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Transfer of Learning in Perception with Haptic Sensory Substitution Devices

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TRANSFER OF LEARNING IN PERCEPTION WITH HAPTIC SENSORY-SUBSTITUTION DEVICES

TYLER DUFFRIN

36 Pages

Studies have shown that perceiving a given property of a wielded object requires *task-specific sensitivity* to the patterns of mechanical stimulation that support perceiving that property. The same is true for perceiving properties of the environment *by means of* a wielded object. Recently, studies using the Enactive Torch—a novel vibrotactile sensory-substitution device—have shown that these mechanical stimulation patterns are invariant across *medium* (Favela et al., 2018; 2021). The current study used a transfer of recalibration paradigm to the invariant patterns of mechanical stimulation that support perceiving surface distance by means of a wooden rod and by means of the Enactive Torch. In a pretest and posttest, participants used each of these modalities to explore an occluded surface and reported the perceived distance of that surface. In the practice session, we manipulated which modality participants used to perform this task and whether feedback about performance was provided. We found that transfer of recalibration occurred with feedback regardless of practice modality. Results are discussed in the context of the invariant stimulation patterns that support perceiving and acting.

KEYWORDS: haptic perception; calibration; sensory substitution; enactive torch

TRANSFER OF LEARNING IN PERCEPTION WITH HAPTIC SENSORY-SUBSTITUTION DEVICES

TYLER DUFFRIN

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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2023

TRANSFER OF LEARNING IN PERCEPTION WITH HAPTIC SENSORY-SUBSTITUTION DEVICES

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Thanks, Jeff Wagman, for showing me the ropes—inside and outside the experimental lab. Thanks also to Maisha Orthy, and good luck in your career as an experimental researcher. The same goes to the rest of the Perception-Action lab students who I was lucky enough to share my progress and results with.

T. D.

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CHAPTER I: INTRODUCTION

Successfully performing a particular perceptual or behavioral task requires being or becoming sensitive to the stimulation pattern that supports the performance of that task. The stimulation patterns that are most useful in this respect are those that support performance of a given task across the wide variety of circumstances in which it might be performed. In other words, the stimulation patterns that are most useful in performing any perceptual or behavioral task are those that are *invariant* across the changing circumstances in which that task might occur. For example, the optical stimulation patterns that are most useful in supporting the control of locomotion are those that are invariant across circumstances including the means of locomotion (e.g., crawling, walking, driving) and environmental conditions (e.g., weather conditions, ground surfaces). Therefore, performing a given perceptual or behavioral task under any set of circumstances requires developing task-specific sensitivity to invariant stimulation patterns (Blau & Wagman, 2023; Turvey, 2019).

However, even after a person has developed task-specific sensitivity to the stimulation pattern that supports performance of a given perceptual or behavioral task, they must discover how to use that stimulation pattern to perform that task across a variety of circumstances. That is, they must *calibrate* their use of this stimulation pattern to perform the task under a particular set of circumstances and *recalibrate* their use of that variable as circumstances change (Jacobs & Michaels, 2007). Whereas developing sensitivity to invariant stimulation patterns makes it possible to perform a given perceptual or behavioral task under any set of circumstances, calibration of performance to that invariant stimulation pattern makes it possible to perform that task under a particular set of circumstances.

Calibration is a continual process of fine-tuning the scaling relationship between an informative stimulation pattern and performance of a given perceptual or behavioral task. Accordingly, calibration can occur relatively quickly (e.g., on the order of minutes), but typically requires experiences in addition to the performance of the task itself, usually in the form of implicit or explicit feedback about performance (Adolph & Avolio, 2000; Jacobs & Michaels, 2006; Stephen & Azramarski, 2009; Wagman, McBride, Trefger, 2008; Wagman, Shockley, Riley, & Turvey, 2001).

The Transfer of Recalibration Paradigm

A more complete understanding of the process of calibration requires a more complete understanding of the stimulation patterns to which people become calibrated in the process of performing a given perceptual or behavioral task. That is, it requires a more complete understanding of the invariant stimulation patterns that support the successful performance of a particular perceptual or behavioral task. One methodology by which to develop such an understanding is *the transfer of recalibration paradigm*. In this paradigm, participants repeatedly perform a particular perceptual or behavioral task and are given (implicit or explicit) feedback about their performance in that task. This feedback calibrates their use of the invariant stimulation pattern that supports performance in that task. For example, a person may walk toward a visible target and be given feedback about how their walking path deviates from the location of the target. This feedback would allow them to calibrate their use of the invariant optical stimulation patterns that support the performance of that task. Then, that same person might be asked to perform a perceptual or behavioral task that differs in one or more specific ways from the initial task. It might be an entirely different task, the same task using a different set of anatomical components (that differ in sensitivities or capabilities), or the same task using the same set of anatomical components but coordinated or configured in a different way. For example, they might be asked to turn in place to face a visible target, throw a ball toward a visible target, or crawl toward a visible target (cf., Bruggeman & Warren, 2010; Reiser et al., 1995; Withagen & Michaels, 2002).

The degree to which calibration transfers from the first task to the second task is expected to reveal the degree to which the stimulation pattern that the person has become calibrated to (as a result of feedback provided in the first task) is independent of (or invariant across) the differences in the two tasks. In other words, it is expected to reveal the degree to which the stimulation pattern that supports performance of each task is independent of circumstances such as (1) the overarching task goal, (2) the sensitivities or capabilities of the anatomical components used to perform the task, or (3) the coordination and configuration of such components.

In general, studies using this methodology have shown that the stimulation patterns to which people become calibrated depends on—is specific to—the overarching goal of the task but is independent of—is invariant across—circumstances including (1) the sensitivities or capabilities of the anatomical components used to perform that task and (2) the coordination or configuration of such components. For example, calibration to the optical stimulation pattern that supports walking toward a visible target transfers to crawling toward a visible target, but not turning in place to face a target, or throwing or kicking a ball to a target (Bruggeman & Warren, 2010; Reiser et al., 1995; Withagen & Michaels, 2002).

In short, studies such as these have shown that performing a given perceptual or behavioral task under a given set of circumstances requires that a person develop task-specific sensitivity to stimulation patterns that are invariant across circumstances – including the sensitivities, capabilities, and/or configuration of anatomical components used to perform that task (Blau & Wagman, 2023; Turvey, 2019).

Perception of Properties of a Wielded Object

Many everyday perceptual or behavioral tasks are performed with objects that are hefted or wielded by muscular effort. This kind of everyday manipulation of handheld objects is known as effortful or dynamic touch (Carello & Turvey, 2015, 2017). People can perceive many different geometric and functional properties of a given occluded object when wielding that object with a particular set of anatomical components. For example, when wielding a given object with the hand and wrist, people can perceive its length, width, shape, orientation, and heaviness, as well as whether and how that object might be used to perform many different behavioral tasks (Carello & Turvey, 2015, 2017; Wagman, Blau, & Duffrin, 2023).

Moreover, people can perceive a given property of an occluded object when wielding that object by different (sets of) anatomical components or different configurations of a given set of anatomical components. For example, people can perceive the length of an object that is wielded by either hand, both hands, one hand and one knee, a foot, the torso, or even the head (Carello et al., 1992; Hajnal et al., 2007; Palatinus et al., 2011; Wagman et al., 2017). Finally, people can perceive a given property of an occluded object when wielding that object in different media. For example, people can perceive the length of an object that is wielded in air or water (Cabe & Pagano, 2003; Manalgam et al., 2017; 2018).

When hefting or wielding a given object, there are (at least) two sources of mechanical forces at play – muscular forces that generate the movement of the object, and inertial forces that result from the movement of the object. Together, these mechanical forces create patterns of deformation that span skin, muscles, and connective tissue. Studies have systematically demonstrated that perceiving a given property of a wielded object requires task-specific sensitivity to patterns in this mechanical stimulation that are invariant across circumstances. These circumstances include the sensitivities, capabilities, coordination, or configuration of anatomical components used to perform that task, as well as the medium through which such patterns are generated and propagated (see Carello & Turvey, 2017, 2015; Turvey & Fonseca, 2014).

Research using the transfer of recalibration paradigm has generally corroborated these findings. For example, calibration to the mechanical stimulation patterns that support perceiving the length of a wielded object transfers across the anatomical component used to wield the object – from one hand to the other (Withagen & Michaels, 2004), and from hand to foot, and vice versa (Stephen & Hajnal, 2011). Moreover, calibration to such stimulation patterns transfers to other means of perceiving the length of that object, such as listening to the sound that the object makes when it strikes a surface—such as when it clatters to the floor (Wagman & Abney, 2012, 2013).

Perception by Means of a Wielded Object

Just as people can perceive many different properties of a wielded object, they can perceive many different properties *with* or *by means of* a wielded object by using that object to explore (probe, prod, or poke) surrounding surfaces. For example, when probing one or more occluded surfaces with an object wielded by hand, people can perceive how far away a given surface is (Carello et al., 1992; Wagman et al., 2020), how wide a gap is between two surfaces (Barac-Cikoka & Turvey, 1991, 1995), and whether and how they might be able to perform behaviors with respect to that surface (e.g., Wagman & Hajnal, 2014a, 2014b, 2016; see Pagano & Day, 2019; Wagman & Chemero, 2014).

Similarly, people can perceive a given property of a surface when exploring it with an object wielded by different (sets of) anatomical components, or by different configurations of a given set of anatomical components. For example, people can perceive how far away a surface is by exploring it with an object held in their hand or attached to their foot (Carello et al., 1992), or by plucking a taut string attached to that surface (Kinsella-Shaw & Turvey, 1992). People can also differentiate between how far away a given surface is and how long the wielded object used to explore that surface is—and they can do so both when the object is wielded by the hand and when the object is wielded by the foot (Wagman et al., 2020).

When exploring a given surface with a wielded object, there are (at least) three sources of mechanical forces at play. In addition to the muscular forces that generate the movement of the object and the inertial forces that result from the movement of the object, there are also the impact forces that result from the contact between the object and the surface. Together, these mechanical forces create a pattern of deformation in bodily tissue such as skin, muscles, and connective tissue. Given that invariant patterns of mechanical stimulation support perception of properties *of* wielded objects, it is likely that these patterns also support perception of properties *by means of* wielded objects (Carello & Turvey, 2015, 2017; Turvey & Fonesca, 2014; Wagman et al., 2014).

The studies just described provide preliminary evidence that this is the case. In particular, they provide preliminary evidence that perceiving a given property by means of a wielded object requires task-specific sensitivity to patterns of mechanical stimulation that are likewise invariant across circumstances—including the sensitivities, capabilities, and/or configuration of anatomical components used to perform that task, and the medium through which such patterns are propagated (Carello et al., 1992; Stephen & Azramarski, 2009; Wagman & Taylor, 2005; Wagman et al., 2020).

Perception by means of the Enactive Torch

Studies using a device known as the Enactive Torch (henceforth, ET) have provided preliminary evidence that the patterns of mechanical stimulation that support perception of properties by means of wielded objects are invariant across the medium through which such patterns are generated and propagated. The ET is a handheld, vibrotactile sensory substitution device (SSD). It uses infrared range sensors to measure the distance of a given surface (at ranges up to 1.2 m) (Froese et al., 2012). Distance information is converted into vibrations generated by a motor that can be attached to the wrist of the user. The intensity with which the motor vibrates is inversely proportional to the distance of the surfaces detected (see Figure 1). Thus, when a person uses the ET to explore a surface that is relatively far away, it will elicit a weaker vibration in the motor than when they explore a surface that is relatively nearby. By exploring surrounding surfaces with the ET, the user can obtain information about the layout of those surfaces. In this way, the ET is akin to a digital version of the traditional long white cane.

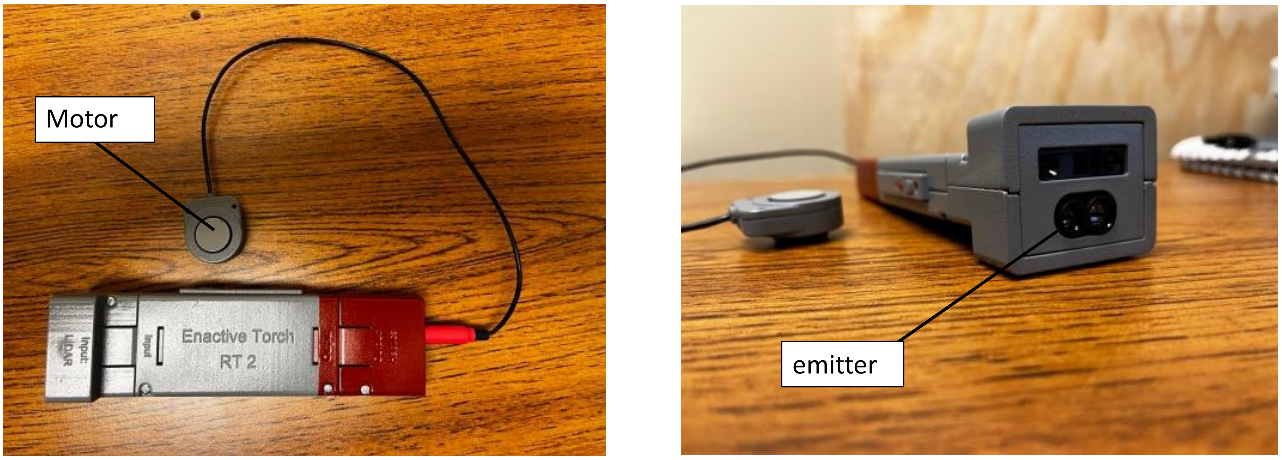

Figure 1. The Enactive Torch.

Research has shown that, with minimal practice, blindfolded people can use the vibrotactile information about the distances of the surrounding surfaces provided by the ET to perform relatively complex perceptual or behavioral tasks, such as navigating an obstacle maze or hitting an approaching ball (Cancar et al., 2013; Froese et al., 2012; Grandon et al., 2018; Maidenbaum et al., 2014). Other studies have shown that blindfolded people can use the ET to determine whether they would be able to walk through a gap between two surfaces (Favela et al., 2018), and that performance in this task is no different than when people explore the two surfaces with a wooden rod.

The stimulation patterns that are most useful for a person performing a particular perceptual or behavioral task are those that are invariant—that remain unchanged across changing context or circumstances (Blau & Wagman, 2023; Turvey, 2019). Previous research has provided preliminary evidence that perceiving a given property of surrounding surfaces by means of a wielded object requires task-specific sensitivity to invariant patterns in mechanical stimulation (e.g., Wagman & Hajnal, 2014 a, b; 2016). Studies using the ET have provided preliminary evidence that such patterns are invariant across the *medium* through which such mechanical stimulation is generated or propagated (e.g., Favela et al., 2018, 2021). The current experiment used a transfer of recalibration paradigm to further investigate the extent to which this is the case. Specifically, we investigated transfer of recalibration to the invariant patterns in mechanical stimulation that support perceiving surface distance by means of a wooden rod (hereafter, "rod") and an ET.

We chose to study this property, and these two means of exploring the surface, for three reasons. First, studies have shown that surface distance is perceivable by means of a rod that is wielded by anatomical components with varying sensitivities and capabilities (Carello et al., 1992; Wagman, Hartling, & Mason, 2020), as well as by means of vibrotactile SSDs such as the ET (Grespan et al., 2008; Maidenbaum et al., 2014). Second, studies explicitly comparing perception by means of a rod and an ET have provided preliminary evidence that the patterns of mechanical stimulation that support perception of properties by means of a wielded object are invariant across the medium through which such patterns are generated or propagated (Favela et al., 2018; Kinsella-Shaw & Turvey, 1992). Third, studies have demonstrated both recalibration and transfer of recalibration in perceiving the length of a wielded object—a task that is analogous to perceiving surface distance by means of a probe. In short, we investigated perception of this property by these particular means to evaluate the general hypothesis that the stimulation patterns of relevance to performing a given perceptual task are invariant across the medium through which such patterns are generated or propagated.

The experiment consisted of a pretest, a practice session, and a posttest (see Figure 2). In the pretest, all participants perceived the distance of an occluded surface by exploring it with both a rod and an ET (on separate blocks of trials). During the practice session, participants performed only one of these tasks. That is, half of the participants perceived the distance of an occluded surface by exploring it with a rod, and the other half perceived the distance of the same occluded surface by exploring it with an ET. Within each of these groups, half of the participants received inflated feedback (1.5 × actual surface distance) after every practice trial and half received no feedback.

Inflated feedback was provided during the practice session (1) to increase the potential for recalibration during the practice session, and (2) to avoid conflating recalibration based on feedback with other changes in perceived surface distance that might occur with repeated experience in a given perceptual task[1] (cf. Stephen & Hajnal, 2011). The posttest was identical to the pretest. That is, during the posttest, all participants perceived the distance of the occluded surface by exploring it with both a rod and the ET on separate blocks of trials.

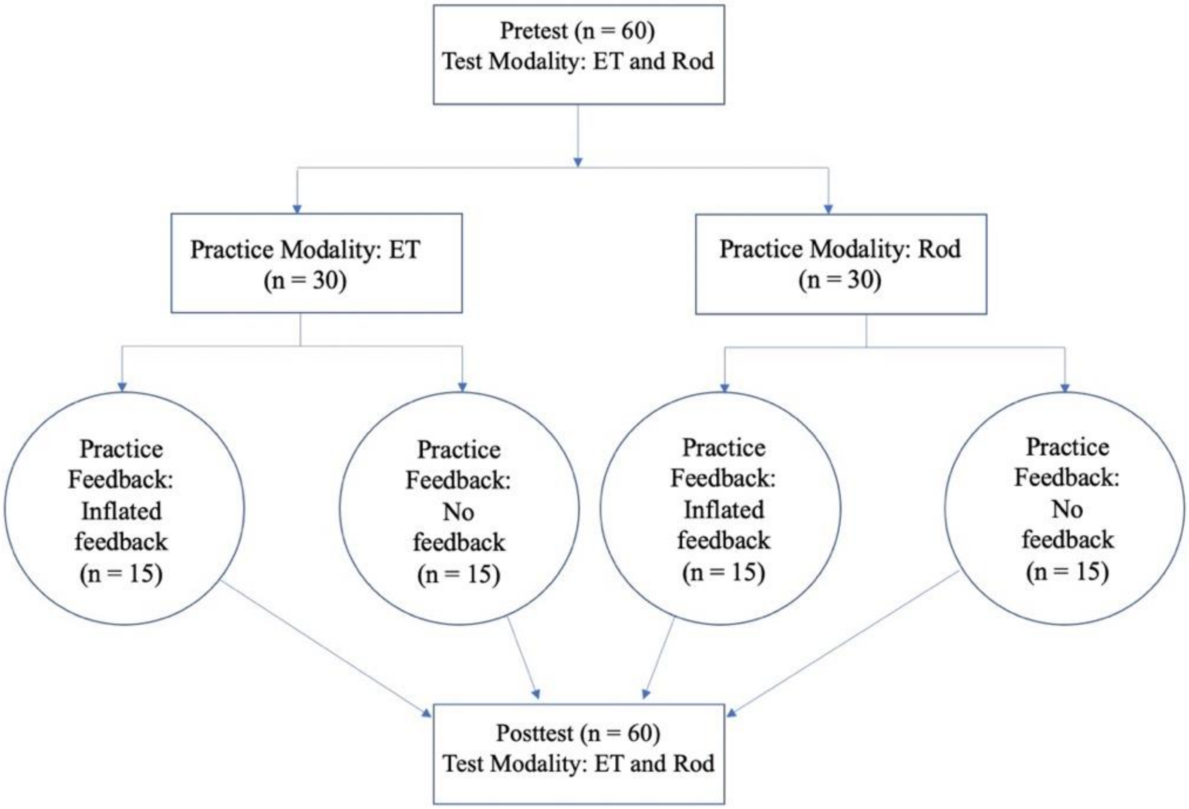

Figure 2. The experimental design.

We assessed calibration and transfer of calibration in two different ways. First, we investigated whether perceived surface distance changed from pretest to posttest – if so, by how much, and under what conditions. For this test, we compared ratios of perceived surface distance

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[1] It is possible that perceived surface distance could more closely reflect actual surface merely by virtue of practice performing the perceptual task, even in the absence of explicit feedback. It is unlikely that perceived surface distance would more closely reflect 1.5 × surface distance under such circumstances, however.

to actual surface distance in the pretest and the posttest. Second, we investigated how and why such changes occurred—specifically, whether they were due to changes in scaling (i.e., the mapping between perceived and actual values), changes in offset (i.e., a consistent tendency to over- or underestimate), or both. To examine these possibilities, we computed regression lines, with perceived length as the dependent variable and actual length as the independent variable for each participant for each modality in the pretest and posttest. Changes in the slopes and intercepts of these lines from pretest to posttest were used to quantify any changes in scaling and offset, respectively (see Cabe & Wagman, 2010; Wagman & Abney, 2012, 2013).

Recalibration of perception typically requires experiences in addition to the perceptual task itself, usually in the form of implicit or explicit feedback about performance. Therefore, we expected that there would be recalibration of perceived surface distance within each modality (rod and ET, respectively), but only for those participants who received inflated feedback during practice[2]. Given that we expected that patterns that support perceiving surface distance by means of a wielded object are invariant across the medium through which (or by which) such patterns are generated and propagated, we also expected that there would be a complete transfer of recalibration across modalities (from ET to rod and vice versa).

Therefore, we expected that (1) mean ratios of perceived to actual surface distance would be larger in the posttest than in the pretest for all Test Modality and Practice Modality conditions, but only in the Inflated Feedback condition and (2) mean slopes of the regression lines plotting the relationship between perceived and actual surface distance would be larger in the posttest than in the pretest for all Test Modality and Practice Modality conditions, but only in

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[2] Given that feedback was inflated (rather than veridical), we expected that such recalibration would generally be observed as increases in perceived distance from pretest to posttest.

the Inflated Feedback condition. Finally, given that we expected such changes to be the result of a rescaling of the relationship between a mechanical stimulation and perceived distance (and not merely a post-hoc adjustment of perceived length values), (3) we expected that these changes would not be accompanied by changes in the intercepts of the regression lines from pretest to posttest in any condition.

CHAPTER II: THE EXPERIMENT

Participants

We conducted an *a priori* power analysis using the G*Power program (Faul et al., 2007). Assuming a small to medium effect size ($f = 0.15$), G*Power suggested that a sample size of approximately 60 participants would be sufficient to achieve power of 0.80, given the experimental manipulations and expected patterns of results.

Sixty undergraduates from Illinois State University participated in exchange for credit in psychology courses. Each participant provided written consent prior to participation. The protocol was approved by the Illinois State University Institutional Review Board in accordance with the Declaration of Helsinki.

Materials and apparatus

Each participant sat in a right-handed student desk. They placed their right arm on the desk and their right hand through a small opening in an occlusion curtain. A thin wooden board (120 cm tall × 60 cm wide) was affixed to the front face of a cardboard box (approximately 120 cm tall × 60 cm wide × 45 cm deep), secured on a wheeled dolly such that the wooden surface was flush with the edge of the dolly and oriented vertically. The dolly was rolled along the floor so that the surface could be positioned at a given distance from the edge of the desk (and the zero point of the report apparatus). Each participant explored the surface with a rod (1.2 cm in diameter; 100 cm long, 81.4 g) and/or the ET (RT 2.0, Creative Robotics; length: 15.8 cm; width: 5.8 cm; height: 4.6 cm; weight: 350 g) (see Figure 3, left). Two Velcro straps secured the vibrotactile motor of the ET to the underside of the participant's wrist.

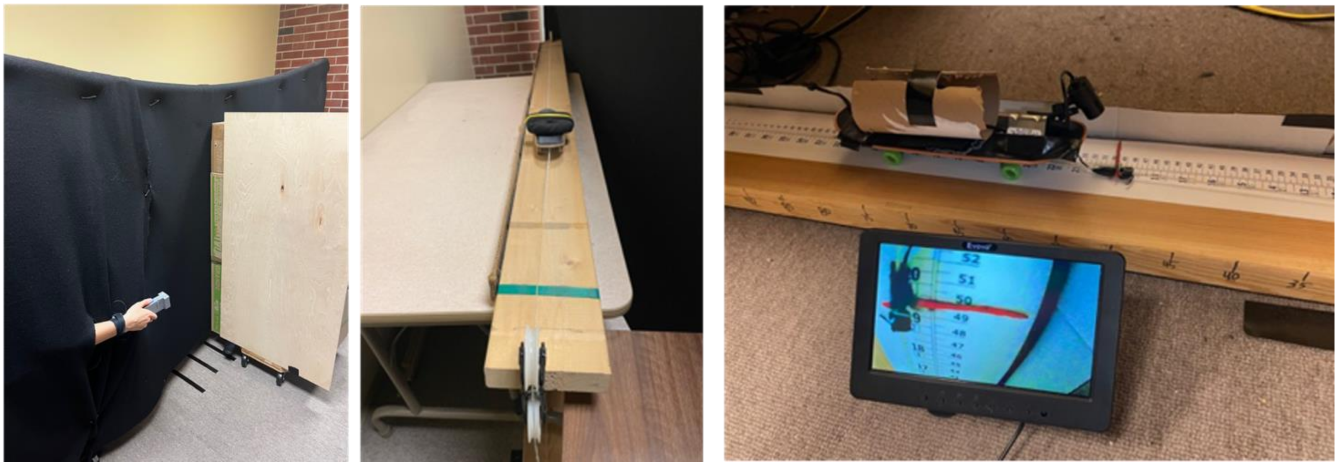

Figure 3. The experimental apparatus. Participants explored the surface with the Enactive Torch or a rod (left) and reported the perceived distance of that surface by adjusting the distance of a movable marker on a skateboard on the upper report apparatus (center). The experimenter recorded measurements of perceived surface distance from a monitor connected to a camera on a skateboard on the lower (occluded) report apparatus.

Each participant made perceptual reports using the upper portion of the apparatus. The upper portion of the apparatus consists of a marker mounted on a toy skateboard that can be moved toward or away from the edge of the desk with a pulley, along a 240-cm horizontal track on a large rectangular table. The participant made perceptual reports by using their left hand to move the marker so its distance from the edge of the desk (and the zero point of the apparatus) corresponded to perceived surface distance (see Figure 3, middle).

The lower portion of the report apparatus was under the table and was not visible to the participant. It consists of a small camera, mounted on another toy skateboard, that moves along a tape measure affixed to a plank on the laboratory floor (see Figure 3, right). The movements of the two skateboards were yoked such that as a participant moved the marker a particular distance along the track on the upper portion of the report apparatus, the camera moved that same distance on the tape measure on the lower portion of the report apparatus.[3] Images from the camera were displayed on a small monitor from which experimenters recorded participants' reports of perceived distance on each trial.

Design

We used a 2 (Test: Pretest vs. Posttest) × 2 (Test Modality: ET vs. Rod) × 2 (Practice Modality: ET vs. Rod) × 2 (Practice Feedback: Inflated feedback vs. No feedback) mixed design. Test and Test Modality were within-participant variables, while Practice Modality and Practice Feedback were between-participant variables.

During both the pretest and the posttest, participants explored the surface with the rod and the ET, and attempted to perceive the distance of that surface, on separate blocks of trials. During the practice session, half of the participants explored the surface with the rod, while the other half did do so with the ET only. Within these two groups, half of the participants received inflated feedback after every practice trial, and half received no feedback. The posttest was identical to the pretest.

Procedure

Before beginning the experimental protocol, each participant was provided the opportunity to explore the door of the laboratory with both the rod and the ET from two distances: 40 and 70 cm.

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[3] No explicit measures were taken to prevent the participant from hearing the contact between rod and surface· Previous research has failed to show any effect of acoustic information incidental to mechanical contact with a surface on perception by means of dynamic or effortful touch (Burton, 2000; Carello Fitzpatrick, & Turvey, 1992).

Pretest. Participants placed their right forearm on the desk and hand through the occlusion curtain so that their right wrist was aligned with the edge of the desk and the zero point of the apparatus. The experimenter placed either the rod or the ET in the participant’s hand, depending on the Test Modality condition. In either case, the object was placed in the participant’s hand so that one end was flush with the bottom of the fist and the object was oriented vertically. In the case of the ET, the experimenter secured the vibrotactile motor to the underside of the participant’s wrist using Velcro straps. Then the experimenter positioned the vertical surface at one of four distances (35, 50, 65, 80 cm) from the zero point of the apparatus. The participant then used the wielded object to explore the surface and attempted to perceive the distance of that surface. Participants reported the perceived distance of the surface by adjusting the report apparatus as described above.

Exploration of the surface was not restricted in any way except that participants were asked to maintain a firm grip on the object and to refrain from lifting their forearm off the desk. Participants explored the surface as long as necessary and were able to continually adjust the distance of the marker while exploring the surface. On a given trial, after participants finished adjusting the marker, the experimenter recorded the measurement displayed on the monitor, then asked the participants to return the marker to the zero point of the apparatus, and reoriented the object to the vertical position. Then, the next trial began. Each surface distance was presented twice in random order in each Test Modality condition, and order of Test Modality conditions was counterbalanced across participants.

Practice. Following the pretest, all participants completed a practice session using the same four surface distances as in the pretest. Participants assigned to the Rod Practice modality condition explored the surface with the rod (and attempted to perceive the distance of that surface), and participants assigned to the ET Practice Modality condition did so with the ET. Within each of these conditions, participants in Feedback Conditions received inflated feedback after every trial. After participants finished adjusting the marker on a given trial, the experimenter readjusted the marker such that the distance of the marker from the edge of the desk (the zero point of the apparatus) corresponded to 1.5 × the distance of the surface (e.g., when the surface distance was 35 cm, the feedback indicated that the surface distance was 52.5 cm). Participants in the No Feedback condition did not receive any feedback. Surface distances were presented twice in random order in each Practice Modality condition.

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

Results

Ratio Values

We computed ratio values by dividing mean perceived surface distance in the posttest by mean perceived surface distance in the pretest for each distance, condition, and participant. Ratios less than 1.0 indicate that perceived distances were underestimated relative to actual distance, and ratios greater than 1.0 indicate that perceived distances were overestimated relative to actual distance.

A 2 (Test: Pretest vs. Posttest) × 2 (Test Modality: ET vs. Rod) × 2 (Practice Modality: ET vs. Rod) × 2 (Practice Feedback: Inflated Feedback vs. No Feedback) mixed-design analysis of variance (ANOVA) was conducted on ratio values. A main effect of Test, $F(1, 56) = 14.20$, $p < .001$, $\eta_p^2 = .20$, showed that overall, ratio values were larger (surface distance was underestimated to a lesser degree) in the posttest ($M = .99$, SD = 0.13) than in the pretest ($M = .88$, SD = 0.12). A main effect of Test Modality, $F(1, 56) = 5.17$, $p < .05$, $\eta_p^2 = .09$, showed that overall, ratios were larger (surface distance was underestimated to a lesser degree) with the Rod

(*M* = .97, SD = .11) than with the ET (*M* = .89, SD = .14).There was also an interaction of Test × Practice Feedback, $F(1, 30) = 12.07$, $p < .001$, $\eta_p^2 = .18$, suggesting that the differences in ratio values across the two Test conditions (Pre vs. Post) differed across the two Practice Feedback (No Feedback vs. Inflated Feedback) conditions. However, this two-way interaction was superseded by a four-way interaction of Test × Test Modality × Feedback × Practice Modality, $F(1, 60) = 4.32$, $p < .05$, $\eta_p^2 = .07$. There were no other significant effects (all other *p*s > .05).

Follow up ANOVAs were conducted to further investigate the significant four-way interaction. In particular, four separate 2 (Test: Pretest vs. Posttest) × 2 (Test Modality: ET vs. Rod) ANOVAs were conducted—one on the ratio values from each combination of the Practice Modality and Practice Feedback conditions (Practice Modality: ET vs. Rod; Feedback: Inflated Feedback vs. No Feedback) (See Figure 4).

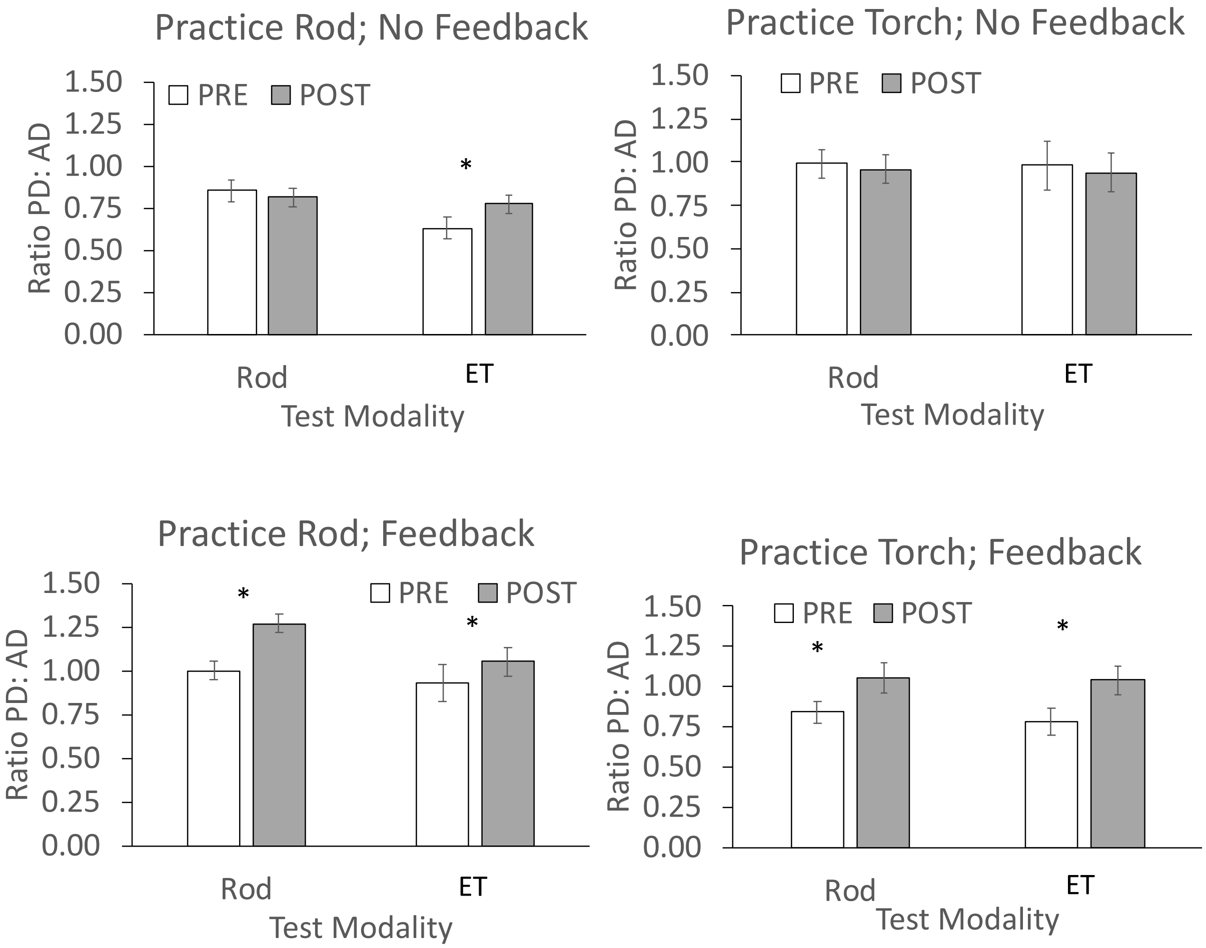

*Figure 4. Ratios of perceived length in the pretest and the posttest for the four combinations of Practice Modality and Feedback conditions. * indicates significant differences in follow up t-tests, with Bonferroni corrections.*

No Feedback condition. The first follow up ANOVA was conducted on ratio values from conditions in which participants practiced with the rod and received no feedback (i.e., Rod Practice Modality; No Feedback). In this ANOVA, there was a main effect of Test Modality, $F(1, 14) = 11.65$, $p < .05$, $\eta_p^2 = .45$, and an interaction of Test Modality and Test, $F(1, 14) = 10.66$, $p < .05$, $\eta_p^2 = .43$. Follow up t-tests with Bonferroni corrections revealed that in this combination of Feedback and Practice Modality conditions, ratio values increased from pretest to posttest for the ET (pre: *M* = 0.63, SD = 0.24; post: *M* = 0.78, SD = 0.22), *t*(14) = 2.15, $p < .05$, but not for the Rod (pre: *M* = 0.85, SD = 0.24; post: *M* = 0.81, SD = .20), *t*(14) = 0.87, *ns (see Figure 4, top left).*

The second follow up ANOVA was conducted on ratio values from conditions in which participants practiced with the torch and received no feedback (i.e., ET Practice Modality, No Feedback). In this ANOVA, there were no significant effects (see Figure 4, bottom left).

Inflated Feedback condition. The third follow up ANOVA was conducted on ratio values from conditions in which participants practiced with the rod and received inflated feedback (i.e., Rod Practice Modality, Inflated Feedback). In this ANOVA, there was a main effect of Test Modality, *F*(1, 14) = 12.81, $p < .05$, $\eta_p^2 = .48$. Overall, for this combination of Feedback and Practice Modality conditions, ratio values increased from pretest (*M* = 0.97, SD = 0.28) to posttest (*M* = 1.16, SD = 0.05). Neither the main effect of Test Modality nor the interaction of Test × Test Modality was significant (see Figure 4, top right).

The fourth follow up ANOVA was conducted on ratio values from conditions in which participants practiced with the torch and received inflated feedback (i.e., ET Practice Modality, Inflated Feedback). In this ANOVA, there was a main effect of Test Modality, *F*(1, 14) = 20.33, $p < .05$, $\eta_p^2 = .59$ Overall, for this combination of Feedback and Practice Modality conditions, ratio values increased from pretest (*M* = 0.81, SD = .25) to posttest (*M* = 1.04, SD = .35). Neither the main effect of Test Modality nor the interaction of Test × Test Modality was significant (see Figure 4, bottom right).

Regression Statistics

We computed regression lines—with perceived surface distance as the dependent variable and actual surface distance as the independent variable—for each condition and participant. At the level of the mean data, there was a linear relationship between perceived surface distance and actual surface distance in all conditions (see Figure 5).

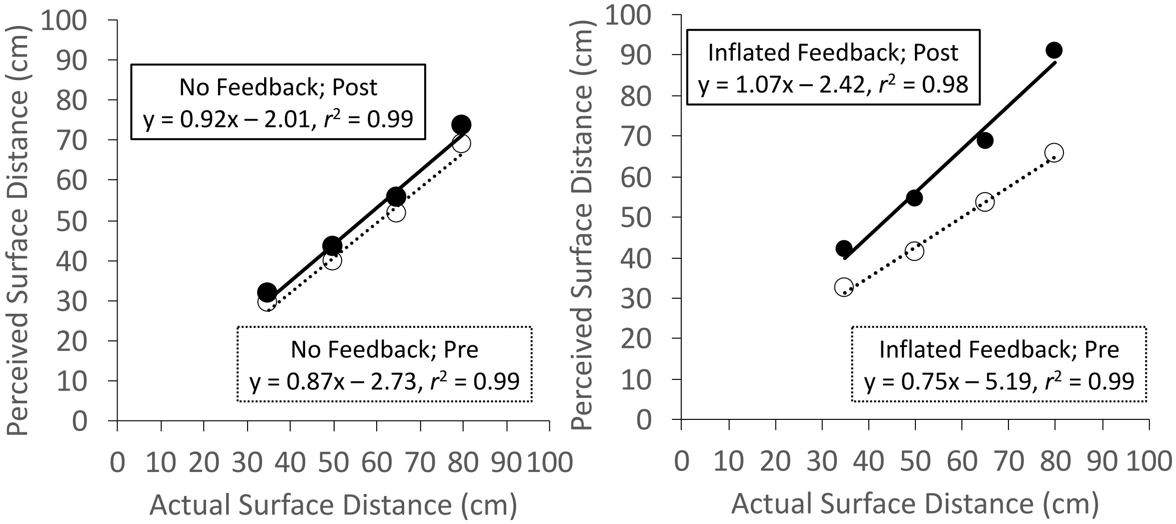

Figure 5. Linear regression of perceived surface distance on actual surface distance for the No Feedback condition (left) and the Inflated Feedback condition (right).

At the level of the individual participant data, two separate 2 (Test: Pretest vs. Posttest) × 2 (Test Modality: ET vs. Rod) × 2 (Practice Modality: ET vs. Rod) × 2 Practice Feedback (Inflated Feedback vs. No Feedback) mixed-design ANOVAs were conducted—one on the slope values and one on the intercept values.

Slope. For the ANOVA on slope values, there was a main effect of Test, $F(1, 56)$ = 20.17, $p < .001$, $\eta_p^2 = .27$. Overall, slopes were larger in the Inflated Feedback condition (M = 0.91, SD =.19) than the No Feedback Condition (M = .89, SD = 0.17). There was also an interaction of Test × Feedback, $F(1, 56) = 10.90$, $p < .05$, $\eta_p^2 = .16$. Follow up t-tests with Bonferroni corrections showed that slopes increased from pretest to posttest in the Inflated Feedback condition (pre: $M = 0.75$, SD = 0.23; post: $M = 1.07$, SD = 0.23), $t(14) = 5.50$, $p < .05$, but not in the No Feedback Condition (pre: $M = 0.875$, SD = 0.203; post: $M = 0.92$, SD = 0.22) $t(14) = 0.80$, *ns*. The ANOVA showed no other significant main effects or interactions (see Figure 6).

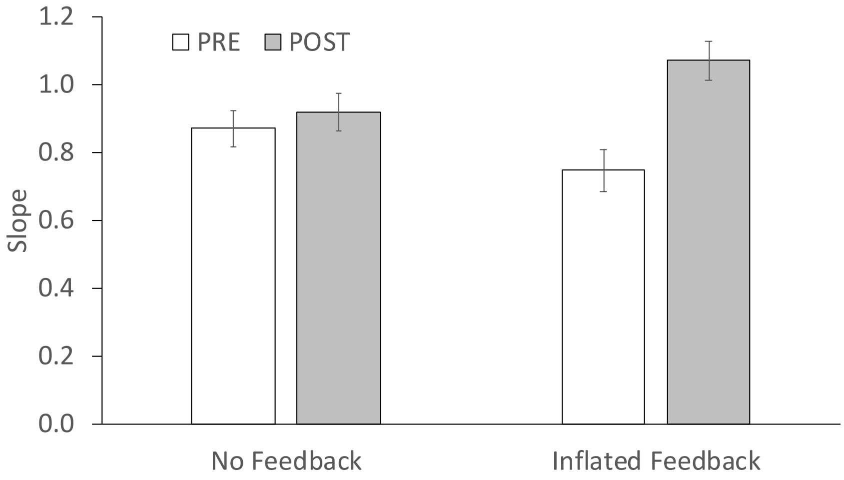

Figure 6. Mean slope values in the pre- and posttest in the No Feedback and Inflated Feedback conditions.

Intercept. For the ANOVA on intercept values, there was an interaction of Test × Test Modality × Feedback, $F(1, 56) = 5.21$, $p < .05$, $\eta_p^2 = .09$. The ANOVA showed no other significant main effects or interactions.

Follow up ANOVAs were conducted to further investigate the significant three-way interaction. In particular, two separate 2 (Test: Pretest vs. Posttest) × 2 (Test Modality: ET vs. Rod) ANOVAs were conducted—one on intercepts in the No Feedback Condition and one in the Feedback Condition. In the ANOVA on intercepts in the No Feedback condition, there were no significant effects. In the ANOVA on the intercepts in the Feedback condition, there was an interaction of Test × Test Modality, $F(1, 14) = 11.2$, $p < .05$, $\eta_p^2 = .44$. Follow up t-tests with Bonferroni corrections showed that, in the posttest, intercept values were larger for Rod (M = 6.8, SD = 13.4) than for ET (M = -1.9, SD = 14.6), t (14) = 3.756, p < .05 (see Figure 7).

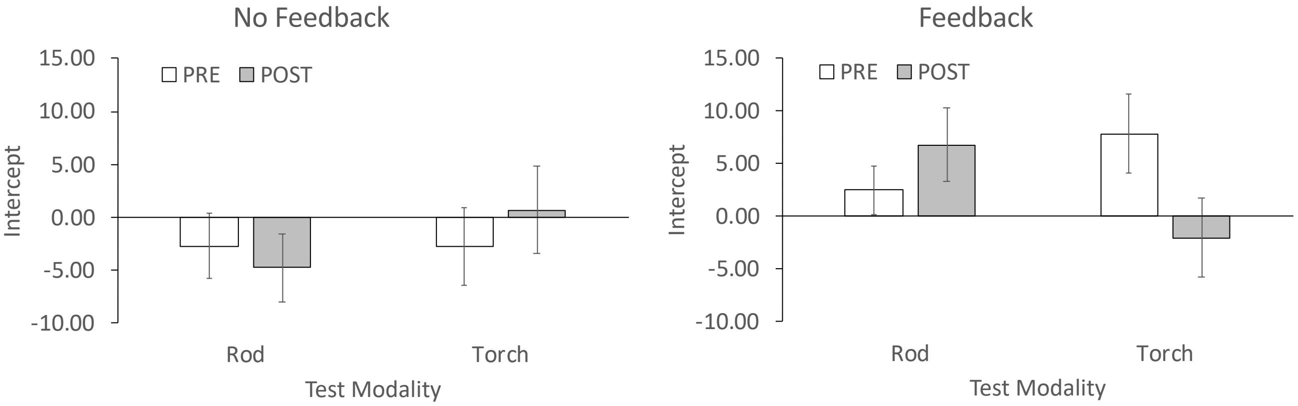

Figure 7. Mean intercept values in the pretest and the posttest for the No Feedback condition (left) and the Feedback condition (right).

CHAPTER III: GENERAL DISCUSSION

Previous research has shown that perceiving properties of surrounding surfaces by means of a wielded object requires task-specific sensitivity to invariant patterns in mechanical stimulation. Studies using the ET have provided preliminary evidence that such patterns are invariant across the medium through which such mechanical stimulation is generated or propagated (Favela et al., 2018, 2021; Froese et al., 2012). The current study used a transfer of recalibration paradigm to further investigate whether this is the case. Specifically, we investigated transfer of recalibration to the invariant mechanical stimulation patterns that support perceiving surface distance by means of a rod and an ET.

We had three main hypotheses. Given that recalibration of perception typically requires experiences in addition to the perceptual task itself—usually in the form of implicit or explicit feedback—we hypothesized that there would be recalibration of perceived surface distance by both modalities (Rod and ET), but only for participants who received inflated feedback during practice. We expected to observe such recalibration in pretest to posttest increases in both the ratios of perceived surface distance to actual surface distance and in the slopes of the regression lines relating perceived surface distance to actual surface distance.

Second, given that we expected that the patterns that support perceiving surface distance by means of a wielded object would be invariant across the medium through which (or by which) such patterns are generated and propagated, we hypothesized that there would be a complete transfer of recalibration across modalities (that is, there would be a transfer of recalibration from ET to Rod and vice versa).

Third, given that we expected such recalibration to be the result of a rescaling of the relationship between a mechanical stimulation variable and perceived distance (and not merely a post-hoc adjustment of perceived length values), we hypothesized that the pretest to posttest changes in ratio and slopes of the regression lines would not be accompanied by changes in the intercepts of the regression lines.

The overall pattern of results supported the hypotheses. Analysis of both ratio values and slopes of regression lines showed (1) recalibration with inflated feedback and (2) a complete transfer of recalibration, from ET to rod and vice versa. Given that these changes were unaccompanied by pretest to posttest changes in intercept[4], such recalibration (and transfer of recalibration) seemed to be the result of a rescaling of the relationship between a mechanical stimulation and perceived distance and not merely a post-hoc adjustment of perceived length values.

Overall, this pattern of results suggests that the mechanical stimulation patterns that support perceiving properties of surrounding surfaces by means of a wielded object are invariant across the medium through which such mechanical stimulation is generated or propagated (see Favela et al., 2018; 2021; Froese et al., 2012).

The one finding that was inconsistent with our hypotheses was that—under one particular combination of conditions— ratios of perceived surface distance to actual surface distance increased from pretest to posttest even when no feedback was provided. Specifically, this occurred only when participants explored the surface with the ET during the pretest and the posttest but explored the surface with the rod during practice. This suggests that—in this combination of conditions only—there may have been transfer of recalibration *without feedback* in the form of self-training (Abney et al., 2014; Stephen & Arzmarski, 2009). We discuss this possibility in what follows. Notably, though technically inconsistent with our hypotheses, this

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[4] Such changes were accompanied by post-test differences in intercept across Test Modality, but such differences do not bear on the hypotheses of the study, nor do they change the interpretation of the results.

finding is not inconsistent with the main finding that there was a complete transfer of recalibration of perceived surface distance with inflated feedback or with the main conclusion that the mechanical stimulation patterns that support perception of surface properties by means of wielded objects are likely to be invariant across medium.

Invariant stimulation patterns and calibration

The results of the experiment reported here contribute to an understanding of the stimulation patterns to which people become calibrated in the process of performing a given perceptual or behavioral task (especially when provided with feedback about such performance). Previous research has shown that such stimulation patterns are specific to the overarching goal of the task but are independent of—are invariant across—circumstances. When perceiving properties of a surface by means of a wielded object, these circumstances include the sensitivities, capabilities, coordination, or configuration of anatomical components used to do so (Carello et al., 1992; Wagman & Hajnal, 2014a, b, 2016; Wagman et al., 2020).

Together with the results of previous research (Favela et al., 2018), the results of the experiment reported here suggest that these circumstances also include the *medium through which* such patterns are generated and propagated. In the case of perceiving surface properties by means of a wielded object, it is likely the stimulation pattern of relevance is anchored in the mechanical forces that bring about deformation in bodily tissue such as skin, muscles, and connective tissue that occurs when the wielded object is brought into contact with that surface (Wagman & Duffrin, 2023; Wagman et al., 2020). The complete transfer of recalibration of perception of surface distance from ET to Rod (and vice versa) suggests that such stimulation patterns are invariant across the medium by which contact is made with the surface (mechanical or optical) and by which such forces are generated and propagated (by rod or by motor).

The results also contribute to an understanding of the stimulation patterns that support perception in general. In particular, they are consistent with the more general proposal that performing a given perceptual or behavioral task under any set of circumstances requires developing task-specific sensitivity to invariant stimulation patterns (Blau & Wagman, 2023; Turvey, 2019). In this proposal, objects and events lawfully structure patterned energy distributions such that the structure encountered by a given animal (at a given point of observation) provides information about those objects and events. The lawful structuring of stimulation patterns means that the structure in a given patterned energy distribution is lawfully related, though not identical to structure in other energy distributions (Gibson, 1966). Said differently, objects and events analogously structure multiple energy arrays simultaneously, and structure in any one of them may be sufficient to provide information about the object or event that creates that structure. Identifying the lawfully generated stimulation patterns that support perception of a given environmental property with a variety of different perceptual modalities has been the focus of a number of recent studies, and is an important step in better understanding perception in general (e.g., Wagman & Abney, 2012, 2013).

The possibility of self-training in perception by means of effortful touch

The results of the experiment reported here also contribute to an understanding of the conditions under which calibration to informative stimulation patterns can occur. Such calibration typically requires experiences in addition to the performance of the task itself. Usually, such experiences are in the form of implicit or explicit feedback about performance. In the context of perception by effortful touch, this may be feedback from an external source (such as an experimenter) or by a perceptual modality other than the one used to perceive the property (visual feedback on a property perceived by touch). However, while such feedback may be sufficient to bring about calibration, it may or may not be necessary. Rather, research has shown that the touch system may be capable of generating (or revealing) its own mechanical information about a given property of a wielded object that serves to calibrate perception of that property. For example, striking a wielded object against an unseen surface can recalibrate (i.e., serve as self-training for) the perception of length by wielding (Stephen & Arzamarski, 2009). In this case, striking provided access to a set of mechanical variables above and beyond those provided by wielding alone. Similarly, changing grasp position on a wielded object can recalibrate (serve as self-training for) perception of the length of the object (Abney et al., 2014).

The results of the current experiment suggest that self-training can also occur in perception by means of a wielded object. In particular, exploring an unseen surface with a rod can recalibrate (i.e., serve as self-training for) perception of surface distance with an ET. While surface distance can be perceived when that surface is explored with a wooden rod or an ET, it is possible that the mechanical stimulation variables that are relevant to perceiving surface distance are more easily detected when mechanical contact is made between rod and surface than when contact is made between ET and surface. This is an interesting avenue for future research. More studies are needed to address why this might be the case, and whether it is consistent across different contexts.

Tool use, functional transparency, and extended cognition

Part of becoming skillful in using a tool of any kind is a shifting of the user's awareness from *the tool itself* to *what the tool allows them to do with it.* As this occurs, the tool itself becomes *functionally transparent*—it disappears in the user's experience (Pagano & Day, 2019). Although we did not collect data on this phenomenon per se, the ease with which participants could perceive surface distance in both modality conditions, and the fact that calibration transferred both within and across modalities, suggests that the rod and the ET exhibited at least some degree of functional transparency to our participants.

Functional transparency is a powerful demonstration of the notion that cognition is *extended*. To claim that cognition is extended is to claim that external objects (in this case, haptic tools and the surface that was perceived) *constitute* part of the perceptual or cognitive process—at least in the context of performing a given task (Favela, 2019; Favela & Chemero, 2015; Silberstein & Chemero, 2012). Said differently, when functional transparency occurs, the task is performed by a perceptual and cognitive system that *includes* the object rather than by a perceptual or cognitive system that *uses* the object. The implication of this notion is that cognition is not confined to the skin and skull, rather it extends out into the environment. While this may seem like a challenging idea, it is empirically demonstrable (Wagman & Chemero, 2014). Indeed, the current study contributes to this growing body of literature.

The Enactive Torch as a tool for rehabilitation

A number of studies have shown that the vibrotactile stimulation elicited by the ET (and other similar devices) can be used in the context of functional therapeutics and rehabilitation (Jaffe et al., 2004; Maidenbaum, 2014; Priplata et al., 2003). In particular, studies have shown that blindfolded individuals can use the ET to perceive affordances for behaviors such as whether and how they can move through and around surfaces and objects in a cluttered environment (Favela et al., 2018, 2021; Froese et al., 2012). The current study shows that people can use the vibrotactile stimulation elicited by the ET to perceive surface distance, and that this transfers to perception of surface distance by means of a rod (and vice versa). The ET is therefore well suited to support performance of goal-directed behaviors. This makes it a useful tool for rehabilitation (Hartling, 2020).

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