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The Role of Feedback Information for Calibration and Attunement in Perceiving Length by Dynamic Touch

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Two processes have been hypothesized to underlie improvement in perception: attunement and calibration. These processes were examined in a dynamic touch paradigm in which participants were asked to report the lengths of unseen, wielded rods differing in length, diameter, and material. Two experiments addressed whether feedback informs about the need for reattunement and recalibration. Feedback indicating actual length induced both recalibration and reattunement. Recalibration did not occur when feedback indicated only whether 2 rods were of the same length or of different lengths. Such feedback, however, did induce reattunement. These results suggest that attunement and calibration are dissociable processes and that feedback informs which is needed. The observed change in variable use has implications also for research on what mechanical variables underlie length perception by dynamic touch.

Keywords: attunement, calibration, feedback, dynamic touch

In the ecological literature on perceptual learning, two processes have been suggested to underlie improvement in the accuracy of perceptual judgments about object properties. The first process entails learning to attend to the right informational variable. A novice perceiver might exploit a nonspecifying informational variable—a variable that relates ambiguously to the perceived property. The accuracy of such a perceiver's perceptual judgment can improve by converging on a specifying variable, that is, converging on a variable that relates one to one to the perceived property (see, e.g., Michaels & de Vries, 1998; Runeson, Juslin, & Olsson, 2000). The Gibsons (e.g., E. J. Gibson, 1963/1991; J. J. Gibson, 1966) referred to this process as the *education of attention*. It has also been termed *attunement* and *differentiation*. The detection of specifying information is a necessary but not a sufficient condition for a perceptual judgment to be accurate. Relying on a specifying variable yields perceptual judgments that are related one to one to the perceived property; however, to be metrically accurate, the judgment must also be appropriately scaled to the detected information (e.g., Bingham & Pagano, 1998). The second hypothesized process, *calibration*, is the process that determines this scaling. Because any perceptual report implies both the detection of some variable and the scaling of perception to that variable (i.e., calibration), we refer to changes as *reattunement* and *recalibration*.

In the last 2 decades, several studies have examined these two processes. Michaels and de Vries (1998) asked participants to judge the pulling force exerted by a (stick-figure) puller. Many participants began by exploiting nonspecifying variables, but with feedback, they converged on more useful informational variables. A similar change in variable use was demonstrated in the colliding balls paradigm in which participants reported the relative mass of two colliding balls (Jacobs, Michaels, & Runeson, 2000; Runeson, Juslin, & Olsson, 2000). Perceptual recalibration, on the other hand, has been observed in several paradigms, among which are visual perception of the sit-on-ability and climb-on-ability of objects (Mark, 1987), visual slant perception (Bhalla & Proffitt, 1999), visual distance perception (Pagano & Bingham, 1998), length and sweet-spot perception by dynamic touch (Withagen & Michaels, 2004, 2005), and height and width perception by dynamic touch (Wagman, Shockley, Riley, & Turvey, 2001).[1]

Information of some sort (e.g., perceivable action consequences or extrinsic feedback) is required to induce the processes of attunement and calibration. Determining the conditions needed for recalibration or for reattunement to occur has been a long-standing enterprise. In the 1950s and 1960s, prism studies were often used to examine what information is required for calibration, in particular, the alignment of the visual system and the proprioceptive system. Held and Hein (1958), for instance, found that self-produced arm movements are needed for the alignment of seen and felt hand position—when the arm is moved by the experimenter, there was no realignment. Consequently, Held and Hein suggested that reafference stimulation is required. Around the same time, the conditions needed for the improvement of perceptual judgments were also examined. E. J. Gibson and Bergman (1954), for instance, investigated whether visual judgments of distance im-

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[1] Recalibration has also been observed in the action domain (e.g., Bingham, Zaal, Robin, & Shull, 2000; Durgin & Pelah, 1999; Rieser, Pick, Ashmead, & Garing, 1995; Withagen & Michaels, 2002). However, in this article we limit ourselves to the domain of perceptual judgments.

proved in the absence of feedback, and they found a decrease only in variable error and not in constant error. More recent studies also demonstrated the importance of information for improvement of perceptual judgments. In a study by Wagman et al. (2001), participants were to perceive the height and width of handheld, unseen objects. Wagman et al. found that a change in variable use and a rescaling of the judgments occurred only if feedback was provided (see also Withagen & Michaels, 2004).

The fact that there seem to be two processes by which perceptual judgments can improve, however, raises the question of whether feedback informs a perceiver about whether reattunement and/or recalibration is needed for judgments to be more accurate. In the literature on motor learning, it has been suggested that extrinsic feedback has an informational function (e.g., Elwell & Grindley, 1938; Salmoni, Schmidt, & Walter, 1984; Schmidt & Lee, 2003); it not only informs that the action is inaccurate but also how to improve (see also Fowler & Turvey, 1978). We hypothesize that in the case of perception, feedback can indicate whether reattunement and/or recalibration are needed (cf. Jacobs & Michaels, 2005). After all, over trials the detection of a nonspecifying variable would be expected to yield errors of a different type than would be expected from miscalibrations. Let us illustrate some of these error types in the paradigm used in the present study, length perception by dynamic touch.

In this paradigm, a participant estimates the length of unseen, wielded rods (see, e.g., Solomon & Turvey, 1988). What will happen when a perceiver's reports of rod length are based on a nonspecifying variable? A nonspecifying variable is by definition related ambiguously to the perceived property; that is, the same value of the variable can occur with rods of different lengths, and rods of the same length can have different values of the variable. Hence, a perceiver who relies on a nonspecifying variable could perceive rods of different lengths to be of the same length and rods of the same length to be of different lengths. This type of error does not occur if the perceiver relies on a specifying variable. When a specifying variable is exploited, equal-length rods should be perceived as being of the same length, and rods of different lengths should be perceived as being of different lengths. A miscalibration, on the other hand, yields errors of a different type. A miscalibration is an inappropriate scaling of the perceptual judgment to the exploited information. Hence, such an inadequate scaling can yield a general under- or overestimation of perceived rod length.

The fact that the pickup of nonspecifying variables would yield errors that differ from errors that result from miscalibrations implies that appropriate feedback could inform the perceiver of whether reattunement or recalibration is needed to improve the accuracy of perceptual judgments. For instance, in the perception of rod length, feedback regarding actual rod length informs both about variable use and about the adequacy of the calibration. Hence, if perceivers can take advantage of this type of feedback, both reattunement and recalibration should be induced. A different effect is to be expected when feedback merely informs about which of two simultaneously or successively held rods is longer. Such feedback indicates whether the right variable is exploited but carries only trivial information about the adequacy of the calibration—it can only inform about whether the calibration coefficient that captures how perceived length is scaled to the exploited information has the correct sign. A third type of feedback might inform about whether two rods are of the same length or of different lengths. Such feedback informs about the usefulness of the variable exploited but provides no information whatsoever about the adequacy of the calibration. Hence, if the processes of calibration and attunement are independent and guided by information present in the feedback, the latter type of feedback ought to induce a change in variable use but ought not to yield a rescaling of the perception.

In the present experiments, the effect of two types of feedback on the processes of calibration and attunement are tested: (a) whether feedback informing about actual rod length indeed induces both reattunement and recalibration and (b) whether feedback informing only about variable use yields reattunement and no recalibration. We used a dynamic touch paradigm in which participants were to make length judgments about rods that differed in length and diameter and that were made of materials with different densities. The reason for using this paradigm was threefold. First, there is ample evidence that perceivers exploit variables that are related ambiguously to the length of homogeneous rods made of different materials.[2] In recent years, three mechanical variables have been hypothesized to underlie length perception by dynamic touch. First, in their pioneering work, Solomon and Turvey (1988) suggested that the major principal moment of inertia of the rod (I_1) constrains length perception. Later, Fitzpatrick, Carello, and Turvey (1994) found length perception to be a function of both I_1 and I_3, the rod's minor principal moment of inertia. More recently, Kingma, van de Langenberg, and Beek (2004) showed that length perception by dynamic touch is governed by both I_1 and the first moment of mass distribution (M).

The mechanical variables I_1, I_3, and M are all functions of a rod's length, radius, and material density, implying that these individual mechanical variables are related ambiguously to the length of homogeneous rods that differ in material and radius. Rods with identical I_1, I_3, or M can differ in length. Hence, the empirical studies to date suggest that perceivers exploit nonspecifying variables to perceive the lengths of homogeneous rods (see also Carello, Fitzpatrick, Domaniewicz, Chan, & Turvey, 1992; Turvey & Carello, 1995). However, there are other mechanical variables available that specify the length of homogeneous rods (cf. Kingma, Beek, & van Dieën, 2002). Examples of such variables are the ratio of I_1 to M, and the ratio of M to mass. (See Kingma et al., 2002, for other specifying variables.) Consider, for instance, the ratio of M to mass,

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[2] It is important to note that an informational variable is not in and of itself specifying or nonspecifying. Whether a variable is specific to the perceived property can depend on the constraints in the task ecology (Runeson, 1988). For instance, the major principal moment of inertia of a homogeneous rod, I_1, is a function of the rod's diameter, material density, and length. Thus, if the task ecology contains homogeneous rods of the same diameter and density, I_1 is related one to one to rod length. If, on the other hand, the ecology consists of homogeneous rods of different diameters and made of materials with different densities, this variable is not specific to rod length. In the present study, we qualify mechanical variables as nonspecifying or specifying depending on their relation with rod length in a task ecology consisting of homogeneous rods made of materials with different densities.

$$\frac{M}{m} = \frac{m(L / 2)}{m}$$

where m is mass and L is length. The mass cancels out, implying that the ratio of M to m is a single-valued function of rod length. This means that rods of different lengths differ in M/m, and equal-length rods have the same M/m, even if the rods are made of materials with different densities. Given perceivers' reliance on nonspecifying variables, and given the availability of specifying information, the dynamic touch paradigm seems convenient for the study of attunement. Third, the dynamic touch paradigm has proven to be a fruitful paradigm for the study of perceptual calibration. Perceivers often start out poorly calibrated. However, a few feedback trials informing the perceivers about absolute rod length suffice to appropriately rescale length perception (Withagen & Michaels, 2004, 2005).

Experiment 1

Experiment 1 had two goals. The primary goal was to test whether feedback can induce perceivers to converge on more useful informational variables in the perception of length by dynamic touch. To test what type of feedback suffices to induce this process of attunement, one requires a demonstration that perceivers can come to rely on these more useful informational variables. We used a pretest–feedback–posttest design. In the feedback phase, visual information about absolute rod length was fed back. Following previous findings (Jacobs, Runeson, & Michaels, 2001; Michaels & de Vries, 1998), we presumed that such feedback lays a sufficient basis for convergence on a specifying variable (though no type of feedback would guarantee convergence). To find out whether reattunement occurred, we tried to determine what mechanical variables constrained length perception in the different phases of the experiment.

The second goal was to replicate the finding that feedback on absolute length induces a recalibration of length perception by dynamic touch. As argued above, this type of feedback informs participants about how their length judgments are scaled to actual length, and thus guides possible rescaling. In sum, we hypothesized that feedback informing about absolute length would induce both reattunement and recalibration.

Method

Participants. Six men and 2 women volunteered to participate by giving their informed consent. The participants ranged from 23 to 34 years of age. All were right handed.

Materials. To help ensure that participants were not simply learning to identify individual rods, we used two sets. One set was used in the test blocks; the other set was used in the feedback blocks. Each set contained carbon pipes and solid, cylindrical rods made of wood, aluminum, or steel. The carbon pipes had an outer diameter of 2.0 cm and an inner diameter of 1.7 cm. Within each set, the rods differed in length and diameter. An identical 11-cm plastic handle was affixed to each rod; this prevented the participants from feeling either the rod's diameter or the material from which the rod was made. The geometric and mechanical properties of the rods are provided in the Appendix. The particular values of the collections of rods were chosen so that I_1, M, and any combination of I_1 and I_3 would have low correlations with actual length.[3]

Table 1
Correlations Between the Logarithms of the Candidate Variables and Actual Length

Variable	1	2	3
		Test rod set	
1. Length	—	.375	.002
2. I_1		—	.928
3. M			—
		Feedback rod set	
1. Length	—	.185	−.138
2. I_1		—	.948
3. M			—

Note. I_1 = the major principal moment of inertia of the rod; M = the first moment of mass distribution.

The correlations between actual length and I_1 and M are provided in Table 1. Multiple regressions of the logarithm of actual length against the logarithms of I_1 and I_3 revealed that the best combination of the latter two mechanical variables have a correlation with actual length of .407 for the test rods and of .319 for the feedback rods. The reason for choosing the values of the variables such that the correlation with actual length was low was twofold. First, low correlations made it easier to determine whether a perceiver exploits a specifying or a nonspecifying variable. Second and more important, the low correlations between actual length and I_1, M, and any combination of I_1 and I_3 implied that they would be poor variables to base length judgments on, which, in turn, would be obvious in the feedback and increase the likelihood that a change in variable would occur (see Jacobs, Runeson, & Michaels, 2001). The relations between actual length and I_1 and M for the test rods are plotted in Figure 1. The graphs make clear that these mechanical variables are related ambiguously to rod length. Equal-length rods differ in I_1 and M. Further, rods of different lengths, radii, and material densities sometimes were similar in I_1 and M. Hence, the reliance on these variables would yield inaccurate length judgments. The ratio of I_1 to M, however, is specific to the length of the rods as is the ratio

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[3] It is important to note that we computed the mechanical variables I_1, I_3, and M with respect to the end of the rod. Because the values of the mechanical variables differ when computed with respect to different points, one should be careful when comparing the present results with findings reported in the literature. Often, these mechanical variables are computed with respect to the wrist, the presumed rotation point. As it turned out, the multiple correlation of length with I_{1w} and I_{3w} (i.e., moments computed with respect to the wrist, assuming a fixed distance between the end of rod and this joint) was perfect. In other words, I_{1w} and I_{3w} together specify length with this collection of rods. The implication of this relation is that later when we claim evidence that participants accurately perceive length, they may exploit I_{1w} and I_{3w} together as well as the length-specifying variables described in the text. We did not feel justified, however, in reporting these moments with respect to the wrist because of reasons laid out in the *Method* section: The participants were not instructed to hold the rod's handle at a specific point in their hands, nor were the participants instructed to grip the handle firmly. Both of these factors may influence the actual rotation point of the rod. Because of this, we measured moments around the arguably more neutral locus, the end of the rod.

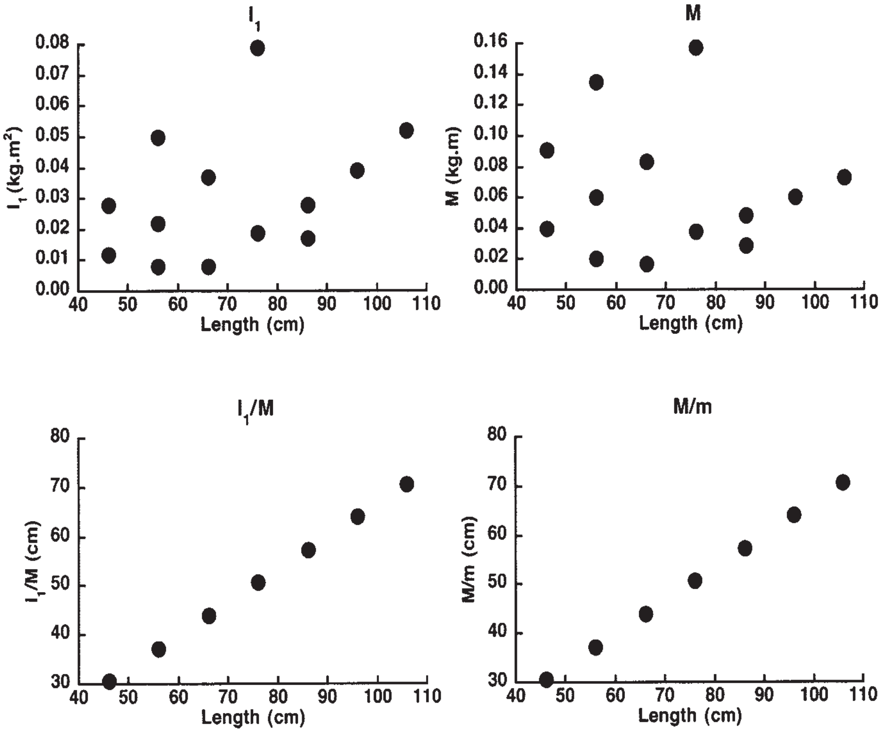

Figure 1. The relation between actual length and the major principal moment of inertia of the rod (I_1), the first moment of mass distribution (M), I_1 / M, and M / m (where m refers to mass) for the test rods.

of M to m.[4] Thus, converging on such a specifying variable would yield length judgments that relate one to one to the length of the rods.

Design and procedure. The experiment consisted of a pretest, four feedback blocks, and a posttest. The experiment was conducted over 2 consecutive days. The first day consisted of the pretest and two feedback blocks; the second day consisted of two feedback blocks and the posttest. In each phase, the participant was to estimate the length of the handheld rod. The participant sat in a chair with an armrest on the right side supporting his or her forearm. A curtain between the armrest and the chair prevented the participant from seeing the rod. Because a change in variable use is likely to be accompanied by a change in the exploratory behavior, we did not impose many restrictions on the wielding of the handheld rod. The participant was allowed to hold it loosely in the hand and wield it freely, with the exception that the rod was not to touch the curtain or the floor. On a table in front of the participant was a small planar surface that the participant could move along a 1.66-m rail by rotating a wheel with the left hand. The participant was to position the surface at the maximum distance reachable with the handheld rod, in other words, such that the surface coincided with the perceived distal end of the rod. The distance of the surface from the hand defined *perceived length.*

The test phases consisted of 26 trials. Each test rod was offered twice; the order of presentation was randomized. After each trial, the planar surface was to be repositioned at the proximal end of the rail. The feedback blocks also consisted of 26 trials. After the participants positioned the surface at the perceived distance reachable, they were allowed to touch the curtain with the rod so that they could see the position of the distal end of the handheld rod. Participants were allowed to reposition the surface if they wished so that they could see the curtain displacement more easily. As in the test phases, the surface was to be repositioned at the proximal end of the rail after each trial. Each feedback rod was offered twice in a random order. Between the blocks there was a short break.

Results and Discussion

To test whether length perception was more closely tied to actual length after the training blocks than it was before, we computed the Pearson product–moment correlations between perceived length and actual length for each participant in the pretest and in the posttest. The correlations averaged[5] over participants were .420 in the pretest and .780 in the posttest. A paired t test showed that this difference was significant, $t(7) = 3.790$, $p < .01$, suggesting that participants learned to better perceive length.

The significant increase in the judgment–length correlation between the pretest and posttest does not prove, of course, that participants exploited different informational variables in the posttest and pretest. To test whether they did so, we computed the correlations between perceived length and the candidate variables I_1 and M. Because the relationship between perceived length and these variables is expected to be nonlinear (e.g., for a homogeneous rod of some density, I_1 increases as the cube of length), the

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[4] Strictly speaking, the ratio of I_1 to M is specific to the length of homogeneous rods only if the rods have a constant diameter. After all, I_1 of a homogeneous rod is a function of the rod's mass, length, and diameter; M of a homogeneous rod is a function of the mass and the length. However, because there was only a small variation in rod diameter in these collections of rods, to all intents and purposes the ratio is related one to one to length, as is clear in Figure 1.

[5] All averaging and statistical tests done on correlations in both Experiments 1 and 2 used the correlations' z transformations.

correlations were computed on the logarithms of perceived length and the variables. To make the analyses parallel, we also recomputed the perceived length to actual length correlation using logarithms.

In the pretest, the correlations averaged over participants showed that perceived length was correlated most highly with I_1 (.902), followed by M (.852) and length (.402). This hints at the exploitation of I_1 in perceiving rod length by dynamic touch. To test whether the participants' length judgments were based on a combination of I_1 and I_3, we computed multiple regression lines, with the logarithm of perceived length as the dependent variable and the logarithms of I_1 and I_3 as the independent variables for each participant. It appeared that for none of the participants was I_3 a significant predictor of length judgments ($ps > .05$), indicating that length perception was not governed by a combination of I_1 and I_3. To determine whether, on average, participants reliably exploited a nonspecifying variable on the pretest, we tested whether the predictive superiority of I_1 over length was significant over participants. The difference between the correlations was indeed significant, $t(7) = 3.885$, $p < .01$, indicating that in the pretest a nonspecifying variable was exploited.

In the posttest, on the other hand, actual length had the highest correlation with perceived length (.757). This correlation was significantly higher than the second highest correlation, the correlation with I_1 (.524), $t(7) = 3.410$, $p < .05$. To ensure that the participants did not rely on a combination of I_1 and I_3 in the posttest, we again computed multiple regression lines, with the logarithm of perceived length as the dependent variable and the logarithms of I_1 and I_3 as the independent variables for each participant. As in the pretest, I_3 was not a significant predictor of length judgments for any of the participants ($ps > .05$). This suggests that with feedback, participants reattuned to one of the variables that is specific to the length in this collection of rods.

As argued in the introduction, the feedback provided in this experiment informs the perceiver not only about variable use (e.g., how well the exploited variable informs about length) but also about the perceiver's calibration. Thus, we expected to observe both reattunement and recalibration. To test whether recalibration occurred, we computed the constant error for each participant in both the pretest and the posttest. The constant error was computed as the average of perceived lengths minus actual lengths. Averaged over participants, the constant error changed from −13.15 cm in the pretest to 7.46 cm in the posttest. A paired t test indicated that this difference was significant, $t(7) = 3.000$, $p < .05$, showing that recalibration occurred.

A more detailed picture of the process of attunement is provided in Figure 2, which presents the correlations between perceived length and the candidate variables for each participant and each test and feedback block. To test for significant differences within individuals, we performed t tests for dependent correlations (Bruning & Kintz, 1987, p. 228; see also Jacobs et al., 2000, 2001). Because we were primarily interested in whether specifying or nonspecifying variables were exploited, we tested for differences between the correlation with actual length and the correlation with whichever nonspecifying variable explained most of the variance in perceived length on that block of trials for that participant. In the pretest, perceived length correlated more highly with I_1 than with actual length ($ps < .05$) for all but 1 participant, reiterating the general tendency to rely on a nonspecifying variable in the pretest. With regard to reattunement to a specifying variable, Participants 2, 3, 6, 7, and 8 demonstrated use of a specifying variable on at least one block of the feedback or test phases; they had correlations between perceived and actual length that were significantly higher than the correlation between perceived length and the most highly correlated nonspecifying variable.

Three participants failed to show significant reattunement. Participants 1 and 4 showed nonsignificant trends to rely on specifying information on later blocks. One participant, Participant 5, demonstrated reliance on the specifying variable in the pretest, rendering change in variable use unnecessary. The length perception of that participant correlated significantly higher with actual length than with the most highly correlated nonspecifying variable on all but one of the blocks of trials ($ps < .05$). After the experiment, she volunteered that she had been a top national fencer. During training sessions, she used foils made of materials with different densities. Probably because of her experience with haptically perceiving the length of the foils, this participant had attunement to a specifying variable prior to the experiment. To summarize, in general, novice perceivers use nonspecifying variables in the perception of length by dynamic touch. Feedback about absolute length, in turn, induces the processes of attunement and calibration, at least in most participants.

Experiment 2

Experiment 2 was conducted to test whether feedback that provides information only about variable use and not about the adequacy of the calibration induces reattunement and does not yield recalibration. As argued in the introduction, feedback indicating whether two rods are of the same length or of different lengths provides such information. When informed that rods are incorrectly perceived to be of the same length or incorrectly perceived to be of different lengths, a perceiver receives feedback indicating that he or she is exploiting a nonspecifying variable. Hence, in principle, the feedback information indicates the need for reattunement. However, because this type of feedback does not inform of how well perceived length is scaled to actual length, it does not provide information regarding calibration. Hence, we expect such feedback to induce reattunement but not to induce recalibration.

Method

Participants. Eight new participants (4 men and 4 women) volunteered to participate; each gave their informed consent. Their ages ranged from 19 to 46 years. All were right handed.

Materials. The rods were the same as in Experiment 1. In the test phases, the test rods were used; in the feedback phase, the feedback rods were used.

Design and procedure. As in Experiment 1, the experiment was conducted over 2 consecutive days. The first day consisted of the pretest and two feedback blocks; the second day consisted of two feedback blocks and the posttest. The experimental set-up was identical to that of Experiment 1, except that there was also an armrest on the left side of the participant; a screen between this armrest and the rail prevented the participant from seeing a rod held in the left hand. The test phases were identical to those in Experiment 1.

In the feedback phase, the rods were offered in pairs. Rod A was presented to the participant's right hand. As in the test phases, the participant was to position the movable surface at the perceived maximum

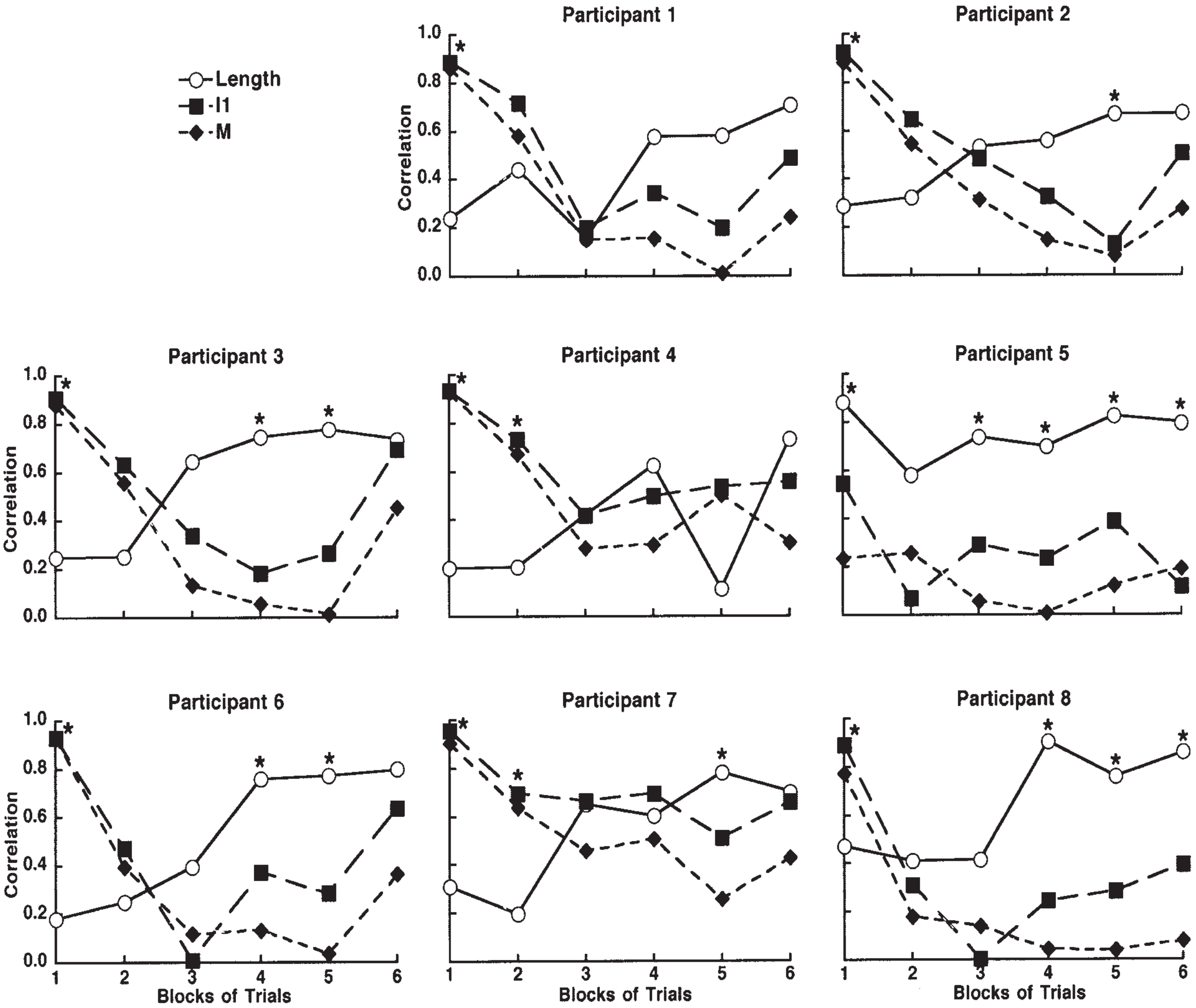

Figure 2. The correlations between the length judgments and the major principal moment of inertia of the rod (I_1), the first moment of mass distribution (M), and actual length in Experiment 1: pretest (Block 1), training (Blocks 2, 3, 4, 5), and the posttest (Block 6). In the blocks marked with an asterisk, there is a significant difference ($p < .05$) between the correlation with actual length and the correlation with the most highly correlated nonspecifying variable.

distance reachable with the rod. After the length judgment was made, the participant was instructed not to reposition the surface. Then, Rod B was offered to the participant's right hand, and, again, the participant was to estimate the length of the rod. This procedure provides information about whether the rods are perceived as being of the same length: Repositioning the surface meant that the rods were perceived as being different in length; not repositioning meant that the two rods were perceived as being of the same length. The participant was then told either that Rod A and Rod B were of the same length or that Rod A and Rod B differed in length by 10 cm or more. Rod A was then presented to the left hand, and the participant could simultaneously wield the two rods, knowing whether they were the same or different. Note that when the rods differed, the participant was not informed as to which was longer. The participant was not allowed to touch the floor, the screen, or the curtain with the rods. After some exploration by the participant, the rods were switched: Rod A was presented to the right hand, Rod B to the left hand, and the participant could again wield the rods for some time. In each feedback block, 13 pairs of rods were offered: 7 pairs of equal-length rods and 6 pairs of rods that differed in length. (The two sets of rod pairings, one for Blocks 1 and 3 and one for Blocks 2 and 4, are provided in the Appendix.[6])

Each pair was offered once in each feedback block; the order of presentation was randomized. After each pair, the participant was to reposition the surface at the proximal end of the rail as in the test blocks. There was a short break between the blocks.

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[6] Note that feedback on pairs of rods that differ in length is likely to be less effective than feedback on the pairs of equal-length rods. After all, for the former pairs, feedback informs about the exploitation of a nonspecifying variable if and only if the two rods had been perceived to be of the same length, an occurrence that is not likely to occur frequently. However, one must include pairs of rods of different lengths to prevent the perceivers from knowing that a second rod is of the same length as the first.

Results and Discussion

We first tested whether recalibration was induced by feedback on whether two rods are of the same length or of different lengths. Given that in Experiment 2 the feedback provides no information about how perceived length is scaled to actual length, we expected no recalibration. To test whether recalibration occurred, we computed, as in Experiment 1, the constant error for each participant and each test phase. The average constant error was -24.95 cm in the pretest and -25.72 in the posttest. A paired *t* test showed that this difference was not significant, $t(7) = 0.176$, $p = .86$, suggesting that recalibration did not take place.

However, length perception was more closely related to actual length after feedback. As in Experiment 1, we calculated the correlations between perceived length and actual length for each participant and each test phase. The correlation averaged over participants was .389 in the pretest, which was significantly lower than the average correlation of .730 found in the posttest, $t(7) = 4.558$, $p < .01$. Thus, providing participants only with feedback about whether two rods are of the same length or of different lengths led to higher correlations between perceived length and actual length.

To examine the extent to which participants changed in variable use, we calculated the correlations between the logarithms of perceived length and I_1, M, and actual length for each participant on each of the six blocks. In the pretest, perceived length was correlated most highly with I_1 (.757 averaged over participants), followed by M (.682) and length (.364). As in Experiment 1, we tested whether length perception by dynamic touch was based on a combination of I_1 and I_3. We computed the multiple regression lines, with the logarithm of perceived length as the dependent variable and the logarithms of I_1 and I_3 as the independent variables for each participant. For none of the participants was I_3 a significant predictor of perceived length ($p\text{s} > .05$). To test the difference between the correlation of judgment and I_1 and the correlations of judgment and the specifying variable, we performed a paired *t* test; the difference was significant, $t(7) = 5.442$, $p < .01$. We concluded that, on average, participants exploited a nonspecifying variable in the pretest.

In the posttest, perceived length correlated most highly with actual length (.704), although this correlation was only slightly higher than the correlation with I_1 (.656), the second highest correlation. The multiple regression of the logarithm of perceived length against the logarithms of I_1 and I_3 showed that also in the posttest perceived length was not constrained by a combination of these moments of inertia; for none of the participants was I_3 a significant predictor of length judgments ($p\text{s} > .05$). A paired *t* test showed that the difference between the correlation with actual length and the correlation with I_1 was not significant, $t(7) = 0.384$, $p = .71$. Thus, looking only at the averages over participants, we cannot conclude that a specifying variable is exploited in the posttest. However, there were large individual differences.

Figure 3 presents the correlations between perceived length and the various predictor variables for each individual on each block of trials. With regard to reattunement to specifying variables, individual participants can be divided into two groups. Participants 1, 2, 4, and 8 appeared to learn to attend to specifying information after feedback, whereas Participants 3, 5, 6, and 7 did not.

As in Experiment 1, we compared the correlation with actual length and the correlation with the most highly correlated nonspecifying variable on each block of trials for each participant. In the pretest, all but 2 participants had a significantly higher correlation with I_1 than with actual length ($p\text{s} < .05$), reiterating the general reliance on a nonspecifying variable in the pretest that we had seen in Experiment 1. We would expect this similarity, of course, because the methods of the two experiments did not diverge until the feedback phase. On the basis of the significance of *t* tests, we concluded that Participants 1, 2, and 4 reattuned to a specifying variable after being given feedback. Participants 1 and 2 used a specifying variable in at least one of the feedback blocks, though not in the posttest. Participant 4 discovered a specifying variable in the last feedback block and maintained reliance on specifying information in the posttest. As an aside, the posttest length judgments of Participant 4 nicely demonstrated that reattunement to a specifying variable does not necessarily yield judgments that are in the ballpark of the actual length. Although that participant volunteered that he was quite convinced that his length judgments were also metrically accurate in the posttest, a linear regression of perceived length against actual length revealed an intercept of -5.4 cm and a slope of 0.37, indicating a considerable underestimation of rod length. Note also the high correlations with actual length of Participant 8 in the posttest (.917) and later feedback blocks. The nominal correlations suggest that this participant also reattuned to the specifying variable. However, because of the absence of a significant difference between the correlation with I_1 and the correlation with actual length in the first blocks of the experiment, we cannot say with certainty that this participant changed in variable use.

Participants 3 and 7 clearly did not discover a specifying variable. The *t* tests showed that as in the pretest, these participants' length perceptions were reliably based on a nonspecifying variable in two of the feedback blocks and the posttest. Participant 5 relied on a nonspecifying variable in the pretest, and Participant 6 did so in the posttest, but it was not clear what variables were exploited in the other blocks.

In summary, we conclude that (a) feedback about whether two rods are of the same length or of different lengths did not induce recalibration and (b) such feedback induced a reattunement—a change from exploitation of a nonspecifying variable in the pretest to exploitation of a specifying variable in later blocks of trials but not for all participants.

General Discussion

In the present study, perceivers were trained to estimate the length of unseen, wielded rods that differed in length, material, and diameter. Inclined to an ecological theory of perceptual learning, we hypothesized that there are two processes by which the accuracy of the perceptual judgments can improve: attunement and calibration. We investigated whether feedback informs the perceiver about which processes are needed to improve the accuracy of the perceptual judgment. It was argued that feedback informing the perceiver that rods are incorrectly perceived to be of the same length or to be of different lengths indicates that a nonspecifying variable is exploited and, thus, that reattunement is needed. Feedback informing about a general over- or underestimation of rod length indicates the need for recalibration.

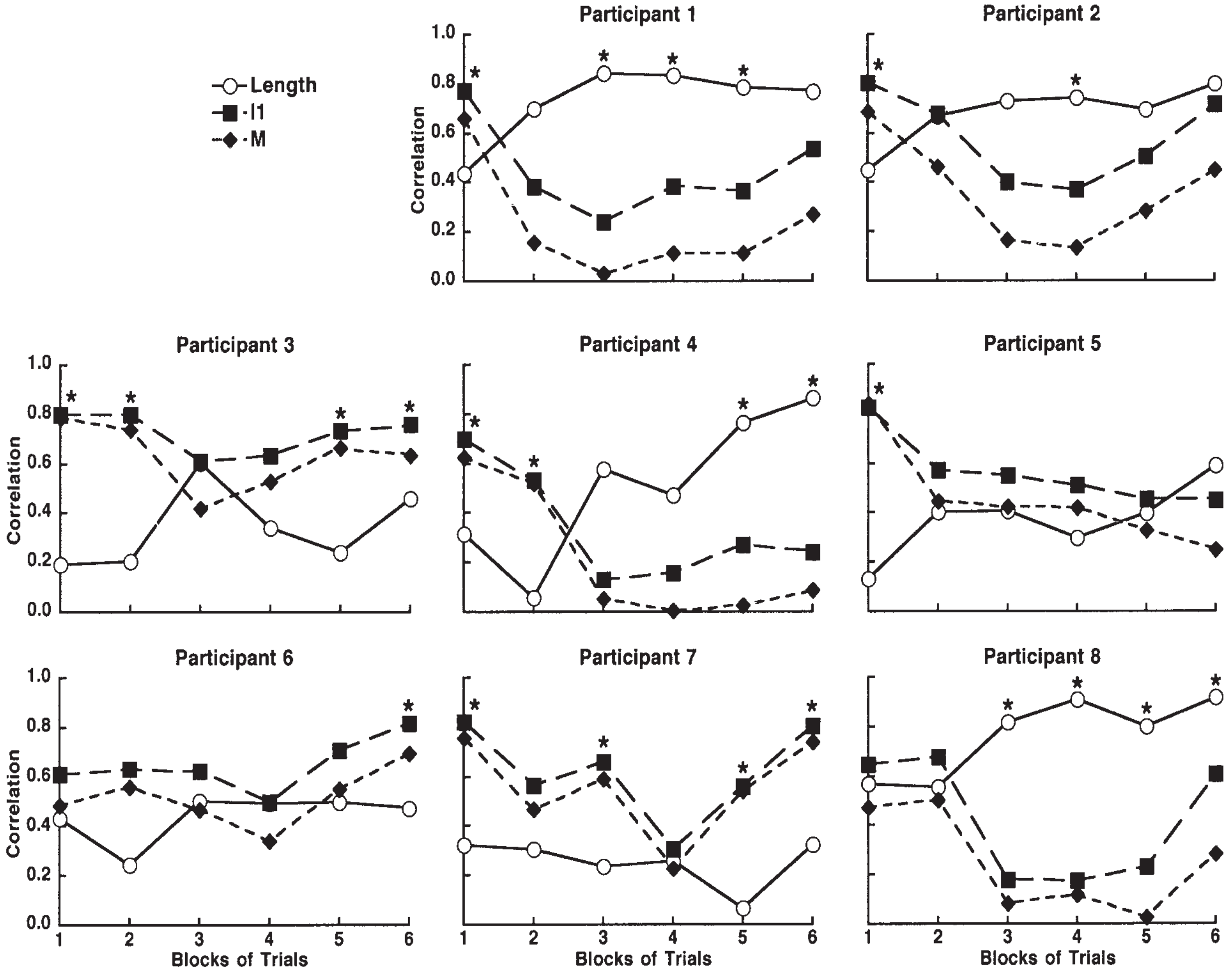

Figure 3. The correlations between the length judgments and the major principal moment of inertia of the rod (I_1), the first moment of mass distribution (M), and actual length in Experiment 2: pretest (Block 1), training (Blocks 2, 3, 4, 5), and the posttest (Block 6). In the blocks marked with an asterisk, there is a significant difference ($p < .05$) between the correlation with actual length and the correlation with the most highly correlated nonspecifying variable.

Two pretest–feedback–posttest experiments were performed; they differed in the types of feedback provided. In Experiment 1, actual rod length was fed back. Because over trials this type of feedback constitutes information about both variable use and calibration, we expected that it would induce both recalibration and reattunement. Recalibration was evidenced by the fact that participants underestimated rod length in the pretest and were more accurate in the posttest. Reattunement was evidenced by the fact that most participants relied on a nonspecifying variable in the pretest and learned to attend to specifying information when feedback was provided.

In Experiment 2, the feedback indicated only whether two rods were of the same length or of different lengths. This type of feedback did not induce recalibration; despite the considerable underestimation of rod length in the pretest, perceivers' constant error did not decrease when feedback was provided. We expected this outcome because the feedback did not inform about the adequacy of the calibration. Judgments, however, were more highly correlated with actual length in the posttest than in the pretest. Analyses of what mechanical variables underlay the length judgments revealed that convergence on specifying information occurred, at least in some participants. We concluded that the processes of attunement and calibration are guided by information available in the feedback.

In what follows, we consider the implications of the study for the ecological approach to perceptual learning. First, the dissociability of attunement and calibration is addressed. Then we consider the implications for the suggested informational function of feedback. Two hypotheses on how attunement information guides convergence are presented. Lastly, we explore the implications of our study for the discussion on what mechanical properties constrain length perception by dynamic touch.

Attunement and Calibration

In the present study, we asked whether feedback informs the perceiver about whether reattunement and/or recalibration is needed to improve the accuracy of judgments. Obviously this question assumes that the two processes are independent, that is, that a perceiver can reattune but not recalibrate and vice versa. But are they independent? To make a judgment, one must be both attuned and calibrated, as we noted in the introduction; the report of a perceived quantity always entails both an attended-to variable and a relation between that variable and judgment. So the question of dissociability is whether changes in each can occur without changes in the other.

Earlier studies had already provided some evidence of the dissociability of attunement and calibration. In particular, it had been demonstrated that perceivers can recalibrate but not change in variable use. In Experiment 1 of Jacobs and Michaels (in press), for instance, observers were trained to report the passing distance of balls that swung toward them on thin lines. Jacobs and Michaels (in press) found that for several perceivers the improvement in the judgments was the result of recalibration, not reattunement; there appeared to be only minor changes, if any, in which informational variables constrained judgments. Nevertheless, perceivers rescaled the relation between their judgments and this information so that the judgments were more accurate.

One might suppose that recalibration, especially in the absence of reattunement, might be simply a cognitive effect: adding some fixed amount to judgments or doubling perceived amounts, for example. We do not believe this to be the case for two reasons. First, the recalibrations-without-attunement reported by Jacobs and Michaels (in press) in their Experiment 1 were neatly paralleled in the hand movements when participants actually caught the balls in their Experiment 2. A cognitively based adjustment of rapid, real-time interceptive movements does not seem plausible. Second, in our own previous demonstrations of recalibration of length perception by dynamic touch (Withagen & Michaels, 2005), we found that the 1 participant who volunteered that he had done cognitive rescaling was patently in error: A claim that 15 cm was added to perceived length was belied by a change in slope of 0.82 and a change of -13.2 cm in the intercept in the relation between actual and perceived. In that article, we also presented logical arguments against the view that calibration is cognitive. In sum, there are several reasons to believe that calibration is not mere cognitive compensation.

The present study finishes the double dissociation of attunement and calibration by showing that perceivers can also reattune but not recalibrate. Experiment 2 showed that some perceivers converged on specifying information but did not improve in their scaling of their judgments; their judgments consistently underestimated length across the experiment. This led us to conclude that these two hypothesized processes, attunement and calibration, are indeed independent—a perceiver can reattune but not recalibrate and vice versa.

Information for Attunement and Calibration

The present study further confirms the idea of the informational function of feedback. In the literature on motor learning, extrinsic feedback has been suggested to have a "directive effect" (Elwell & Grindley, 1938). That is, extrinsic feedback not only informs an animal about the inaccuracy of its action but also informs about what was wrong and how to improve (see, e.g., Fowler & Turvey, 1978; Salmoni, Schmidt, & Walter, 1984; Schmidt & Lee, 2003). The present study suggests a parallel function for feedback in the perceptual domain. It suggests that there is information available in the feedback that informs the perceiver about whether reattunement and/or recalibration is needed to improve the accuracy of the perceptual judgment. Feedback that indicated that recalibration and reattunement were needed induced both processes. Feedback indicating only the need for reattunement induced the process of attunement to a specifying variable but did not induce calibration.

However, looking at the individual differences, it seems that feedback on absolute length, as provided in Experiment 1, is more effective in inducing the process of attunement than feedback informing about whether two rods are of the same length or of different lengths, as provided in Experiment 2. After all, only 3 of 8 participants in Experiment 2 showed a significant convergence on the specifying information, and 1 showed a nonsignificant convergence. In Experiment 1, on the other hand, 5 of the 8 participants demonstrated a significant convergence, and 2 demonstrated a nonsignificant convergence. The only nonconverger was the fencer.

This asymmetry in reattunement might have been the result of the difference in amount of attunement information available in the two experiments. First, and as noted in Footnote 6, information indicating reliance on a nonspecifying variable comes primarily from feedback on the pairs of equal-length rods; feedback on the pairs of different-length rods indicates the exploitation of a nonspecifying variable only on the rare occasions that the rods are perceived as being of the same length. Hence, in comparison with Experiment 1, feedback indicating the detection of nonspecifying variables was less frequent in Experiment 2. Further, in the feedback blocks of Experiment 1, information was available that is likely to facilitate the process of attunement. For instance, there was information about how much (successive) rods differed in length and which rod was longer, information that was absent in Experiment 2. And, as noted in the introduction, such information informs about both the adequacy of the calibration and variable use. For instance, feedback that informs that the rods are correctly ordered (e.g., that Rod A is longer than Rod B) indicates that the calibration coefficient that relates perceived length to the exploited information has the appropriate sign. In addition, it also informs that the participant is relying on a useful informational variable. A perceiver who relied on a nonspecifying variable, say I_1, would have made ordinal errors in the experiments reported here. And feedback that indicates how much two rods differ in length informs about how perceived length should be scaled to the information. Moreover, because it indicates the difference in length, this feedback provides more information about the usefulness of the exploited variable than does feedback that informs merely that the rods were different. Hence, it is likely that the asymmetry in reattunement between the experiments was the result of the difference in amount of attunement information.

How Does the Feedback Guide the Processes of Attunement and Calibration?

As argued above, the present study contributes to the idea that feedback has an informational function. However, the experiments reported here suggest only that feedback informs the perceiver about which processes are needed to improve the accuracy of the perceptual judgment. The study does not provide insight into the important issue of how the information in the feedback guides these processes.

Consider, for instance, attunement information. How does this information guide the process of attunement? Does it direct one toward better information, or does it merely inform the perceiver that the detected information is nonspecifying and, thus, that a different variable should be exploited? In this study, we hypothesized that attunement information indicates reliance on a nonspecifying variable, so attunement information would not in itself guide the perceiver to the specifying information. Instead, it would merely inform the perceiver that a wrong variable is attended to. Evidence for this destabilizing function has been reported elsewhere; some perceivers learned not to use the nonspecifying variables but did not succeed in discovering specifying information (see, e.g., Jacobs et al., 2001). Apparently, feedback can at least sometimes merely inform the perceivers not to rely on the currently exploited variable without guiding the perceiver to a better variable.

However, some studies on attunement show that many perceivers progressively converge on the specifying variable, exploiting more useful information in each feedback block (e.g., Jacobs & Michaels, 2005; Michaels, Jacobs, & Withagen, 2003). This suggests that the attunement information does not only indicate whether the exploited variable is nonspecifying but also seems to suggest that there is information available that guides the perceiver to the specifying variable.

Finally, it is worth noting that the reattunement observed in Experiment 2 was probably not due to the feedback alone. Participants wielded two rods simultaneously while knowing whether they were the same or different. One can imagine that these perceivers sought exploratory movements that either revealed invariants in the two rods (in the case of feedback that rods were the same length) or variants (in the case of feedback that the rods were of different lengths). In short, Experiment 2 provided an opportunity to search for specifying information through exploration.

Mechanical Variables Underlying Length Perception

The present study has implications also for research on length perception by dynamic touch. As noted earlier, because we computed the mechanical variables I_1, M, and I_3 with respect to the end of the rod, it is hard to compare our results with many studies on length perception by dynamic touch in which variables are computed with respect to the wrist. Nevertheless, the demonstration that providing participants with feedback yielded changes in variable use has theoretical and methodological implications for research on what mechanical variables constrain length perception by dynamic touch.

First, it suggests that there is no such thing as the mechanical variable that constraints the length perception of unseen, wielded rods. Perceivers can rely on different variables to perceive length. This is in line with Kingma et al. (2004), who showed that I_1 and M can constrain length judgments by dynamic touch. Second, the present study suggests that which variable a perceiver exploits depends on his or her level of expertise. Consistent with other studies on attunement (Jacobs et al., 2001; Michaels & de Vries, 1998; Runeson et al., 2000), the present study revealed that experts detect more useful variables than novices. This has an important methodological implication for the study of dynamic touch. In general, perceivers who participate in dynamic touch studies ought to be considered novices, in spite of their considerable experience wielding everyday objects. The present study suggests that it is likely that the results of those studies would have been different if experts had participated (cf. Runeson, 1995, for the same argument regarding the colliding balls paradigm). The fencer who participated in Experiment 1 (Participant 5) is a nice illustration of the consequences of expertise. This means that if one is interested in what mechanical variables underlie length perception by dynamic touch, experts should be tested as well. Because humans wield various objects every day, it is easy to infer that they are all experts at dynamic touch, but clearly more nuance is needed. It is likely that there are different types of expertise. For example, what sets fencers apart from many other wielders (e.g., tennis players, batters, sawyers) is that their actions relate specifically to the location of the tip of the implement.

In the present study, we did not attempt to identify the precise mechanical variable(s) that underlay the length judgment of experts. As argued in the introduction and the *Method* sections, there are several mechanical variables that are specific to the length of homogeneous rods. Hence, the confounding of these variables renders it impossible to test which variables were exploited. To perform such a test, one would need to disentangle these variables. The present study, however, suggests that such a test is called for: The experts' length judgment by dynamic touch is constrained by mechanical variables that differ from the variables that are exploited by novices.

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(*Appendix follows*)

Appendix

Properties of the Rods Used in the Test and Feedback Blocks of Experiments 1 and 2

Rod no.	Material	Length (*m*)	Diameter (*m*)	m (kg)	M (kg × m)	I_1 (kg × m^2)	$I_3 \times 10^4$ (kg × m^2)
Test rod set							
1	Carbon	0.56	0.020	0.073	0.020	0.008	0.063
2	Carbon	0.76	0.020	0.099	0.038	0.019	0.086
3	Carbon	0.86	0.020	0.112	0.048	0.028	0.097
4	Carbon	0.96	0.020	0.125	0.060	0.039	0.108
5	Carbon	1.06	0.020	0.139	0.073	0.052	0.119
6	Aluminum	0.76	0.016	0.412	0.157	0.079	0.132
7	Steel	0.46	0.012	0.395	0.091	0.028	0.071
8	Steel	0.56	0.012	0.481	0.135	0.050	0.087
9	Wood	0.66	0.012	0.052	0.017	0.008	0.009
10	Wood	0.86	0.012	0.068	0.029	0.017	0.012
11	Steel	0.46	0.008	0.176	0.040	0.012	0.014
12	Steel	0.56	0.008	0.214	0.060	0.022	0.017
13	Steel	0.66	0.008	0.252	0.083	0.037	0.020
Feedback rod set							
1	Carbon	0.71	0.020	0.093	0.033	0.016	0.080
2	Carbon	0.91	0.020	0.119	0.054	0.033	0.102
3	Carbon	1.01	0.020	0.132	0.067	0.045	0.114
4	Carbon	1.11	0.020	0.145	0.081	0.060	0.125
5	Carbon	1.21	0.020	0.158	0.096	0.077	0.136
6	Aluminum	0.91	0.016	0.494	0.225	0.136	0.158
7	Steel	0.61	0.012	0.524	0.160	0.065	0.094
8	Steel	0.71	0.012	0.610	0.217	0.102	0.110
9	Wood	0.81	0.012	0.064	0.026	0.014	0.012
10	Wood	1.01	0.012	0.080	0.040	0.027	0.014
11	Steel	0.61	0.008	0.232	0.071	0.029	0.019
12	Steel	0.71	0.008	0.271	0.096	0.046	0.022
13	Steel	0.81	0.008	0.309	0.125	0.068	0.025

Note. In the feedback blocks of Experiment 2, the following pairs were presented. Feedback Blocks 1 and 3: Rods 1 and 8, 1 and 12, 8 and 12, 7 and 11, 6 and 2, 13 and 9, 3 and 10, 2 and 13, 3 and 7, 4 and 6, 4 and 11, 5 and 9, and 5 and 10. Feedback Blocks 2 and 4: Rods 1 and 8, 1 and 12, 8 and 12, 7 and 11, 6 and 2, 13 and 9, 3 and 10, 2 and 10, 3 and 13, 4 and 11, 6 and 5, 4 and 9, 5 and 7. m = mass; M = the first moment of mass distribution; I_1 = the major principal moment of inertia of the rod; I_3 = minor principal moment of inertia of the rod.

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