual reports to some extent. However, on both logical and empirical grounds, we believe that it is unlikely that this is the only reason that perceptual reports changed from pretest to posttest.

Logically, for this to have occurred, participants would need to have known (or guessed) that the largest and the smallest objects used during (auditory) training were also the largest and smallest objects in (both modality conditions of) the posttest. While this is possible, participants were not explicitly (or implicitly) informed that this was the case. In fact, they were not given any information at all about the rods that would be used in the experiment.

Moreover, such a deduction is especially unlikely given that the range of the response apparatus (240 cm) was nearly three times the range of the objects presented during the training session (90 cm). However, even if participants successfully deduced that this was the case, they would have then needed to fit perceptual responses for the posttest objects in both modalities into the range experienced after feedback in the (auditory) training session despite the fact that in the posttest, blocks of five trials in the touch condition were alternated with blocks of five trials in the audition condition and rod lengths were randomized within a given modality condition.

While we believe that this scenario is unlikely, if it did occur, the finding that a range experienced in one perceptual modality influenced perception by means of a different perceptual modality would still be evidence for transfer from one perceptual modality to another (though of a different kind). Ultimately, however, we believe that a more parsimonious explanation of the results is that the feedback provided during training served to recalibrate perception of length by audition, and such recalibration transferred to perception of length by dynamic touch (because the stimulation patterns that support perception of object length in each case are anchored in the object's mechanical properties).

Our strategy for making an empirical argument against this alternative explanation involves comparing ranges of posttest perceptual reports across the three experiments. Therefore, we will delay this empirical argument until the discussion of the results of Experiment 3.

Experiment 2

Experiment 1 found that recalibration of perception of length transferred from audition to dynamic touch. Such transfer suggests that calibration of perception of a given environmental property is not specific to a given perceptual modality. However, when participants perceived length by touch in Experiment 1, they did so by wielding the rod while grasping it at one end. For all intents and purposes, this choice of grasp position was an arbitrary one. We could have asked participants to perceive the length of the object by wielding it while grasping it at any location along its length. In fact, previous research has shown that participants are capable of perceiving length while grasping a rod at a number of different grasp positions (e.g., Carello, Santana, & Burton, 1996).

Experiment 2 provides a somewhat stronger test of whether calibration of perception of a given environmental property is specific to a particular modality by investigating whether the transfer of recalibration of perception of object length from audition to touch depends on where those objects are grasped. If calibration is not specific to a given perceptual modality, such recalibration should not depend on where the objects are grasped. That is, recalibration should transfer from audition to touch both when objects are grasped at one end and when they are grasped at a different location (e.g., the middle). Alternatively, if calibration is specific to a given perceptual modality, then there should be no such transfer of recalibration (across changes in grasp position).

Experiment 1 adds to a large body of research showing that recalibration of perception of properties of wielded objects requires experiences over and above the perceptual task itself such as feedback (e.g., Cabe & Wagman, 2010; Stephen & Arzamarski, 2009; Wagman et al., 2009; Wagman, Shockley, Riley, & Turvey, 2001; Wagman, McBride, & Trefzger, 2008; Withagen & Michaels, 2005). In particular, previous research has shown that this is the case for perception of length of wielded objects both when those objects are grasped at one end and when they are grasped at the middle (Wagman & Van Norman, 2011). Given (1) the many studies that have shown that feedback of some kind is required for calibration (including the results of Experiment 1), (2) that the conditions of the pretest and posttest of Experiment 2 are the same as those used by Wagman & Van Norman (2011), and (3) that the purpose of Experiment 2 is to further investigate the circumstances under which recalibration transfers from one perceptual modality to another, we did not include a no-feedback condition during the training session in this experiment (cf. Withagen & Michaels, 2004, 2007).

Method

Participants

Seventeen right-handed undergraduate students (five men and 12 women) from Illinois State University participated in this experiment. All participants received extra credit in their psychology courses in exchange for their participation.

Materials and Apparatus

The materials and apparatus were the same as in Experiment 1 except that the 30-cm and 120-cm rods were not used in Experiment 2.

Procedure

As in Experiment 1, the experiment consisted of three sets of trials: a pretest, a training session, and a posttest.

Pretest. Each participant was seated and placed his or her right arm on the armrest. The participant then placed his or her right hand through the curtain such that the wrist was aligned with the zero point of the report apparatus.

The pretest consisted of three different conditions—Touch/End, Touch/Middle, and Audition. Trials in the Touch/End and Audition conditions were identical to trials in the Touch and Audition conditions from Experiment 1, respectively. Trials in the Touch/Middle condition were identical to trials in the Touch/End condition except that participants were handed each rod such that they grasped it at its midpoint. The participant was not informed that he or she would be grasping the rod at this location. In all three conditions, the participant reported perceived length by adjusting the distance of the marker as described in Experiment 1. Each participant reported perceived length once for all eight rods in a given condition before doing so in a different condition. The order of conditions was randomized, and the order of rod lengths was randomized within a given condition. The participant was not informed that the same rod set was used in all three conditions.

Training session. Following the pretest, each participant completed a training session. The training session consisted of six audition trials using a subset of rods from the pretest in the following order: 40 cm, 90 cm, 110 cm, 60 cm, 50 cm, and 100 cm. After a participant reported perceived length on a given trial, the experimenter repositioned the marker such that the distance between the marker and zero point corresponded to the actual length of the rod. As in Experiment 1, the participant was not informed that the rod set used in the training session was a subset of the rod set used in the pretest.

Posttest. The posttest was identical to the pretest. As in the pretest, the order of conditions was randomized across participants, and the order of rod lengths was randomized within a condition. As in Experiment 1, the participant was not informed that the rod set used in the posttest was identical to the rod set used in the pretest or that it was a superset of the rod set used in the training session.

Results

As in Experiment 1, we computed regression lines with perceived length as the dependent variable and actual length as the independent variable for all three conditions in the pretest and the posttest. Figure 3 shows the regression plots at the level of the aggregate data for all three conditions in the pretest and posttest. In the Audition condition, the r^2 values for the fit between actual length and mean perceived length were .84 in the pretest and .88 in the posttest. In the Touch/End condition, the r^2 values were .97 in the pretest and .99 in the posttest. In the Touch/Middle condition, the r^2 values were .98 in the pretest and .99 in the posttest (all $ps < .001$). Such results confirm that perceived length is systematically (and linearly) related to actual length in the pretest and posttest of all conditions.

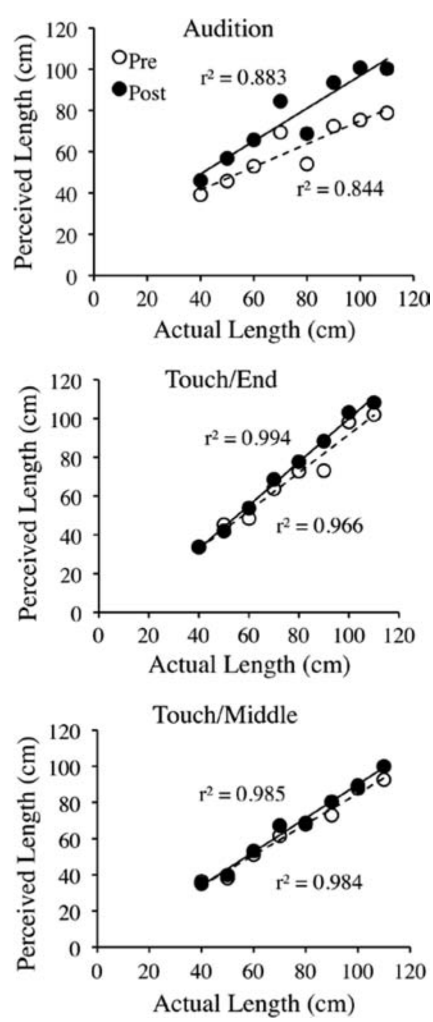

Figure 3. Regression plots for mean perceived length versus actual length in the pretest and posttest for the three conditions in Experiment 2.

A 3 (Condition: Audition vs. Touch/End vs. Touch/Middle) × 2 (Test: Pre vs. Post) ANOVA was performed on the slopes of the regression lines. A main effect of Condition, $F(2, 32) = 21.90$, $p < .001$, $\eta_p^2 = .58$, showed that slopes differed across the three conditions. Follow-up *t* tests with Bonferroni corrections found that slopes were larger in the Touch/End condition ($M = 1.05$)[5] than in the Touch/Middle condition ($M = 0.89$) and were larger in the Touch/End condition than in the Audition condition ($M = 0.68$) (all corrected *p*s $< .025$). A main effect of Test, $F(1, 16) = 11.21$, $p < .01$, $\eta_p^2 = .41$, showed that slopes increased from pretest ($M = 0.80$) to posttest ($M = 0.95$). The Condition × Test interaction was not significant ($p > .30$)[6] (see Figure 4, top).

These results suggest that, in general, perception of length shows less scaling error in touch than in audition, and perception of length by touch shows less scaling error when the object is grasped at one end than when it is grasped in the middle. Both such findings are consistent with previous research (see Wagman et al., 2009; Wagman & Van Norman, 2011). Moreover, the results show that scaling error in all three conditions decreased from pretest to posttest when feedback (on perception of length in audition) was provided during a training session. Thus, there was transfer of recalibration of perception of length from audition to touch, and such a transfer of recalibration occurred both when the object was grasped at one end and when it was grasped at the middle.

A 3 (Condition: Audition vs. Touch/End vs. Touch/Middle) × 2 (Test: Pre vs. Post) ANOVA was performed on the intercepts of the regression lines. A main effect of Condition, $F(2, 32) = 45.84$, $p < .001$, $\eta_p^2 = .74$, showed that intercepts differed across the three conditions. Follow-up *t* tests with Bonferroni corrections found that intercepts were larger in the Audition condition ($M = 18.3$ cm) than in both the Touch/Middle ($M = -1.7$ cm) and the Touch/End ($M = -9.3$ cm) conditions (both corrected *p*s $< .001$) (see Figure 4, bottom). The Condition × Test interaction was not significant ($F < 1$). As in Experiment 1, these results suggest that perception of length showed less offset error in touch than in audition. Moreover, there were no changes in offset error from pretest to posttest.

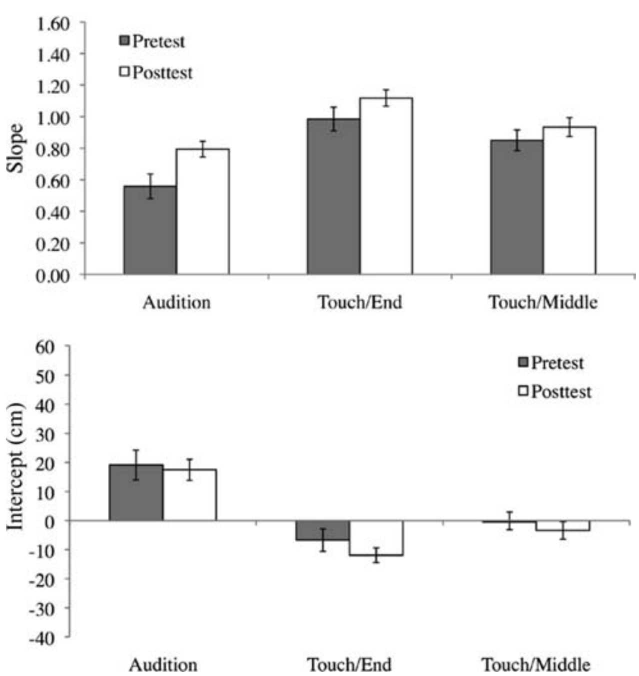

Figure 4. Average regression line slopes (top) and intercepts (bottom) for perception of length in the Audition, Touch/End, and Touch/Middle conditions of the pretest and posttest of Experiment 2. The error bars indicate standard error.

As in Experiment 1, the fact that recalibration of slope was not accompanied by recalibration of intercept provides preliminary evidence that the changes in perceived length from pretest to posttest were the result of a specific rescaling of perceived length to actual length rather than in a nonspecific shifting of all perceived lengths by a constant amount. To provide stronger evidence that this was the case, we conducted the same follow-up analyses as in Experiment 1. A 3 (Condition: Audition vs. Touch/End vs. Touch/Middle) × 8 (Length) ANOVA was conducted on pretest to posttest difference scores. As in Experiment 1, a significant main effect of length, $F(7, 112) = 2.33$, $p < .05$, $\eta_p^2 = .13$, shows that changes in perceived length as a result of feedback differed for different rods and were not merely attributable to a shifting of perceived lengths by a constant amount in the posttest.

In addition, in all three conditions, there were significant positive correlations between changes in perceived length from pretest to posttest on a given rod and the amount of error in the pretest on that rod (Audition: $r = .75$, $p < .001$; Touch/End: $r = .75$, $p < .05$; Touch/Middle: $r = .71$, $p < .05$). Such results show that the amount of change in perceived length for a given rod as a result of feedback is predicted by the amount of error in the pretest for that rod (i.e., feedback resulted in a specific rescaling of perceived length to actual length).

As in Experiment 1, these results suggest that the changes in perceived length from pretest to posttest as a result of feedback were attributable to a specific rescaling of perceived length to actual length (that was based on the amount of error for a given rod in the pretest) and not a nonspecific shifting of posttest perceptual reports on all rods by a constant amount.

As in Experiment 1, it is also possible that changes in perceptual reports after training with feedback in Experiment 2 were merely attributable to the participants fitting posttest perceptual reports into the range of object lengths experienced after feedback in the (auditory) training session. The same logical argument against this explanation applies here as in Experiment 1. An empirical argu-

[5] The particularly high mean slope of the pretest in the Touch/End condition (.98) was primarily attributable to the contributions of three participants. When the data from these participants are removed, the mean slope in this condition is .89.

[6] A power analysis was conducted for this nonsignificant test using the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007). An effect size was estimated using a significant interaction reported by Stephen and Hajnal (2011), which showed asymmetric transfer of recalibration of perception of length by dynamic touch across disparate limbs (i.e., from foot to hand). Although these factors differ from those manipulated in Experiment 2, the effect being tested is analogous to the one being tested here. Cohen's *f* was estimated to be .18 for this interaction (a "small" to "medium" effect size, see Keppel & Wickens, 2004). Using this effect size, G*Power estimated power for the nonsignificant test reported in Experiment 2 to be .98.

ment against such an explanation will be presented in the discussion of the results of Experiment 3.

Experiment 3

Experiment 2 found that recalibration of perception of length transferred from audition to touch both when the object was grasped at one end and when the object was grasped at the middle. Thus, like Experiment 1, Experiment 2 provides evidence that calibration of perception of a given environmental property is not modality-specific. However, given that the average slope of the relationship between perceived length and actual length in the pretest across all three conditions was 0.80 (and was 0.92 in the pretest of the two touch conditions[5]), the capacity for recalibration (to a slope of 1.0) was relatively limited in all three conditions. Experiment 3 was a replication of Experiment 2 except that the feedback provided to the participants was 1.5 times the length of the rod. Providing false (i.e., inflated) feedback enables us to determine whether recalibration transfers under circumstances in which participants are initially less well calibrated to rod length (cf. Withagen & Michaels, 2004). In addition, providing false feedback helps to guard against a conflation of recalibration with improvements in accuracy (Stephen & Hajnal, 2011). In the context of the current experiments, doing so may provide a stronger test of transfer of recalibration from audition to dynamic touch with feedback and subsequently, a stronger test of whether calibration of perception of a given environmental property is specific to a particular modality. We expect to replicate the findings of Experiment 2 except that as recalibration occurs, slopes should approach 1.5. As in Experiment 2 (and for the same reasons), we did not include a no-feedback condition during the training session in this experiment.

Method

Participants

Fifteen right-handed undergraduate students (five men and 10 women) from Illinois State University participated in this experiment. All participants received extra credit in their psychology courses in exchange for their participation.

Materials and Apparatus

The materials and report apparatus were identical to Experiment 2.

Procedure

As in Experiments 1 and 2, the experiment consisted of three sets of trials: a pretest, a training session, and a posttest.

Pretest. The pretest was identical to the pretest in Experiment 2.

Training session. The training session was identical to the training session in Experiment 2, except that after participants reported perceived length on a given trial the experimenter repositioned the marker such that the distance between the marker and zero point corresponded to 1.5 times the actual length of the rod.

Posttest. The posttest was identical to the pretest.

Results

The same analyses were conducted in Experiment 3 as in Experiment 2. Figure 5 shows the regression plots at the level of the aggregate data for all three conditions in the pretest and posttest. In the audition condition, the r^2 values for the fit between actual length and mean perceived length were .87 in both the pretest and the posttest. In the Touch/End condition, the r^2 values were .99 in both the pretest and the posttest. In the Touch/Middle condition, the r^2 values were .98 in both the pretest and the posttest. All $ps < .001$. Such results confirm that perceived length is systematically (and linearly) related to actual length in the pretest and posttest of all conditions.

A 3 (Condition: Audition vs. Touch/End vs. Touch/Middle) × 2 (Test: Pre vs. Post) ANOVA was performed on the slopes of the regression lines. The results of this analysis replicated those of Experiment 2. A main effect of Condition, $F(2, 28) = 27.05$ $p < .001$, $\eta_p^2 = .66$, showed that slopes differed across the three conditions. Follow-up t tests with Bonferroni corrections found that slopes were larger in the Touch/End condition ($M = 1.1$) than

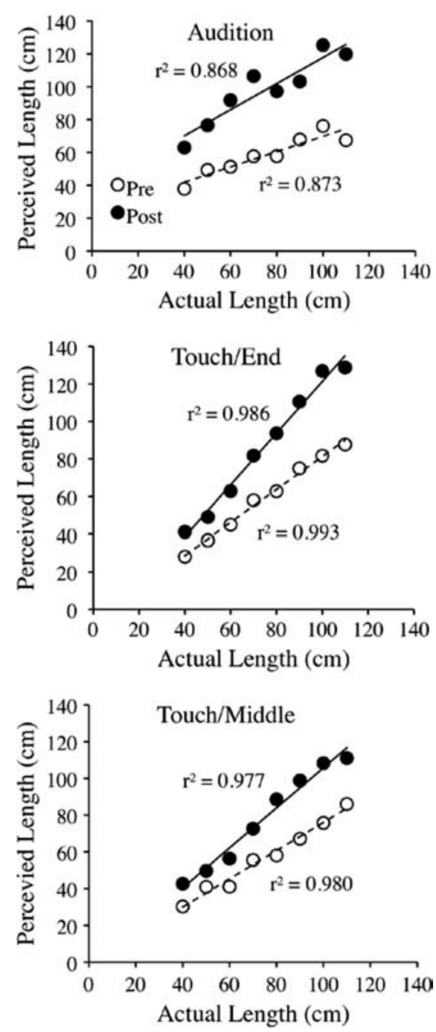

Figure 5. Regression plots for mean perceived length versus actual length in the pretest and posttest for the three conditions in Experiment 3.

in the Touch/Middle condition ($M = 0.93$) and were larger in the Touch/Middle condition than in the Audition condition ($M = 0.63$) (all corrected *p*s < 0.025). A main effect of Test, $F(1, 14) = 40.35$, $p < .01$, $\eta_p^2 = .74$, showed that slopes increased from pretest ($M = 0.70$) to posttest ($M = 1.09$). The Condition × Test interaction was not significant ($p > .27$) (see Figure 6, top). These results show there was transfer of recalibration of perception of length from audition to touch both when the object was grasped at one end and when it was grasped at the middle when false (inflated) feedback (on perception of length in audition) was provided during a training session.

A 3 (Condition: Audition vs. Touch/End vs. Touch/Middle) × 2 (Test: Pre vs. Post) ANOVA was also performed on the intercepts of the regression lines. As in Experiment 2, there was a main effect of Condition, $F(2, 28) = 37.59$, $p < .001$, $\eta_p^2 = .73$. Follow-up *t* tests with Bonferroni corrections found that intercepts were larger in the Audition condition ($M = 30.8$ cm) than in both the Touch/End condition ($M = -11.5$ cm) and in the Touch/Middle condition ($M = -2.0$ cm) (both corrected *p*s $< .001$). However, an interaction of Test and Condition, $F(1, 24) = 4.80$, $p < .05$, $\eta_p^2 = .26$, showed that changes in intercept from pretest to posttest depended on condition. Follow-up *t* tests with Bonferroni corrections found that intercepts decreased (became more negative) from pretest to posttest in the Touch/End condition (pre: −6.4 cm vs. post: −16.5 cm) ($p < .05$) but did not change in either of the other two conditions. The main effect of Test was not significant ($F < 1$) (see Figure 6, bottom). As in Experiments 1 and 2, these results show that perception of length showed less offset error in touch than in audition. Moreover, offset error decreased from pretest to posttest but only in the Audition condition.

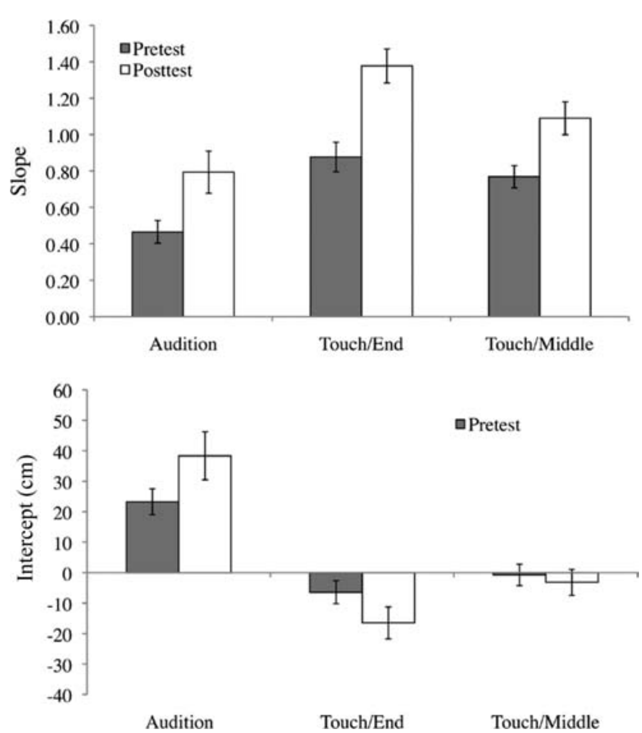

Figure 6. Average regression line slopes (top) and intercepts (bottom) for perception of length in the Audition, Touch/End, and Touch/Middle conditions of the pretest and post test of Experiment 3. The error bars indicate standard error.

As in Experiments 1 and 2, the fact that recalibration of slope was not accompanied by recalibration of intercept (i.e., intercept values that more closely approximate 0.0) provides preliminary evidence that the changes in perceived length from pretest to posttest were the result of a specific rescaling of perceived length to actual length. To provide stronger evidence that this was the case, we conducted the same follow-up analyses as in Experiments 1 and 2. A 3 (Condition: Audition vs. Touch/End vs. Touch/Middle) × 8 (Length) ANOVA was conducted on pretest to posttest difference scores. As in Experiments 1 and 2, a significant main effect of length, $F(7, 98) = 9.35$, $p < .001$, $\eta_p^2 = .40$, shows that changes in perceived length as a result of feedback differed for different rods and were not merely attributable to a shifting of perceived lengths by a constant amount in the posttest.

In addition, in all three conditions, there were significant positive correlations between changes in perceived length from pretest to posttest on a given rod and the amount of error in the pretest on that rod (Audition: $r = .75$, $p < .05$; Touch/End: $r = .79$, $p < .05$; Touch/Middle: $r = .90$, $p < .01$). Such results show that the amount of change in perceived length for a given rod as a result of feedback is predicted by the amount of error in the pretest for that rod (i.e., feedback resulted in a specific rescaling of perceived length to actual length).

As in Experiments 1 and 2, these results suggest that the changes in perceived length from pretest to posttest as a result of feedback were attributable to a specific rescaling of perceived length to actual length (that was based on the amount of error for a given rod in the pretest), and not a nonspecific shifting of posttest perceptual reports on all rods by a constant amount.

Again, it is possible that the rescaling of perceptual reports after feedback in Experiment 3 is merely attributable to a fitting of posttest perceptual reports into the range of object lengths experienced during feedback during (auditory) training. The same logical argument against this explanation of our results applies here as in Experiments 1 and 2. However, we can now present an empirical argument against such an explanation. The range of objects experienced during training differs across the three experiments. In Experiment 1, this range of was 90 cm (min. = 30 cm; max. = 120 cm), in Experiment 2, this range was 70 cm (min. = 40 cm; max. = 110 cm), and in Experiment 3, this range was 105 cm (with inflated feedback) (min. = 60 cm; max. = 165 cm). If participants are merely fitting posttest perceptual responses into the range of objects experienced during training (with feedback), then the (mean) ranges of the posttest perceptual responses should also differ in this same way across experiments. Alternatively, if participants are doing something other than (or in addition to) this, then there should be no such differences in ranges of posttest perceptual responses across experiments.

To investigate this, we calculated mean posttest ranges of perceptual responses for participants receiving feedback in Experiment 1 and for all participants in Experiments 2 and 3. We then compared these values across the three experiments in a one-way between-participants ANOVA (with Experiment as a between-participants factor). Despite the differences in ranges of objects experienced during training across the three experiments, there was no difference in mean ranges of posttest perceptual responses across experiments ($p > .05$). This result suggests that posttest perceptual reports are not merely being fitted into the range of objects experienced during feedback. Rather, it is (more) likely that the feedback served to recalibrate perception of length by audition, and such recalibration transferred to perception of length by dynamic touch.

General Discussion

Three experiments investigated transfer of recalibration of perception of object length from audition to touch. In particular, the experiments investigated whether recalibration of perception of length transferred from audition to dynamic touch when the objects were grasped at one end (Experiment 1), when objects were grasped both at the end and at a different location (i.e., the middle) (Experiment 2), and when false (i.e., inflated) feedback was provided about object length (Experiment 3).

Consistent with a large body of research (e.g., Stephen & Arzamarski, 2009; Wagman et al., 2009; 2008, 2001; Withagen & Michaels, 2005, see E. Gibson, 1969), Experiment 1 found that recalibration occurred only when experience above and beyond task performance (in this case, feedback on perception of length by audition) was provided during a training session. In all three experiments, recalibration (and transfer of recalibration) of perception of length was observed in changes in slope values from pretest to posttest (Cabe & Wagman, 2010; Wagman & Van Norman, 2011; Withagen & Michaels, 2004). Also in all three experiments, recalibration transferred from audition to dynamic touch when feedback was provided on perception of length by audition. Thus, the results of all three experiments are consistent with the hypothesis that calibration of perception of a given environmental property is not specific to a given perceptual modality.

Becoming clearer on what it is that participants become calibrated to as a result of feedback has been the focus of a number of studies on transfer of recalibration in both perception and behavior (e.g., Reiser et al., 1995; Wagman & Van Norman, 2011; Withagen & Michaels, 2004, 2007; see Redding & Wallace, 1997; Schmidt & Lee, 2005, for reviews). Previous research has shown that calibration of perception and behavior is anatomically independent (Reiser et al., 1995; Withagen & Michaels, 2004) and that calibration of perception by dynamic touch is independent of both object property and grasp position (Wagman & Van Norman, 2011; Withagen & Michaels, 2007). The three experiments reported here build on and extend these findings by showing that recalibration of perception of a given environmental property transfers from one perceptual modality to another (i.e., that calibration of a given environmental property is not specific to a particular modality). As a result, such findings provide preliminary evidence that calibration might be independent of a given perceptual modality. To this end, the results suggest that the anatomical independence of recalibration might not only apply within a given perceptual modality but also across different perceptual modalities (see Wagman et al., 2009).

Transfer of Recalibration and Modality-Independent Stimulation Patterns

The finding that calibration of perception of a given environmental property is not specific to perceptual modality is consistent with the more general proposal that the stimulation patterns that support perception of environmental properties are modality-independent (or that such patterns are not specific to a particular perceptual modality) (Carello, Wagman, & Turvey, 2005; Rosenblum & Gordon, 2001; Fowler, 2004). 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; Turvey, 2002). Such stimulation patterns that specify environmental properties to a perceiver have been described as the *information for perception* (J. Gibson, 1966, 1979).

A related proposal is that structure in a given patterned energy distribution (e.g., the optic array) is lawfully related to (although not identical to) structure in other energy distributions (e.g., the acoustic array) (Burton, 2001; J. Gibson, 1966, 1979; Rosenblum & Gordon, 2001). In other words, objects and events simultaneously structure multiple energy arrays, and structure in any one of these arrays may be sufficient to provide information about the object or event that created such structure. The particulars of a given energy array may be irrelevant so long as (1) the structure in that array is sufficient to support perception of that property and (2) the perceiver is capable of detecting this structure. Identifying the (potentially modality-independent) stimulation patterns that support perception of a given environmental property by a number of different perceptual modalities has been the focus of a number of studies and is an important step in better understanding perception in general (Turvey, 2002; Turvey & Shaw, 1999).

In the context of the three experiments reported here, one likely possibility is that the stimulation patterns that support perception of object length by dynamic touch and audition are each anchored in the object's mechanical properties (specifically mass, static moment, and moment of inertia). Such variables (1) influence both the patterns of muscular deformation when an object is wielded and the patterns of vibrations when an (unsupported) object strikes a support surface and (2) have been shown to constrain perception of a number of object properties (including length) by both dynamic touch and audition[1] (Carello et al., 1998; Carello & Turvey, 2004; Kingma et al., 2002; Withagen & van Wermeskerken, 2009).

Importantly, the claim that the stimulation patterns that support perception of length by dynamic touch and audition are each anchored in the object's mechanical properties is not as strong as the claim that the stimulation patterns that support perception of length in each case are *identical*. We are precluded from making the second, stronger, claim on at least two grounds. First, the existence of lawful relations between two stimulation patterns does necessarily imply that those patterns are identical (see Wagman, 2010). Second, the objects in the three experiments reported were homogeneous uniformly cylindrical wooden rods that varied only in length. As a result, candidate mechanical variables that might provide information about length (e.g., mass, static moment, and moment of inertia) were perfectly correlated with each other as well as with length itself. Although such a design feature allows for an investigation of the transfer of calibration of perceived length from audition to touch, it precludes an investigation of whether perception of length by dynamic touch and audition are constrained by the same mechanical variable(s). An investigation of transfer of recalibration of perception of object length from audition to touch in which object length and candidate mechanical variables are independently manipulated is an important topic for future research.

The possibility that a given object or event simultaneously structures multiple energy arrays in analogous ways likely underlies comparable performance in perceiving a given environmental property across perceptual modalities (e.g., Fitzpatrick et al., 1994; Wagman et al., 2009). However, the mere fact that such structure is simultaneously available in multiple energy arrays does not necessarily guarantee an equivalent ability to perceive that property by means of different perceptual modalities (e.g., the differences in scaling error between touch and audition in all three experiments reported here). First, as we point out above, a lawful relationship between two stimulation patterns does not necessarily imply that those patterns are identical. Therefore, perception of a given property by one perceptual modality can be expected to be analogous to (but necessarily not identical to) perception of that same property by a different perceptual modality. Second, the mere availability of analogous stimulation patterns to different perceptual modalities does not guarantee that a perceiver has the same ability to detect (or use) such stimulation patterns by means of those perceptual modalities. Practice perceiving a given environmental property by a given perceptual modality typically leads to changes in what stimulation variable is used to perceive a given property and how that stimulation variable is used to do so (especially when such practice is accompanied by feedback, Stephen & Arzamarski, 2009; Wagman et al., 2001; Withagen & Michaels, 2005). Thus, when there is a difference in how well-practiced an individual is in perceiving a given environmental property by one perceptual modality and how well-practiced they are in doing so by a different perceptual modality, there are likely to be differences in perception of that property despite the availability of analogous stimulation patterns to each modality. Importantly, such differences become less pronounced as the perceiver practices perceiving that property by means of the less well-practiced modality (especially when such practice includes feedback, Wagman et al., 2009).

The possibility that stimulation patterns that support perception are modality-independent (or are not specific to a given perceptual modality) not only accounts for comparable performance perceiving a given environmental property by different perceptual modalities but may also account for the transfer of recalibration from one perceptual modality to another (when feedback is provided on perception by one of those modalities). In general, when feedback is provided on perception of a given environmental property, such feedback provides information about the mapping between detectable stimulation patterns and the perceptual report provided by the participant. As a pattern of such comparisons occurs over time, the perceiver becomes increasingly attuned to a (or the) detectable stimulation pattern that supports perception of that environmental property by that perceptual modality. Subsequently, there is recalibration of perception of that environmental property. Such a pattern of comparisons over time that specifies the required change in perception has been described as the *information for calibration* (Withagen & Michaels, 2004).

If the stimulation patterns that support perception of a given environmental property are modality-independent (or are not specific to a particular perceptual modality), then feedback about perception of an environmental property by a given perceptual modality will lead to an increased attunement to a (or the) modality-independent stimulation pattern that supports perception of that environmental property by multiple perceptual modalities. In such a case, a pattern of comparisons that provides information for calibration to a given environmental property by a given perceptual modality will also provide information for calibration of that same property by a different perceptual modality. Such a pattern of comparisons might be termed the *information for transfer* (of calibration from one perceptual modality to another).

Transfer of Recalibration and Smart Perceptual Devices

The finding that calibration of perception of a given environmental property is not specific to perceptual modality is also consistent with a description of perceptual systems as smart perceptual devices. Smart perceptual devices are flexibly recruited to solve task-specific perceptual problems by exploiting regularities in stimulation patterns. Moreover, smart perceptual devices exhibit both anatomical and modality independence (Bingham, 1988; Runeson, 1977). In many ways, wielding a hand-held object and listening to that (unsupported) object strike a surface are very different tasks. They differ not only in the anatomical components involved and in the energy arrays to which those components are sensitive but also in the location at which the perceiver encounters those energy arrays (the wrist in the case of a wielded object and the ear in the case of an unsupported object striking a surface). However, if the stimulation patterns that support perception are modality-independent (or are not specific to a particular perceptual modality), then access to either stimulation pattern by either perceptual modality at either location may be sufficient to provide information about a given environmental property to a perceiver. In this way, the modality-independence of stimulation patterns that support perception may provide exactly the kind of regularity required to solve task-specific problems and may also provide the foundation for the anatomical independence of smart perceptual devices.

Conclusion

Three experiments investigated transfer of recalibration of perception of object length from audition to touch. In all three experiments, there was a transfer of recalibration of perception of length from audition to touch (when feedback was provided on perception by audition). The results of the experiments suggest that calibration of perception of a given environmental property is not specific to a given perceptual modality. They provide preliminary evidence that calibration is independent of a given perceptual modality and suggest that the anatomical independence of recalibration may not only apply within a given perceptual modality but also across different perceptual modalities (see Wagman et al., 2009). The results are also consistent with the more general proposal that perception is organized not in terms of the anatomical structures involved but rather in terms of the environmental property being perceived (J. Gibson, 1966).

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