Calibration Is Both Functional and Anatomical

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Bingham and Pagano (1998) described calibration as a mapping from embodied perceptual units to an embodied action unit and suggested that it is an inherent component of perception/action that yields accurate targeted actions. We tested two predictions of this "Mapping Theory." First, calibration should transfer between limbs, because it involves a mapping from perceptual units to an action unit, and thus is functionally specific to the action (Pan, Coats, and Bingham, 2014). We used distorted haptic feedback to calibrate feedforward right hand reaches and tested right and left hand reaches after calibration. The calibration transferred. Second, the Mapping Theory predicts that limb specific calibration should be possible because the units are embodied and anatomy contributes to their scaling. Limbs must be calibrated to one another given potential anatomical differences among limbs. We used distorted haptic feedback to calibrate feedforward reaches with right and left arms simultaneously in opposite directions relative to a visually specified target. Reaches tested after calibration revealed reliable limb specific calibration. Both predictions were confirmed. This resolves a prevailing controversy as to whether calibration is functional (Bruggeman & Warren, 2010; Rieser, Pick, Ashmead, & Garing, 1995) or anatomical (Durgin et al., 2003; Durgin & Pelah, 1999). Necessarily, it is both.

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A classic problem in space perception is perception of metric properties of linear dimension, such as distance and size. The problem originates from the fact that optical information is inherently angular. There are no linear extents in optical pattern that might be described using centimeters or inches (see Bingham and Pagano (1998); Gibson (1966); and Turvey (1977) for discussion.) Visual information that specifies metric linear extents is available, nevertheless, because linear bodily extents are an intrinsic part of the viewing geometry. For instance, the distance of the eyes above a support surface (called Eye Height, EH) is part of the geometry of monocular elevation information (also called height-in-the-visual-field). EH is determined by the seated or standing height of the observer. The elevation angle is formed by the line of sight, relative to the horizontal, when the eye foveates a target object lying at a distance along a level support surface (e.g., the ground). EH is the side of a right triangle that invests the optical elevation angle with both a length dimension and a unit, so elevation specifies distance in EH units.

As another example, the distance between the two eyes (called the Inter-Pupillary Distance, IPD) is part of the viewing geometry of binocular vergence. Vergence angles are formed by the two lines of sight when the eyes foveate on a target object at some distance. IPD is the "side" of the angle-side-angle relation that is the essence of vergence information about distance. This embodied length dimensioned quantity invests the optical information with the ability to specify distance, that is, a metric length dimensioned property. It also yields the unit in which that information is specified, so vergence specifies distance in IPD units.

Units are associated with metric measurements along a dimension. For instance, the length dimension can be measured in feet or alternatively meters. The concept is developed in the literatures on measurement (Duncan, 1953; Ipsen, 1960; Szücs, 1980) and scale engineering (Baker, Westine, & Dodge, 1973; Emori & Schuring, 1977).[1] In our application, distance (a length dimensioned property) is measured in units intrinsic to human perception, either IPD or EH units.

Bingham and Pagano (1998) pointed out that when perceptual information is used to guide targeted actions, like walking, reaching or throwing, the corresponding perceptual units must be mapped to units of action. Targeted actions must also be metric, and thus, must involve units. For instance, the unit of targeted walking might be Stride Length (SL),[2] in which case a target would be acquired by controlling the production of an appropriate number of strides. To achieve this with visual guidance, the unit of visual distance information (e.g., EH) must be mapped to the unit of action (e.g., SL). Bingham and Pagano argued that it is this mapping that requires calibration because it can change. Such changes are governed by dynamics because units are embodied.

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[1] For extended discussion, see Bingham (1995) and references contained therein. Also, see Lockhart (2012) for a more recent informal discussion.

[2] As another example, the unit of targeted reaching has been assumed to be Arm Length (AL) in a number of studies (e.g., Pagano, Grutzmacher, & Jenkins, 2001; Wickelgren, McConnell, & Bingham, 2000).

According to the Mapping Theory of Calibration, calibration is of a mapping from embodied units of perception (like EH and IPD) to embodied units of action (like SL).

These units are embodied (that is, they are both physical and biological) and as such they necessarily entail change in size. Furthermore, different embodied units of perception exhibit differences in their frequency of change or speed of change—that is in their dynamics. The IPD unit changes in size slowly over the course of development and then remains stably unchanging during adulthood. The same is largely[3] true of AL units of reaching or SL units of walking. In contrast, the EH unit changes frequently throughout one's life with change in posture or change in surfaces of support (e.g., floor to table). For instance, when a person changes from seated to standing posture, the EH unit changes. When a person selects foot-ware for the day, choosing between low heeled and high heeled shoes, they also perturb their standing EH unit for the day.

The Mapping Among Embodied Units Theory of Calibration entails a number of predictions that followed from the essential premise of the theory, namely, that what is calibrated is a mapping from embodied units of perception to embodied units of action. The goal of the current study was to test two of these predictions as follows:

(1) Calibration of a given action performed with one limb should generalize or transfer to another limb performing the same action, because the units involved are the same. So, calibration is functional, that is, specific to the type of action.

(2) Limb specific calibration enables adaptation to anatomically specific changes in a limb (injury, weighting of a limb, fatigue, etc.). Units of action are embodied meaning that the anatomy of the limbs contributes to the scaling of such units. For instance, if one arm is longer than the other (or the range of joint motion is restricted), this affects the size of the unit of action for reaching. For instance, what is at maximum reach for one arm will not be for the other. The nature of the unit is the same for both arms, but the size is different. Thus, the arms must be calibrated relative to one another. Calibration is also anatomical.

One of the controversies in studies of calibration is about the relative abstractness of calibration: is calibration fundamentally anatomical or instead, functional? Some studies have provided evidence that calibration is functional, meaning that the task or type of action is calibrated rather than the particular anatomical components used to perform the action (e.g., Rieser, Pick, Ashmead, & Garing, 1995; Withagen & Michaels, 2002, or Bruggeman and Warren, 2010). For instance, Reiser et al. showed that calibration of targeted locomotion generalized from normal forward stepping to side stepping with a change in the anatomical configuration of the musculature required to perform the locomotor task. Similarly, Withagen and Michaels (2002) showed generalization from walking to crawling. Other studies have found evidence of limb specific calibration (e.g., Durgin & Pelah, 1999; Durgin, Fox, & Kim, 2003), supporting the idea that calibration is anatomical. For instance, Durgin et al. showed that calibration of one leg failed to generalize to the other leg used for locomotion. The anatomical specificity approach to calibration extends back to many early studies of prism adaptation, that is, calibration of perceived direction used to control pointing or locomotion (e.g., Harris, 1963, or Redding & Wallace, 1988, although see Bingham and Romack, 1999, for a functional specificity approach to prism adaptation). For instance, Redding and Wallace (1997) provided evidence

that alignment of eyes relative to head and head relative to trunk could be selectively discriminated and realigned through calibration.

A problem with the more recent literature in the functional versus anatomical debate is that almost all of the studies employ varieties of visually guided targeted locomotion. The problem in the context of this particular debate is the specificity of skill and anatomy entailed by locomotion, a problem that applies also to the task of throwing. Skilled locomotion is performed using both legs. The skill extends smoothly or continuously to walking at different orientations, from forward to sideways. This was studied explicitly, for instance, by Warren and Whang (1987). They investigated the perception of aperture widths relative to the need to turn the body while locomoting to be able to pass through an aperture. On the other hand, bipedal locomotion skill does not commonly extend to walking using other limbs, that is, the arms. So, testing the anatomical specificity of calibration is difficult in this case. Similarly, skill in targeted throwing is usually highly developed with a given dominant or preferred arm. Of course, throwing actually does not entail use of only one arm, because the entire body is employed to develop and deploy the kinetic energy imparted to the projectile (Jöris, Muyen, Ingen Schenau, & Kemper, 1985; see Bingham, Schmidt, & Rosenblum (1989) for review and discussion). So, it is this entire asymmetric configuration of the anatomy that is entailed in the skill. In the context of studies of long distance throwing, the striking extent of the anatomical specificity of such skill can be experienced when trying to throw long distance using one's nonpreferred arm. Often, the attempt to throw with the nonpreferred arm yields complete inability to even begin to use or move the arm in an appropriate fashion. Finally, the legs and arms exhibit substantial anatomical differences relevant to, for instance, inability to walk using one's arms or to throw using one's legs (see, e.g., Zhu & Bingham, 2008). In light of such problems, how might one best test this question of functional or anatomical specificity of calibration?

The solution is to use targeted reaching as the relevant task, because people reach readily and often with either the left or the right arm. So, two anatomically comparable limbs can be used with comparable levels of skill to perform the task. Functional versus anatomical specificity of calibration can each be addressed separately and directly. First, functional specificity can be tested using distorted feedback[4] to calibrate targeted reaches performed with one arm and then, reaches can be tested using first one and then, the other arm after calibration. Functional specificity predicts that the distorted calibration should generalize to targeted reaches performed with the uncalibrated arm, because it is the targeted reaching action that is calibrated. Second, anatomical specificity can be tested using distorted feedback to calibrate targeted reaches performed with both arms, but simultaneously calibrating one arm to overshoot targets and the other arm to undershoot targets. The result would be clear limb specific calibration. In response to a target at any single visually specified distance within reach, one arm would reliably over reach and the other would reliably under reach. This would occur strictly as a function of the preceding

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[3] AL or SL units can also change because of injury or other related infrequent perturbations.

[4] Distorted calibration is used so the effect of calibration can be unambiguously detected.

distorted calibration, so it could equally be left arm over shoot and right arm under shoot or the reverse, left under and right over.

Logically, it is possible that only one of these two types of test might yield successful calibration of the limbs revealing that calibration is inherently only functional or anatomical. However, the Mapping Among Embodied Units Theory of Calibration predicts that both must be possible. First, the Mapping Theory predicts that calibration of a targeted action performed with one limb should generalize to performance of that action with another limb. Calibration should be functionally specific because, according to the theory, it is the mapping between units of perception and a unit of action that is calibrated. The calibrated unit of action is intrinsic to the action, not just the limb. However, the Mapping Theory also predicts that anatomically specific calibration is possible, because units of action are embodied. The anatomy of a limb (for instance, the muscles or the length of the limb) thus contributes to the scaling of the unit of action. If one arm has bigger, stronger muscles than the other[5], or is simply longer than the other (due to an injury or a problem in development), then this anatomically specific difference requires calibration. Furthermore, research in dynamic touch has shown that the effect of a weight added to the arm (e.g., a wrist cast or the like) can be to alter the perceived length of the arm (e.g., Solomon & Turvey, 1988). This also would require calibration (Withagen & Michaels, 2004, 2005). If both arms are to be used to perform a task like reaching, then the two arms must be calibrated to one another. Anatomical asymmetries between the two arms could also result from fatigue, the weighting of an arm (e.g., a wrist cast or heavy protective clothing), or use of tools (e.g., a rake used by a dealer or croupier at a roulette table to collect the chips) or a prosthesis. So, the need for anatomically specific calibration would not be unusual. Other investigators (e.g., Bruggeman & Warren, 2010) have acknowledged the possibility that both functionally specific and anatomically specific calibration might be possible, but the reasons why have never been set out explicitly, nor have the two types of calibration been tested explicitly "on a level playing field" with this expectation.

For an observer seated at a table with EH = 24 cm, a target object at a distance of 48 cm will be specified by elevation to be 2 EH units distant. Assuming an arm length unit (AL) for reaching of 48 cm (for simplicity), then, after accurate calibration of targeted reaching, the EH unit would be calibrated as $2 \times EH = AL$. This expresses the functional specificity of calibration if AL is the action unit for reaching. If the left and right arms are of equal length, then $AL = AL_R = AL_L$. On the other hand, if the left arm is shorter[6] than the right arm by 20%, then $AL = AL_R = 1.25 \times AL_L$ ($AL_L = 38.4$ cm). This expresses the anatomical specificity of calibration that requires the arms to be calibrated to one another. If distorted feedback is then used to calibrate over reaching by 10%, then the target object would be $2 \times EH = 1.1 \times AL$ or $\approx 1.82 \times EH = AL$. The target object would still be specified as at a distance of 2 EH units with the result that a reach would overshoot by $0.1 \times AL = 4.8$ cm. Substituting the limb specific calibration relation for the 20% shorter left arm, $1.82 \times EH = (1.25 \times AL_L)$ and for the target at 2 EH, the left arm *overshoots* by $0.1 \times (1.25 \times AL_L) = 0.125 \times AL_L = 4.8$ cm. Notice that 4.8 cm overshoot beyond the actual target distance is 10% of the right arm length and 12.5% of the left arm length. The two arms end up at the same place, but the left arm has to reach proportionally farther by 2.5%. For this outcome, the two arms must be calibrated

accurately to one another as $AL_R = 1.25 \times AL_L$. For this to be possible, it must also be possible for the arms to be inaccurately calibrated to one another. How the two arms are calibrated to one another determines how they behave relative to one another. Using different distorted feedback for each arm, two arms (that are actually equal in AL) could be calibrated to end up in different locations when visually guided to reach to the same visible target distance. This is the expectation of the Mapping Theory.

So, first, action specific (or functionally specific) calibration generalizes to the two limbs alike however they happen to be calibrated to one another. Second, limb specific calibration requires that the two limbs be calibrated to one another. We test the first prediction by calibrating reaching with the right arm using distorted feedback with the expectation that the distorted calibration will generalize to reaches performed with either right or left arm after calibration. We test the second prediction by calibrating reaches performed with each arm with different distorted feedback with the expectation that reaches to the same visually specified target performed with the right and left arm after calibration will end up in different locations (as determined by the different distorted feedback).

Mon-Williams and Bingham (2007) investigated calibration of targeted reaching (see also Bingham (2005); Bingham, Coats, & Mon-Williams (2007), and Coats, Bingham, & Mon-Williams (2008).) Their participants used haptic feedback from contact of hand and object at the end of one reach to calibrate subsequent reaches. The experimenters provided feedback that was initially correct, but then, was increasingly distorted. Participants responded by changing reach distances (with no awareness these changes were occurring or that the feedback was distorted). We now use the same paradigm (apparatus and methods) to investigate the current questions. In Experiment 1, we tested whether calibration of targeted reaches performed with the right arm would generalize to targeted reaches performed with the left arm. That is, is functionally specific calibration possible? In Experiment 2, we tested whether the two arms could be simultaneously calibrated, using distorted feedback, to over reach with one arm while under reaching with the other. That is, is anatomically specific calibration possible? The prediction of the Mapping Theory was that calibration should be specific to the action (and thus, functionally specific) as well as to the embodied unit (and thus, anatomically specific), and thus, both should be possible.

Experiment 1

We tested whether calibration is functionally specific. Distorted haptic feedback was used to calibrate targeted feedforward reaching using the right arm and then, subsequently, targeted reaching

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[5] A past member of the Chinese national badminton team is now a highly ranked player and coach in the United States. The training he had received over his many years in China had been devoted exclusively to his playing arm, with the result that one of his arms is normal while the other is like Popeye! The first issue to be resolved if one was to arm wrestle with this fellow was which arm! Clearly, his arms must be calibrated with respect to one another when used to perform reaching tasks like moving a collection of cups from a drainer by the sink to a shelf above, reaching alternately with either arm and hand.

[6] AL is the maximum distance reachable using only the arm (i.e., no leaning from the waist). One arm might be functionally shorter either because the segments are shorter or because of a limitation in achievable joint angles.

was tested without feedback using the right and then, left arms. The prediction is that the calibration of reaching with the right arm should generalize to reaching with the left arm.

Methods

Participants.   Ten participants (3 females and 7 males) took part in the experiment in the Perception/Action Lab at Indiana University. They were each remunerated at a rate of $10/hr for their time. All participants had normal or corrected to normal vision and were free of motor deficits. Before participating in the experiment, all participants read and signed consent forms approved by the Indiana University Institutional Review Board.

Apparatus.   As shown in Figure 1, the apparatus was the same as used in Mon-Williams and Bingham (2007) adjusted to allow reaching to targets using either left or right arm and hand. Participants sat near the corner of an L-shaped table so that one surface of the table extended in the direction of their sagittal plane and the other arm of the table extended in the direction of the coronal plane to their left. A semisilvered mirror (which reflected 60% of the light and transmitted 40% of the light) extended across the corner of the L so that it was 45° to the line of sight. The mirror was 33.7 cm × 24.3 cm. It was in a black wooden frame supported on a rod that extended upward from the table on the inside of the corner of the L. The top edge of the mirror was at average eye height. We adjusted each participant's eye height to the mirror height by changing the seat height. The bottom edge of the mirror

Figure 1.   Illustration of the apparatus used in these experiments, top and side views. See the text for description.

was 18 cm from the surface of the L-shaped table and, through this gap, participants would extend their arms to reach to objects behind the mirror. A piece of black fabric was attached to the bottom of the mirror and draped over a participant's left shoulder during the experiment to occlude the view of the moving arm during reaching.

Two identical wooden blocks (3.5 cm × 4 cm × 5 cm) were used as the target and feedback objects. On each wooden block, two knobs (1.6 cm diameter and 0.8 cm thickness) were aligned and adhered to the sides of the block. These knobs were where participants should place their thumb and index finger to grasp the object in the experiment. The target object was placed on the table in the coronal plane to the left of the participant and the feedback object was placed on the sagittal arm of the L behind the mirror. Using the semisilvered mirror, target and feedback objects could be placed on the two surfaces so that they appeared coincident and gave the impression that there was a single object. The illusion was absolutely convincing. A black panel was fixed to the back of the semisilvered mirror by a screw at the upper left corner of the mirror. Once lowered, this panel would prevent light from transmitting through the semisilvered mirror and hence, looking through this mirror, the target object would appeared as if located on the sagittal surface behind the mirror extending away from the participant and the feedback object would not be seen. Along the midline of the surface in the sagittal plane and at 16 cm from the edge of the table (where a participant would sit), there was a bump on the surface serving as the starting position, around which the thumb and index finger should be placed at the beginning of each reaching trial.

Reach kinematics were measured using a three-marker Ascension Minibird (Ascension Technology Corporation, Burlington, VT) magnetic measurement system. Movements were sampled at 60 Hz. We calibrated the measurement volume, checking loci every 2 cm in a three-dimensional grid over the reach space. Measurements were reliable and accurate within 1 mm. Using double-sided tape, markers 1.1 cm × 0.8 cm × 0.8 cm were placed on the nail of the left and right index fingers. The wire was held to both the wrist and the forearm with medical tape. The emitter for the measurement system was placed immediately below the wooden table centered in the reach space.

Procedure.   Prior to the experiment, the experimenter placed the feedback object along the midline of the surface in the sagittal plane at 31 cm or 22 cm away from the starting point (which was 16 cm from the near edge of the table, where a participant would sit). She then lifted up the back panel of the semisilvered mirror and carefully placed the target object on the surface in the coronal direction of the L, such that through the 45° angled mirror, image of the target object perfectly coincided with that of the feedback object. The corresponding locations for the target and feedback objects were labeled. Then, she lowered the back panel of the mirror, allowing for only reflection but no transmission of light.

During the experiment, participants first read and signed consent forms. They were then fitted with Mini-Bird markers on the index fingers of both hands. The participants adjusted the seat height and location so that the eyes were aligned with the upper half of the mirror and the participants could extend their arms and comfortably reach to more than 50 cm away from their bodies (the location of the far target). A black cloth was draped over their shoulders to prevent them from seeing their arms. Then, the task and procedure
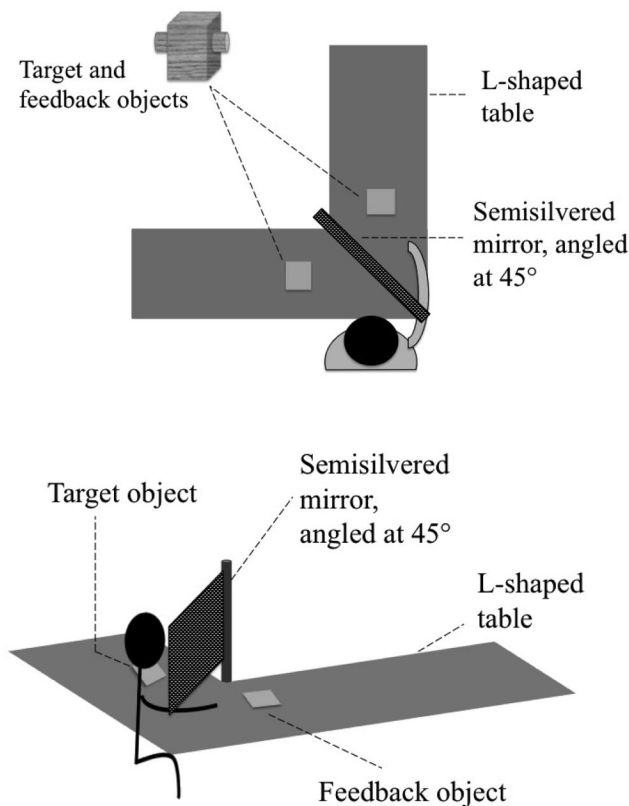
were described. Participants were told to look at the virtual object (the image of the target object) and reach to it. Participants understood that they would be reaching to virtual targets at different distances and that they would be making contact with a real object on some, but not all, trials. If there was an actual object (the feedback object), they were to place their thumb and index fingers on the protruding buttons of the block. If there was no feedback object, they were to hold their hand at the distance of the virtual object as if grasping it by the buttons.

There were three phases in this experiment: Baseline, Feedback, and Snapback. Two distances were tested in all three phases: 22 cm and 31 cm. Reaches were tested in blocks of trials in which both distances occurred once each in a random order, that is, two trials per block. The Baseline condition consisted of a total of 10 blocks of trials, two trials in each block. In the Baseline condition, participants first reached for a virtual target without having an actual feedback object for 3 blocks (i.e., 3 pairs of randomly ordered near and far distances). Then for the next 4 blocks, they reached to both far and near targets, but only received veridical haptic feedback from the near targets. We accurately calibrated their reaching to the near distance. In the next 3 blocks following this, participants reached to near and far distances without feedback. This performance after accurate calibration was recorded and used in analysis as the baseline performance. This was done with both hands and the order in which the hands were calibrated and tested was counterbalanced among participants.

Next, in the Feedback phase, all participants reached with their right hands to the far and near targets for 18 blocks. Each block included one near distance trial and one far distance trial with the order randomized. An actual feedback object provided haptic feedback for reaches to the near objects only. The haptic feedback was gradually distorted: in the first two blocks, the feedback was veridical and then the feedback object was placed 1 cm nearer than the actual near distance (or 1 cm closer to the participant) for the next two blocks (3 and 4), and then again after each succeeding set of two blocks until by 13 and 14, the feedback was shortened by 6 cm from the actual target distance and then this final 6 cm distortion was repeated for 4 more block through block 18. We did not provide any feedback to the reaches to the far target.

Last, in the Snapback phase, participants reached to near and far virtual targets for 6 blocks with the right (calibrated) hand and in 6 blocks with the left (uncalibrated) hand. The order in which the hands were tested were counterbalanced among participants. No feedback was provided to either hand at either distance, that is, only virtual objects were grasped at both distances. This condition is called "snapback" because reaches to the feedback distance are observed to snap back to the same change in proportion to the 6 cm distortion as exhibited at the other distance, a change less that that specified by the distorted feedback due to the lag exhibited in calibration. See Mon-Williams and Bingham (2007) for further discussion.

In all phases, each trial started with the participant's eyes closed and their thumb and index finger of the reaching hand placed on the starting location. The experimenter placed the target object at either near or far locations, started the Minibird sampling and asked the participant to open the eyes and reach. Reaches were performed at a normal speed. The trial ended when the participant had their fingers placed at the (virtual or actual) target and said "done." The participant was told then to close their eyes. Reach

distances were measured by the Mini-Bird marker attached to the index finger of each hand. At the end of the experiment, participants were debriefed and asked if they noticed anything odd. No participant reported having noticed the distortion of haptic feedback in the calibration phase.

Results and Discussion

The distorted calibration of reaching with the right hand generalized to reaches performed with the left hand. As shown in Figure 2, snapback reaches to the near or far targets performed by the right or left hand possessed similar amounts of undershoot.

In the Baseline phase, after receiving veridical haptic feedback for reaches to the near targets, participants' reaches to both near and far distances were accurate, showing no significant differences from 22 cm or 31 cm for either hand, Right Hand, Near Target: $t(9) = 1.9$, $p = .09$; Right Hand, Far Target: $t(9) = 1.9$, $p = .09$; Left Hand, Near Target: $t(9) = 0.3$, $p = .79$; Left Hand, Far Target: $t(9) = -0.04$, $p = 1.0$. Reaching errors in the Baseline phase were not affected by the counterbalancing order, $F(1, 8) = 0.03$, $p = .86$, the reaching hand, $F(1, 8) = 2.12$, $p = .18$, near versus far target locations, $F(1, 8) = 0.05$, $p = .83$ or any interaction among these factors. The mean reaching errors were: Right Hand, Near Target: 0.97 cm; Right Hand, Far Target: 1.35 cm; Left Hand, Near Target: 0.19 cm; Left Hand, Far Target: -0.03 cm (with the negative sign indicating reaching distance smaller than target distance). Performance in the Baseline phase was used to normalize that in the subsequent phases by subtracting these errors from distances recorded in the Feedback and Snapback phases for analyses.

A within-subjects analysis of variance (ANOVA) was performed on normalized reaching errors in the Snapback phase and showed that errors in performance were not affected by the counterbalancing order, whether the left or the right hand was tested first in the Snapback phase, $F(1, 8) = 0.16$, $p = .70$; left versus right hand, $F(1, 8) = 1.52$, $p = .25$; far versus near target locations $F(1, 8) = 0.006$, $p = .94$, or any of the interactions. Means were computed for each participant for each target distance. With the right hand (the calibrated hand), the mean normalized errors were 2.75 cm undershoot of the near target and 2.52 cm undershoot of the far target. A group-t test (2-tailed) was performed showing both normalized errors significantly different from 0, Near Target: $t(9) = -6.12$, $p < .001$; Far Target: $t(9) = -4.07$, $p < .003$. The same pattern of undershoot was found in reaches with the left arm and hand. On average, reaches with the left hand to the near target undershot by 1.80 cm and to the far target reaches undershot by 1.97 cm. Both normalized errors were significantly different from 0, Near Target: $t(9) = -3.42$, $p < .01$; Far Target: $t(9) = -2.23$, $p < .05$. A paired-t test (2 tailed) showed that the normalized reaching errors between the two hands were not significantly different, $t(19) = -1.82$, $p = .08$.

The results revealed incomplete transfer of the distorted calibration in both the right and left hand reaches. Mon-Williams and Bingham (2007) found that responses to distorted haptic feedback lagged the progressive distortion yielding the "snapback" effect that can be seen in Figure 2, that is, reaches to the feedback target reflected only 38% of the distortion after feedback was removed. Specifically, the mean normalized reaching errors in proportion to the amount of distortion in snapback were 44% for the right hand
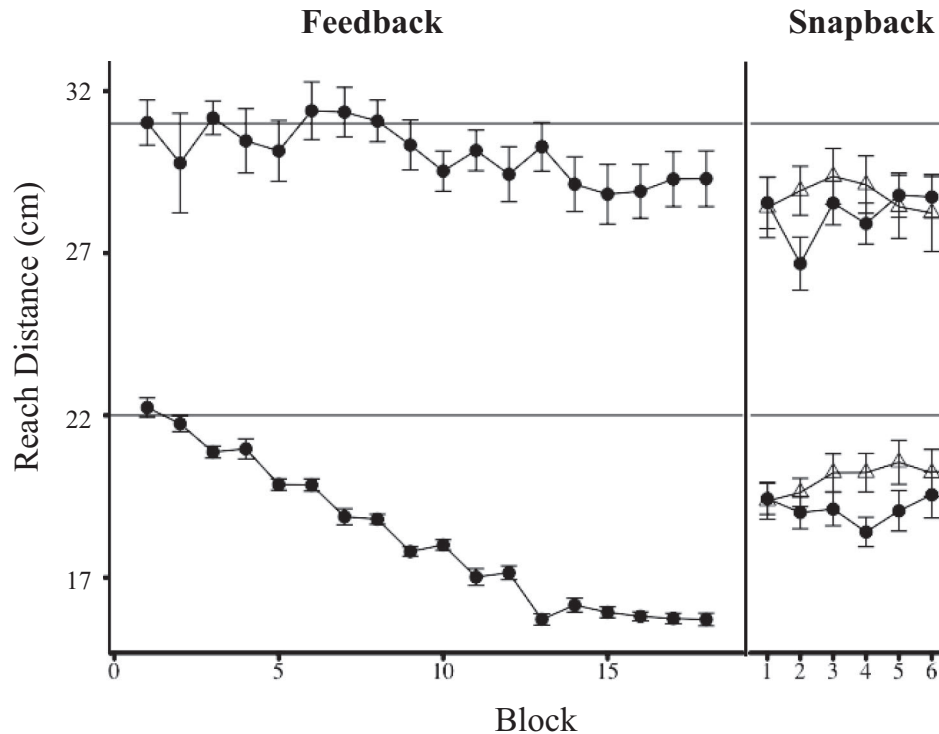
Feedback **Snapback**

Figure 2. Mean reaching distances in Experiment 1 plotted as a function of block order in Feedback and Snapback phases. The distances were normalized by subtracting errors in the postcalibration trials in the Baseline phase from the reaching distances recorded in the Feedback and Snapback phases. Horizontal lines show the visually specified distances of targets at 22 cm and 31 cm. Open triangles are reaches performed by the left arm and hand. Filled circles are reaches performed by the right arm and hand. Error bars show the standard errors.

and 31% for the left hand. The two proportions were not significantly different, $t(9) = 1.30$, $p = .22$. The question here is how much of this response to distorted feedback in right hand reaches, transfers to left hand reaches. The results showed about 70% transfer. Thus, the prediction of the Mapping Theory was confirmed. Action specific calibration generalized across limbs indicating that calibration can be functionally specific.

This experiment was designed to establish whether action specific feedback would transfer between limbs. The finding was that it does. This experiment was not designed to investigate and measure either the maximum possible calibrated response to distorted feedback or the amount of transfer of this calibration from one hand to the other that might ultimately be achieved. Bingham and Mon-Williams (2013) have investigated the dynamics of the response to distorted calibration. There is a lag and they have shown that sustained steady state distorted feedback is required over at least 20 blocks of trials to yield 100% response without feedback in post calibration trials. Thus, it is entirely possible that, with extended steady state feedback at the final level of distortion, the percentage of transfer might be greater than found here.

Experiment 2

The results of Experiment 1 showed that calibration is functionally specific. This was predicted by the Mapping Theory because, according to the theory, it is a mapping from units of perception to a unit of action that is calibrated and thus, calibration is specific to the action whether the action is performed with one skilled limb or another. The flip side of this functional specificity, that is, the specificity of calibration to the particular action that is calibrated was demonstrated by Pan et al. (2014), who found a failure of calibration to generalize to other actions.

However, the Mapping Theory predicts that anatomically specific calibration should also be possible because the mapping is between embodied units. The embodiment means that relevant anatomical properties contribute to the scaling of the calibrated action. Thus, the theory predicts limb specific calibration, meaning the limbs are calibrated to one another in the context of the action. We tested this in Experiment 2 using a variation of the experimental paradigm in Experiment 1. Participants performed blocks of trials in which they alternated reaches performed with the right and the left arm. In the feedback condition, distorted haptic feedback progressively changed right hand reaches in one direction and left hand reaches in the opposite direction. Two groups of participants were tested. One group experienced distorted feedback that moved the left hand farther out and the right hand closer in. The other group experienced the reverse, distorted feedback that moved the left hand closer in and the right hand farther out. The potential effect of this limb specific calibration was tested by analyzing snapback reaches performed after distorted calibration with the left and right hands.

Methods

Participants. 20 participants took part in the experiment in the Perception/Action Lab at Indiana University, 10 in one group and 10 in the other. All were remunerated at a rate of $10/hour for their time. All participants had normal or corrected to normal eyesight and were free of motor deficits. Before participating in the experiment, all participants read and signed consent forms approved by the Indiana University Institutional Review Board.

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

Procedures. The procedure was the same as in Experiment 1 except for the following changes. First, in this experiment, the near target was placed at 18 cm from the starting point and the far target was placed at 25 cm from the starting point. The maximum distortion during feedback was 6 cm (same as that in Experiment 1). Second, throughout the experiment, participants performed alternating blocks of trials in which they performed reaches using the right or the left arm and hand. Each block consisted of two reaches with the particular hand, one to the near target and one to the far target, with order randomized. In the Feedback condition, participants received haptic feedback only from targets at the near distance. A single block was first performed with each hand receiving accurate feedback at the near target. Then distortion was gradually introduced in the feedback. The distorted feedback objects were moved in opposite directions for the left and right hand, 1 cm every 4 blocks (2 blocks performed with each of 2 hands). For one group, the feedback object for the left hand was moved outward or farther away and the feedback object for the right hand was moved inward or closer. For the other group, it was the reverse, left in and right out. Because we were measuring and analyzing the relative behavior of the left and right hands and the relative behavior of a given hand when pulled in versus out, we did not include baseline calibration.

Participants in each group performed a total of 26 blocks of trials in the feedback condition, 13 blocks with one hand and 13 with the other. Alternation of reaching with the left and right hands continued for another 12 blocks in the Snapback condition, switching every two blocks for 6 blocks performed with each hand.

Results and Discussion

As shown in Figure 3, in the Feedback condition, reaches to the nonfeedback far target changed in opposite directions for the two hands as a function of the progressively distorted haptic feedback provided at the near target. After 26 feedback blocks, the left hand was arriving about 3–4 cm from the target and the right hand about 1–2 cm from the target, whether left out and right in or left in and right out. Reaches to the nonfeedback far target, continued at this level of response in the Snapback condition, while reaches to the near target, now no longer receiving feedback, now snapped back to a level of response comparable to that at the far target. Analyses of the data in the Snapback condition showed that left and right hands exhibited reliably different end locations, despite the common visually perceived target, consistent with the distorted feedback.

Due to a malfunction of the Mini-Bird markers, a substantial amount of data was missing for 2 of the participants, one in each group (who had been tested one after the other). We performed analysis, therefore, on data of 9 participants in each group.
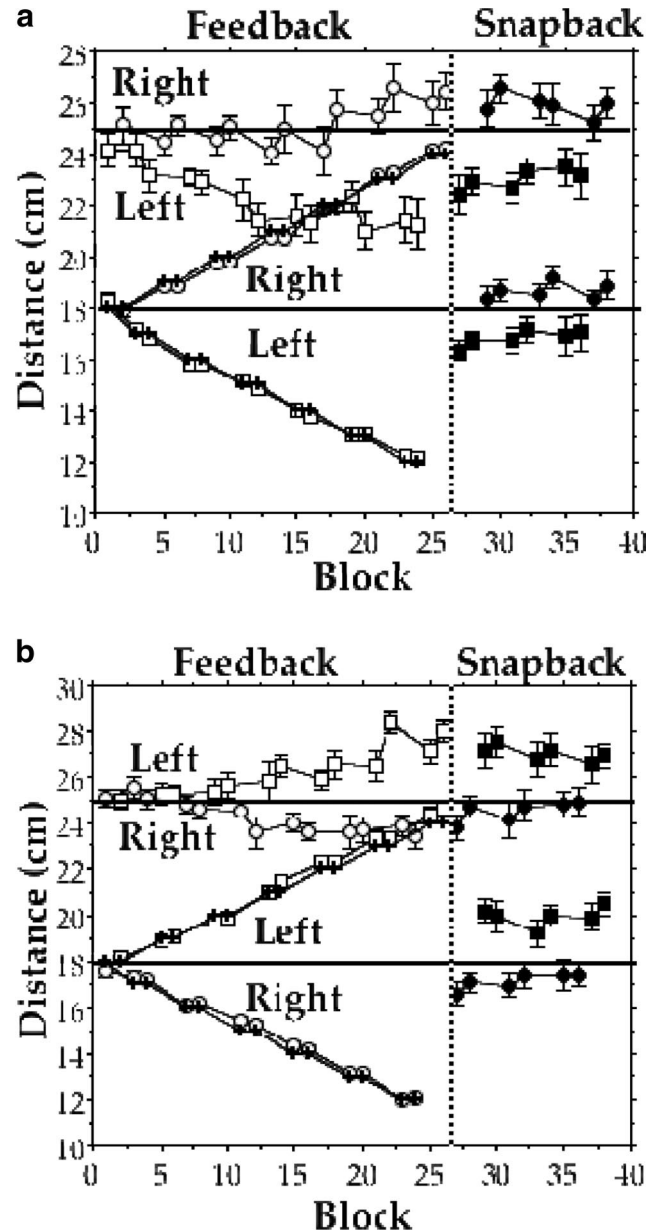

Figure 3. Mean reach distances in Experiment 2 plotted as a function of block order. Dark horizontal lines show the visually specified distances of targets at 18 cm and 25 cm. The dotted vertical line marks the transition from Feedback to Snapback conditions. Open circles are reaches performed in the Feedback condition using the right arm and hand. Open squares are reaches performed in the Feedback condition using the left arm and hand. Filled circles are reaches performed in the Snapback condition using the right arm and hand. Filled squares are reaches performed in the snap back condition using the left arm and hand. Crosses are the feedback object. Error bars show the standard error. Figure 3a shows results for the group that experienced right out and left in distorted feedback. Figure 3b shows results for the group that experienced left out and right in distorted feedback.

Mon-Williams and Bingham (2007) found that, once calibrated, reaches did not exhibit systematic drift when feedback was removed (although random drift was eventually apparent). Mean reach distances were found to exhibit no trend over blocks. We found the same here. We performed separate simple regressions for each target distance (near and far) and hand (left and right) and each group, regressing block on reach distances in the Snapback condition. In all cases, slopes were near zero and all regressions failed to reach significance ($p > .10$).

We computed a mean reach distance for each participant, target distance, and hand in the Snapback condition. Separately for the two groups and at each target distance, we performed 2-tailed paired-t tests to compare left and right hand distances. All four tests were significant as follows:

Left out/Right in at the near target, $t(8) = 6.67$, $p < .001$; Left out/Right in at the far target, $t(8) = 5.13$, $p < .001$; Left in/Right out at the near target, $t(8) = 4.40$, $p < .005$; and Left in/Right out at the far target, $t(8) = 5.04$, $p < .001$. In addition, we performed 2-tailed unpaired-t tests to compare reach distances for a given hand (right or left) when pulled in or out, respectively, at a given target distance (near or far). Three out of four tests were significant as follows: Right hand pulled in versus out at the near target, $t(16) = 2.56$, $p < .05$; Right hand pulled in versus out at the far target, $t(16) = 1.75$, $p = .1$; Left hand pulled in versus out at the near target, $t(16) = 4.53$, $p < .001$; and Left hand pulled in versus out at the far target, $t(16) = 4.65$, $p < .001$. Mean difference for the left hand (3.5 cm) was more than twice that for the right hand (1.4 cm).

Again, we caution that these results should not be understood to represent the maximum response that might be observed for such limb specific calibration, because we did not provide extended steady state feedback at the maximum distortion to allow the response to overcome the lag in the dynamics to settle at the max response. Nevertheless, the prediction of the Mapping Theory was confirmed. Limb specific calibration was achieved indicating that calibration can be anatomically specific.

Finally, as we have reported in all our experiments using distorted feedback to calibrate reaching behaviors, the participants expressed no awareness of these manipulations during debriefing at the end of experimental sessions.

General Discussion

In Experiment 1, we tested whether calibration can be functionally specific, meaning that calibration of an action generalizes to other limbs used for skilled performance of the action. We calibrated targeted reaches performed with the right arm, using distorted feedback, and then tested the response after distorted calibration in both right and left hand reaches. Changes exhibited by right hand reaches transferred to left hand reaches. The transfer was not 100%, but we did not provide sufficient steady state distorted feedback at maximum distortion to allow the calibration response to settle at its maximum response. Nevertheless, the result clearly demonstrated functionally specific calibration. This result is not especially surprising, because a number of previous studies have also found evidence for functionally specific calibration. Perhaps the most relevant is Withagen and Michaels (2004) who found transfer for visual calibration of length perception of a wielded rod (thus, using dynamic touch) from one hand to the

other. This study, using visual feedback to calibrate the mapping from dynamic touch to action, was the converse of the current Experiment 1, where haptic feedback was used to calibrate the mapping from vision to action. Nevertheless, both showed functionally specific calibration of reach like actions using the arms. Other studies providing evidence for functionally specific calibration are Rieser et al. (1995); Withagen and Michaels (2002), and Bruggeman and Warren (2010).

The results of Experiment 2 showing that calibration can be anatomically or limb specific were more surprising. This was especially the case given the results of Experiment 1 showing that calibration can be functionally specific in the context of visually guided targeted reaches. It is surprising enough to find, as did Mon-Williams and Bingham (2007), that participants can look at a target that is visually specified to be in one location, while reliably reaching to a different location up to 8 cm away from the actual target location, without any awareness whatsoever that this is happening. Now we find, that participants can look at a target that is visually specified to be in one location, while reliably reaching to *two* entirely different locations, each up to 4 cm away from the actual target location, using the left and right arms, respectively, so that the two arms are being used to reach to locations up to 8 cm apart with no awareness of this difference, or a difference from the visually specified location! Nevertheless, this was predicted by the Mapping Among Embodied Units Theory of Calibration as a consequence of embodiment. Because the units involved in the calibrated mapping are embodied, the scale associated with relevant anatomical properties must be incorporated into the functional dynamics of calibration. Calibration simply must be *both* functionally and anatomically specific. The controversy thus has been somewhat misguided.

More appropriate to consider are questions raised by the current results. For instance, how do functionally specific calibration and anatomically specific calibration interact? Are they additive or superadditive? Relatedly, are the time constants (both gain and decay or stability) in the respective dynamics the same or different? These are the questions that can be usefully addressed by future research. Obviously, the result obtained in Experiment 1 suggests that the distorted feedback provided simultaneously to the two hands in Experiment 2 should have interacted. For instance, feedback pulling the left hand in or closer than visual targets should have affected the right hand in the same way and vice versa, feedback pulling the right hand out should have generalized to the left hand. Logically, these effects might have limited the strength of the response to the simultaneous calibration of the two hands in opposite directions. The fact that such calibration was effective shows clearly that limb specific calibration occurs. It is likely that the dynamics of functionally specific and anatomically specific calibration are different and these differences would determine the nature of the response under conditions like those investigated in Experiment 2. Parametric study of the respective dynamics will be required as part of future investigations of the nature of the interactions between the two types of calibration.

A theme introduced by the Mapping Theory, associated with the embodiment of both perception and action units, is the importance of the dynamics of calibration. An early study that focused on such dynamics was Bingham and Romack (1999), who investigated whether the time constants for calibration of visual direction and reaching (that is, classic prism adaptation) changed to yield

rapid response to perturbations of perceived direction after repeated perturbations. The answer was that rate constants did not change and that a separate perceptual learning process yielded rapid responses after sufficient training (see Withagen and Michaels, 2005, for another study revealing such dual processes.) A particularly important problem addressed by the Mapping Theory is the combination of sources of perceptual information that entail different units (e.g., IPD units and EH units for distance perception). See Coats, Pan and Bingham (2014). This takes calibration into the domain of "cue combination," where consideration and study of dynamics has been notably missing. Bingham and Mon-Williams (2013) have shown that the lag in the dynamics of calibration requires that these dynamics be taken into account. Unfortunately, results in some weighted cue averaging studies and models are unreliable because they failed to do this. Essentially, their effective mistake, in ignoring the dynamics, is the same as interpreting the results of Experiment 1 as revealing the ultimate amount of transfer that might be expected between calibrated and uncalibrated arms, or as interpreting the results of Experiment 2 as revealing the ultimate amount by which two arms might differ as a function of limb specific calibration. As we have explained, either interpretation is necessarily incorrect. The dynamics in either case were not allowed to settle to steady state so that the effect of the lag in the dynamics would dissipate. Finally, it is likely that the gain of the response in the case of functionally specific and anatomically specific calibration is different and in fact, this might serve as another means by which to establish their respective existence.

To develop some intuition about this, it is worth considering the dark adaptation function well-known to vision scientists. The function exhibits curves that reflect two processes operating at different rates and over different ranges, one associated with the cones and another the rods. The research that revealed this function required parametrically controlled repetitions of conditions that induced adaptation. Another well-known visual phenomenon involving the combination of, and in this case, interaction of two separate dynamics is vergence/accommodation. Again, each process exhibits different time constants that are difficult to measure because of the inherent ways that the two processes interact. The point here is that the challenges presented to researchers by the combination of functionally specific and anatomically specific forms of calibration are actually characteristic of the phenomena tackled in the past by scientists studying the visual system. With this observation, we should certainly expect similar phenomena and challenges when now tackling perception/action.

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