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Perturbation of Perceptual Units Reveals Dominance Hierarchy in Cross Calibration

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Bingham and Pagano (1998) argued that calibration is an intrinsic component of perception–action that yields accurate targeted actions. They described calibration as of a mapping from embodied units of perception to embodied units of action. This mapping theory yields a number of predictions. The authors tested 2 of them. The 1st prediction is that change in the size of perceptual units should yield a corresponding change in the slope of the relation between response distances and actual target distances. In Experiment 1, the authors tested this prediction by manipulating interpupillary distance (IPD) as the unit for binocular perception of distance using vergence angles. In Experiment 2, they manipulated eye height (EH) as the unit for monocular perception of distance using elevation angles. In both cases, the results confirmed the predictions. The 2nd prediction was that perceptual units should interact to cross calibrate one another according to a dominance hierarchy among the units. The theory predicts a more temporally stable unit is used to calibrate a less stable unit but not the reverse. EH units change frequently, but IPD units do not, so IPD should be dominant. Simultaneously available IPD and EH units were perturbed successively (without feedback). As predicted, EH was recalibrated by IPD, but IPD was not recalibrated by EH. The mapping among units theory of calibration was thus supported.

Keywords: calibration, cue combination, perception/action, vergence, elevation

One of the great classic problems in visual space perception is perception of metric properties of linear dimension, like distance and size. This problem originates from the fact that optical information is inherently angular. There are no linear extents in optical pattern. One cannot meaningfully describe optical pattern using centimeters or inches. (See Bingham & Pagano, 1998; Gibson, 1966; and Turvey, 1977, for extended 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 between the two eyes (called the *interpupillary distance* [IPD]) is part of the geometry of binocular vergence information (see Figure 1). *Vergence angles* are formed by the two lines of sight when the eyes each foveate on a target object at some distance. Interpupillary distance is the "side" of the angle–side–angle relation, familiar from high school trigonometry, that is the essence of vergence information about distance.[1] 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. *Vergence* specifies distance in IPD units.[2]

As another example, the distance of the eyes above the support surface (called *eye height* [EH]) is part of the geometry of monocular elevation information (also called *height-in-the-visual-field*; see Figure 1). Eye height is determined by the standing (or seated) 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 the ground (or more generally, a level support surface). Eye height is the side of a right triangle that again invests the optical elevation angle with both a length dimension and a unit. Elevation specifies distance in EH units.[3]

Perception of metric distance and size is used to guide targeted feed-forward actions, like reaching or throwing. To be useful, such actions must be accurate, and this means that the space perception

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[1] Given the size of three parts of a triangle (here, two angles and a side), the size of the rest of the parts of the triangle can be determined and in particular, it's height that corresponds to the perceived distance.

[2] Units are associated with metric measurements along a dimension. For instance, the length dimension can be measured in feet, or alternatively, in 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). See extended discussion in Bingham (1995) and references contained therein. Also, see Lockhart (2012) for a more recent informal discussion. In our application, the length dimensioned property, distance, is measured in units intrinsic to human perception, either IPD or EH units.

[3] As a third example, motion parallax yields distance in units that involve the amplitude or speed of head movement (Bingham & Stassen, 1994; Bingham & Pagano, 1998; Pagano & Bingham, 1998; Panerai, Cornilleau-Peres, & Droulez, 2002; Peh, Fanerai, Droulez, Cornilleau-Peres, & Cheong, 2002; Wickelgren, McConnell, & Bingham, 2000).

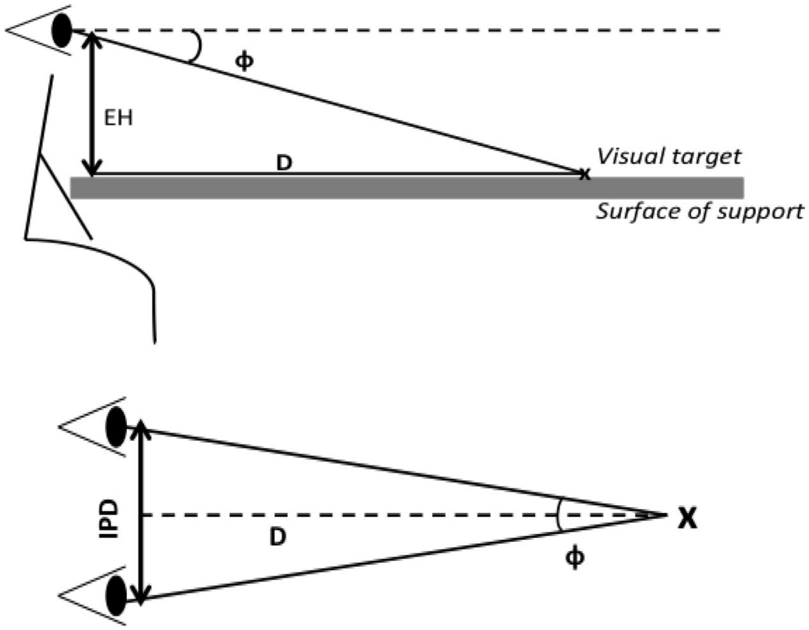

Figure 1. Illustration of the viewing geometry for vergence and interpupillary distance (IPD; bottom panel) and elevation and eye height (EH; top panel). Bottom panel: φ is the vergence angle. IPD is the distance between the two eyes. D is the distance from the eyes to a viewed target. Top panel: φ is the elevation angle. EH is the distance from the eyes to the support surface. D is the distance along the surface from the observer to a viewed target on the surface.

that supports and enables them must be accurate. Bingham and Pagano (1998) reviewed a wealth of judgment studies all showing that space perception was inaccurate and imprecise. They asked: Is it really so poor? As a rule, actions guided by space perception are reasonably accurate and effective. Baseball, cricket, rugby, and (American) football players reliably perform accurate targeted throws. Tennis and badminton players reliably target strategic locations on the court. One can usually reach to grab one object (e.g., the phone or one's coffee) while looking at another (e.g., a computer screen). Bingham and Pagano pointed out that an intrinsic element of perceptually guided action was missing in the judgment studies they had reviewed, namely, calibration. They suggested that relevant action measures should be used to study space perception, instead of judgments, and that calibration should be included because it is a normal part of such actions (see also van Beers, Baradue, & Wolpert, 2002). Bingham and Pagano anticipated that the result should be performance that is both accurate and precise in a normal or representative way.

The first suggestion (use of relevant action measures) was consistent with a similar suggestion made by proponents of the two visual system theory. The second suggestion (to include calibration) was not. In the early 1990s, Milner and Goodale advanced their two visual systems theory (Goodale, Jakobson, & Servos, 1992; Milner & Goodale, 1995). They proposed that one visual system (called the *perception-action* or *dorsal stream*) should be sensitive to metric properties, whereas the other visual system (called the *object recognition* or *ventral stream*) should not be. Also, the latter was theorized to exhibit awareness, and the former not. Accordingly, explicit judgments of perceived space should invoke the ventral stream and thus, exhibit poor perception of metric space. On the other hand, if perception were to be evaluated using relevant action measures, invoking the dorsal stream, then accurate performance might be found. Note that this hypothesis did not involve calibration. The hypothesis was tested in a number of studies of feed-forward reaching (Bingham, Bradley, Bailey, & Vinner, 2001; Bingham, Crowell & Todd, 2004; Bingham, Zaal, Robin, & Shull, 2000; Wickelgren, McConnell, & Bingham, 2000). Feed-forward reaches are performed without continuous online guidance of a visible hand. Feed-forward reaches, guided by space perception, were first tested without terminal feedback. They were reliably found to be inaccurate and imprecise. Next, however, the reaches were tested with terminal feedback. The resulting calibration yielded performance that was both accurate and precise. So, accuracy and precision of performance required calibration, not merely the use of relevant action measures.

Calibration has now been studied in the context of a number of different visually guided targeted actions, including walking (Bruggeman & Warren, 2010; Durgin et al., 2005; Rieser, Pick, Ashmead, & Garing, 1995), crawling (Withagen & Michaels, 2002), reaching (Bingham, 2005; Bingham, Coats, & Mon-Williams, 2007; Mon-Williams & Bingham, 2007), grasping (Coats, Bingham, & Mon-Williams, 2008; Foster, Fantoni, Caudek, & Domini, 2011), throwing–kicking (Bruggeman, Pick, & Rieser, 2005; Bruggeman & Warren, 2010; Rieser et al., 1995), catching (Jacobs & Michaels, 2006; van der Kamp, Bennett, Savelsbergh, & Davids, 1999), tool use (Withagen & Michaels, 2004, 2005), and braking (Fajen, 2005a, 2005b). All of these studies show that calibration (using actual and accurate feedback, not false or distorted feedback) is required to yield reliably accurate performance.

Calibration is required for reliably accurate performance of targeted actions, in part, because the perception–action system is dynamic. If calibration is removed, then performance exhibits drift along a trajectory. This was clearly shown both by Bingham and Pagano (1998) and by Vindras and Viviani (1998), among others (e.g., Wann & Ibrahim, 1992). Over trials, the endpoint of the targeted action gradually moves away from the actual target location. However, with calibration, performance also exhibits a trajectory. Successive responses follow an exponential approach to the actual target, and thus, to accurate performance. The exponential form of the response reflects a lag in the dynamics that preserves the stability of targeting behavior (Bingham & Romack, 1999; Burge, Ernst, & Banks, 2008; Mon-Williams & Bingham, 2007).

Although calibration prevents drift, this is not the only, or perhaps even the main reason that calibration is an important component of visually guided targeted actions. A process that merely prevents drift might not require an exponentially gated response function to preserve the stability of performance. Instead, exponential response is useful as a response to discrete perturbations of larger magnitude. Both Mon-Williams and Bingham (2007) and Bingham and Romack (1999) observed and explicitly modeled exponential response trajectories to larger discrete perturbations contained in feedback (see also Burge et al., 2008; and Ernst & Di Luca, 2011). To better understand what is calibrated by calibration, it is useful to consider what circumstance or event in nature yields such relatively large discrete perturbations. The answer, surmised by Bingham and Pagano (1998), is a change in the unit of perceptual information.

Eye height units of perceptual information change frequently. For instance, when a person changes from seated to standing posture, the EH unit changes. When a woman selects her footwear for the day, choosing between her low-heeled Mary Jane's and her high-heeled boots, she also perturbs her standing EH unit for the day. Mark (1987) investigated the effect of changes in EH on judgments of maximum climbable riser heights in stairs and maximum seat heights. Mark placed his observers on stilts and recorded changes in judgments (see also Mark & Vogele, 1988; and Mark, Balliett, Craver, Douglas, and Fox, 1990). With recalibration, the judgments exhibited the characteristic exponential return to accuracy. Alternatively, Warren and Wang (1987) covertly manipulated EH information used by observers to judge whether apertures were passable when walking (without turning the body to fit through). In this case, observers were not allowed to recalibrate with the result that the judgments were inaccurate in proportion to the distortion of the 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. The unit of targeted walking might be stride length (SL), for instance. A target might 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 is contingent. It can change. 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). This mapping theory yields a number of predictions. We now tested two of them as follows.

1. Change in the size of an embodied unit of perception should yield a change in slope of the function relating actual distances to response distances. We test this in Experiments 1 and 2.

2. Given multiple sources of information about distance (each involving a different embodied unit), a change in one unit should be calibrated by other units according to a dominance hierarchy among units determined by their relative temporal stability. We test this in Experiment 3.

Change of Unit Yields Change of Slope

Mon-Williams and Bingham (2007) investigated the type of changes that could be induced in the distance function.[4] The distance function is the relation between actual target distances and corresponding response distances in a targeted task. Mon-Williams and Bingham found that targeted reaches exhibited a linear relation to actual target distances. Using distorted feedback, they were able to induce changes in either the intercept or the slope of the function. The mapping theory predicts that uncalibrated changes in perceptual units should yield changes in the slope of this function.

For instance, if EH units were calibrated for an actor, then corresponding targeted actions should yield a distance function with a slope near 1 and an intercept near 0. If the EH units were then increased by 25% without recalibration of the perception-action mapping, then the slope of the distance function should decrease by 25% and the targeted actions should systematically undershoot the actual target distances as a result. As shown in Figure 1, elevation angle, φ, specifies distance, D, in EH units:

$$D/EH = 1/\tan\varphi.$$

If D and EH are measured (by an experimenter) in centimeters, then D/EH is a pure number, and this is what the optical information variable returns to the visual system. Nevertheless, the measure is in EH units. The problem for the perceiver is that he or she, in principle, does not know the size of the EH unit until that unit is calibrated. When $\varphi = 45°$, the information will specify the distance as equal to 1 EH. If the EH for a seated observer is 40 cm, then once that unit is calibrated for reaching, then the observer should be able to reach out accurately to a target at a distance of 40 cm. However, if the EH unit is then increased by 25% to 50 cm (by lowering the table, for instance) without recalibrating reaching, then that same target at 40 cm will return an optical value of 0.8 EH. Without recalibration, this would be interpreted in the original calibrated EH unit of 40 cm and thus, the observer should reach to 0.8×40 cm ≈ 32 cm, instead of 40 cm. The observer should undershoot. Essentially, the same analysis applies to information specified in binocular vergence angles where IPD is the unit (typically equal to about 6 cm).

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[4] Bedford (1989) similarly investigated the nature of the function relating actual directions to the directions of targeted reaches with variations in distorted feedback. She also found that function to be linear and that feedback induced changes in the intercept or slope of the function.

We tested these predictions of the mapping theory of calibration in Experiments 1 and 2. In Experiment 1, we tested the effect of both increases and decreases in IPD on a targeted action guided by binocular vergence-based perception of distance. In Experiment 2, we tested the effect of both increases and decreases in EH on a targeted action guided by monocular elevation-based perception of distance.

Method Common to Experiments 1 and 2

In the following experiments, participants sat at the end of a 5 m long, 1 m wide table that was covered in black felt (see Figure 2). They were asked to rest their head on a chin and forehead rest positioned at the front edge of the table. Targets were placed on the table in front of the participant at distances from 50 cm to 250 cm. The targets were placed on the left-hand ("perception") side of the table, and the participant sat to the left of the center of the table so as to be directly in front of the targets. Down the center of the table a large curtain was hung from the ceiling, such that the right-hand ("action") side of the table could not be viewed by participants. Directly to the right of the participant was a small glow-in-the-dark marker attached to a cord on a pulley. This cord ran from the front edge of the table on the action (right) side, horizontally above the surface of the table and ended at the far end of the table. Participants could only see the marker when it was at the end of the pulley nearest them. As soon as they moved it forward, it was no longer in view because it was behind the curtain. A tape measure was attached along each side of the table, each running the length of the table. The participants' task was to grasp the cord and move the marker out until it was at the same distance from them as the target. Lights were switched off at the start of all experiments so all trials were completed in the dark.

Experiment 1

We isolated vergence as the only available information about target distances using a point-light optic fiber target viewed in the dark. Anderson and Bingham (2010) tested judgments of the distance of this optic fiber target when participants used monocular vision and found that they were unable to detect differences in the distance of the target. Using binocular vision, they could well detect changes in the distance of the target. We now tested the effect of perturbations of the IPD unit on action response measures of distance perception. Two different IPD configurations were tested: In one configuration, the IPD was increased by ≈12.5%, and in the other the IPD was decreased by ≈12.5%. The design controlled for the direction of change. One group of participants was calibrated with +12.5% IPD and then tested postcalibration with both +12.5% IPD and −12.5% IPD. The other group was calibrated with −12.5% IPD and then tested postcalibration with both −12.5% IPD and +12.5% IPD. The order of postcalibration conditions was counterbalanced across participants. Then, during analysis, first, the two respective calibrated IPD conditions, tested postcalibration, were compared with the expectation that there would be no differences between the groups and that both would be accurate, that is, slope ≈ 1 and intercept ≈ 0. Second, the two respective perturbed IPD conditions were compared with the expectation that the two groups would exhibit slope differences. Those with +12.5% perturbed IPD should exhibit a slope less than 1 and thus, less than the calibrated condition. Those with −12.5% perturbed IPD should exhibit a slope greater than 1 and thus, greater than the calibrated condition. Note, it is not the absolute IPD size that is important but instead the IPD that was calibrated. The calibrated IPD, whether large or small, should yield accurate performance postcalibration. The uncalibrated changes in the IPD are the key manipulation.

Method

Participants. Sixteen participants (10 male, 6 female) took part in the experiment and were remunerated at a rate of $10/hr for their time. All participants had normal or corrected-to-normal vision and adequate stereovision, as tested by the Stereo Fly Test (Stereo Optical). Before participating in the experiment, all participants read and signed consent forms approved by the Indiana University institutional review board.

Apparatus. The table, described above, was covered in black felt. Participants sat at the end of it and rested their head on a chin and head rest and against a set of goggles to look through a new type of telestereoscope (see Figure 3). The telestereoscope consisted of two flat (0 diopter) 3-cm thick Plexiglas lenses rotated to achieve requisite plus or minus shifts in IPD. Note that even though the Plexiglas lenses are not curved, light is refracted at the front face of the glass and therefore deviated from, for instance, the direction of a target so that it then travels directly through the glass and is refracted again at the back face of the glass to travel once

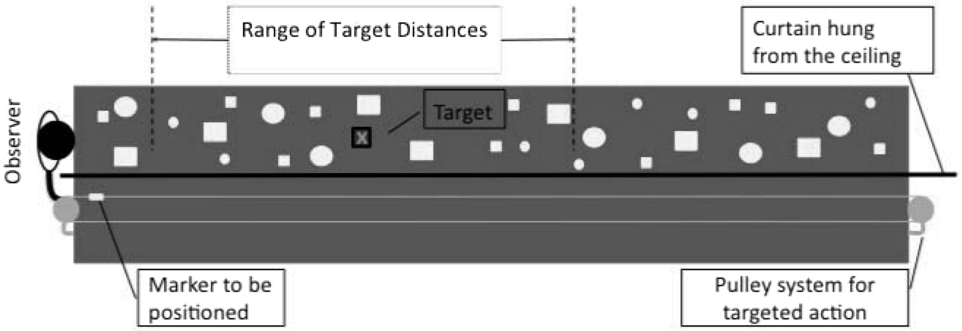

Figure 2. Apparatus used in the experiments viewed from above. See the text for explanation. Note that the texture was more dense than shown (see Figure 5).

Figure 3. A new telestereoscope is illustrated together with the means of changing interpupillary distance (IPD) to be either greater than or less than normal (see the text description and explanation). Additional information is available in Anderson and Bingham (2010).

again in its original direction. Given the 3 cm thickness of the glass, the deviation of the light traveling through the glass is used to produce effective increase or decrease in the IPD, with the amount of deviation being a function of the orientation of the glass. This design for a telestereoscope allows the IPD to be both increased and decreased. Goggles occluded the edges of the lenses so the observer had no information about the perturbation of vision.

A point light was placed between 50 and 250 cm away from the participant directly in front of them at eye level. This was achieved by placing an optic fiber on a stand so that the end of the optic fiber was pointed at the participant. The optic fiber had a small flash light attached to its far end and light sealed. The stand was moved along the surface of the table and placed at the desired target distances. The stand was at a height so as to place the light at the participant's eye level. Participants used the cord and pulley described earlier to make their responses.

Procedures. Participants were first tested to see if their stereovision was good enough to proceed. If it was not, they would not be asked to proceed. Participants who were asked to continue were then seated in a chair and asked to place their chin on the chin rest that was attached to the telestereoscope. Participants were asked to wear a blindfold while the experiment was set up. The lights in the room were switched off and the point light was placed at a particular distance by one of the experimenters, using the tape measure on the side of the table. The blindfold was removed, and participants were asked to first place their hand around the curtain and to grasp the phosphorescent marker and then extend the arm to send the marker out in depth. The participant could repeat extending the arm as many times as needed by pushing the cord to send the marker to a distance that matched the perceived distance of the point light on the perception side. Once they had finished moving the marker, they closed their eyes and alerted the experimenter on the action side of the table who used the tape measure to write down the position of the marker. The experimenter then moved the marker back to the start position next to the participant while the other experimenter moved the point light to the next position.

Of key importance in this experiment was *calibration*. During calibration trials, the experimenter on the action side of the curtain extended a visible rod under the curtain signifying the distance of the marker to provide visual feedback to the participant for calibration. The rod could be seen relative to the target to reveal action response error. Distances were uniformly but randomly chosen to cover the whole space (50–250 cm from the participant).

Four different conditions were completed by each participant. First, each participant completed five precalibration trials with the IPD normal (the prisms were positioned in a frontoparallel plane, perpendicular to the sight line). The angle of the prisms in the telestereoscope was then adjusted. This was done rapidly (within ≈3 s) while the participant was blindfolded. Second, the participant completed 10 calibration trials. Half the participants were calibrated to an IPD 0.8 cm smaller than normal (IPD small), whereas the other half were calibrated to an IPD 0.8 cm greater than normal (IPD large). (Normal IPD was ≈6.4 cm on average, so the ±0.8 cm change was by ≈±12.5% for a total change of ≈25%.) Third and fourth, the participant then completed an additional 15 trials with IPD small and 15 trials with IPD large. The order of these two latter postcalibration conditions was counterbalanced. Between all conditions participants kept their eyes closed and were distracted by one experimenter while the other moved the prisms to the appropriate positions.

Data analysis. We fit linear models to response distances as a function of target distances. Then we used multiple regressions to test for slope, intercept, or both differences in the linear trends of postcalibration performance. The same analyses were done to both groups: calibrate IPD small and calibrate IPD large.

Results

As shown in Figure 4, the results were as predicted by the mapping theory. Postcalibration targeting performance is shown in Figure 4a with the calibrated IPD values. As predicted, there was no difference between IPD large and IPD small because each was calibrated for accurate performance. Postcalibration performance is shown in Figure 4b with the perturbed IPD values. As predicted, slopes were affected by the perturbations to the IPD units. When IPD was decreased, the slope increased, and when IPD was increased, the slope decreased.

We used multiple regression (Pedhazur, 1982) of response distances on target distances to test for differences of slopes, intercepts, or both, comparing postcalibration trials between groups, that is, between IPD large versus IPD small. Separate analyses

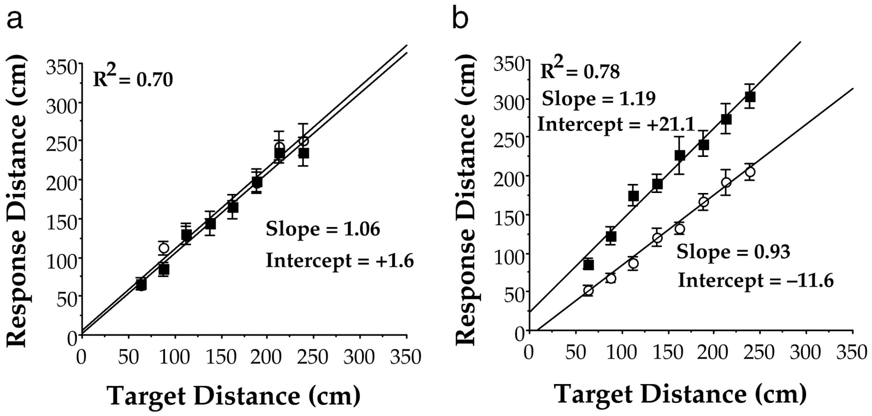

Figure 4. Results of Experiment 1. Responses were collected into 8 bins, and a mean response distance was computed for each bin. Mean response distances are plotted as a function of mean target distances. Error bars are *SE*s. Regression lines were fitted to the means using simple regression. Figure 4a shows the postcalibration results with calibrated interpupillary distance (IPD) values. Figure 4b shows the postcalibration results with perturbed IPD values. Open circles are IPD large. Filled squares are IPD small.

were performed on the data for calibrated IPD values (shown in Figure 4a) and perturbed IPD values (shown in Figure 4b). Regressions were performed on the combined trial data. (Binning was done only to make the figures.)

First, we analyzed postcalibration performance with calibrated IPD values. For participants who were calibrated to IPD small, we compared their postcalibration trials when IPD was small with the group who was calibrated to IPD large and tested postcalibration with IPD large. We predicted no differences because both groups should be equally accurate. This is indeed what we found. The regression was significant ($R^2 = .70$, $F(3, 155) = 123.1$, $p < .001$). Slopes were not significantly different from each other ($p > .7$). Also, intercepts were not significantly different from each other ($p > .9$). The mean slope was 1.06, close to 1, and the mean intercept was 1.6, close to 0.

Next, we analyzed postcalibration performance with perturbed IPD values. So, for those that were calibrated to IPD small, we compared their postcalibration trials when IPD was large with the group who was calibrated to IPD large but tested with IPD small. We predicted that slopes should be different because increasing IPD should make you undershoot while decreasing IPD should make you overshoot. The regression was significant ($R^2 = .78$, $F(3, 161) = 195.3$, $p < .001$). Slopes were 0.93 for calibrated IPD small, tested large, and 1.19 for calibrated IPD large, tested small, and these were significantly different from each other, $t(1{,}161) = 2.0$, $p < .05$. Also, intercepts were −11.6 for calibrated IPD small, tested large, and 21.1 for calibrated IPD large, tested small, and these were significantly different from each other, $t(1{,}161) = 2.6$, $p < .02$.

Experiment 2

In Experiment 1, we isolated the use of IPD-scaled information and tested the effect of changes in the size of this perceptual unit when performance was not recalibrated to the changed unit by feedback. We found, as predicted by the mapping theory, that increase in the perceptual unit yielded a decrease in the slope of the distance function, whereas decreases in the perceptual units yielded an increase in the slope of the function. Next, we tested this same hypothesis in the case of EH scaled information.

We isolated monocular surface relative information as the only available information about target distances. This information was in EH units. Participants sat before an extended table surface and viewed it using only their dominant eye. As shown in Figure 5, the surface was textured with phosphorescent circular and square patches that were viewed in the dark. We tested the effect of perturbations to the EH unit on action response measures of distance perception. Two different EH configurations were tested: in one, the EH was small (≈40 cm), and in the other, the EH was large (≈50 cm). The total difference was ≈25%. The design was essentially the same as that for Experiment 1, controlling for the direction of change. One group of participants was calibrated with large EH and then tested postcalibration with both large and small EH. The other group was calibrated with small EH and then tested postcalibration with both small and large EH. The order of postcalibration conditions was counterbalanced across participants. During analysis, the two respective calibrated EH conditions, tested postcalibration, were compared with the expectation that there would be no differences. Then, the two respective perturbed EH conditions were compared with the expectation that the two groups would exhibit slope differences. Note once again, it is not the absolute EH that is important but instead the EH that was calibrated. The calibrated EH, whether large or small, should yield accurate performance postcalibration. The uncalibrated changes in the EH were the key manipulation.

Method

Participants. Eight participants (5 male, 3 female) took part in the experiment and were remunerated at a rate of $10/hr for their time. All participants had normal or corrected-to-normal eyesight. Before participating in the experiment, all participants read and signed consent forms approved by the Indiana University institutional review board.

Apparatus. An eye patch was used to cover the participant's nondominant eye. Participants were seated in a chair that was used

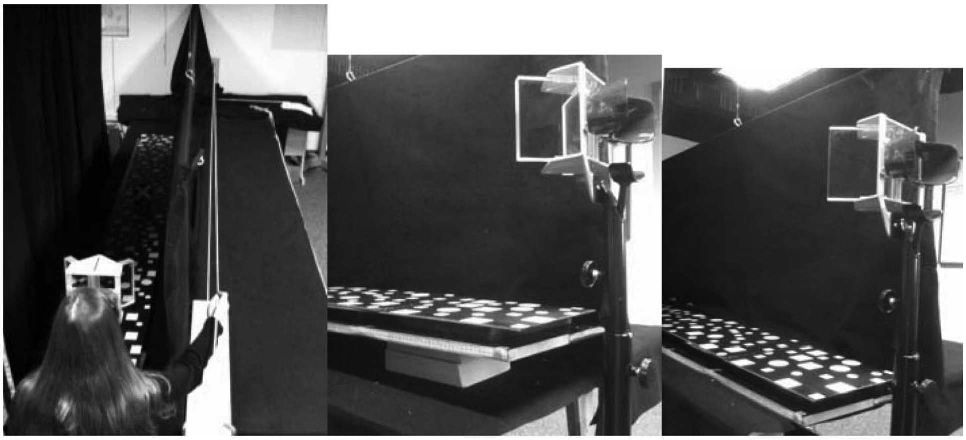

Figure 5. Illustration of the apparatus used in Experiments 2 and 3. The left-hand panel shows the textured surface; the pulley response apparatus; and the telestereoscope, chin rest, and goggles. Note that for Experiment 2, the telestereoscope was set so as not to perturb the interpupillary distance (IPD). The Plexiglas lenses were perpendicular to the line of sight. The middle and right-hand panels show the changes in the textured support surface height yielding small eye height EH (middle panel) and large EH (rightmost panel).

to adjust their height relative to the apparatus so they could comfortably rest their head on the chin rest and goggles. As shown in Figure 5, participants sat in front of a black support surface that was covered by phosphorescent square (sides 1 or 2 in.) and circular (diameters 1 or 2 in.) patches. These patches were stochastically distributed along a board (400 cm long and 30 cm wide) that was placed on the tabletop. The board had vertical supports at its center at either end that projected through the table to latch onto support bars beneath the table. This feature allowed the experimenters to rapidly change the height of the board. On each trial, a target was placed on the board surface. The targets were phosphorescent **X**s mounted on the diagonals of three black wooden square 1-in. thick tiles, with sides of, either, 5.5 cm, 9 cm, or 11 cm. On each trial, one of these three **X**s was randomly selected as the target to control for an effect of image size. The surface of support could be rapidly raised or lowered to produce two different heights: These were 50 cm and 40 cm below the eye level. Participants used the cord and pulley described earlier to make their responses by moving the cord to place a marker on the cord at the distance of the target.

Procedures. Participants were first asked to place a patch over their nondominant eye. They were then seated in a chair and asked to place their chin on a chin rest. Participants were asked to wear a blindfold while the experiment was set up. The lights in the room were switched off, and one of the targets was placed at a distance on the perception side of the table. The participant's blindfold was removed, and the participant was asked to grab the marker attached to the pulley and position the marker by pushing the pulley as in Experiment 1. Once this was done, the participant closed his or her eyes and alerted the experimenter on the pulley (action) side of the table, who then used the tape measure to record the distance of the marker. That experimenter then moved the marker back to the start position next to the participant, while the other experimenter placed the next target in position. The order of target distances was randomized, and distances were uniformly but randomly chosen to cover the space from 50 cm to 250 cm from the participant.

As in Experiment 1, four different conditions were completed by each participant. All participants completed five precalibration trials. For half the participants, the EH was large (50 cm from the eye), and for the other half, it was small (40 cm from the eye). The participants then completed 10 calibration trials with the EH kept the same as in precalibration. During these 10 trials, participants were given feedback as in Experiment 1. All participants then completed an additional set of postcalibration trials, 15 trials with the EH large and 15 with the EH small. Order of these latter two conditions was counterbalanced. Between conditions, participants wore a blindfold while the experimenters changed the height of the board. Also, the texture on the board was actually on 4 cm long 1 cm thick black panels that rested on the black 4 m board. These panels were scrambled (their order was changed, and their orientation was rotated to exchange front and back ends) to prevent participants from using texture elements as landmarks. Participants were warned in instructions not to use texture as landmarks. Data analysis was performed just as in Experiment 1.

Results

As shown in Figure 6, the results were as predicted by the mapping theory. Postcalibration targeting performance is shown in Figure 6a with the calibrated EH values. As predicted, there was no difference between EH large and EH small, because each was calibrated for accurate performance. Postcalibration performance is shown in Figure 6b with the perturbed EH values. As predicted, slopes were affected by the perturbations to the EH units. When EH was decreased, the slope increased and when EH was increased the slope decreased.

First, we examined postcalibration performance with the calibrated EH. For those who were calibrated to large EH, we compared their postcalibration trials when EH was large with the group who were calibrated to small EH and tested with EH small. We predicted there should be no slope or intercept differences between groups. This is indeed what we found. The regression was signif-

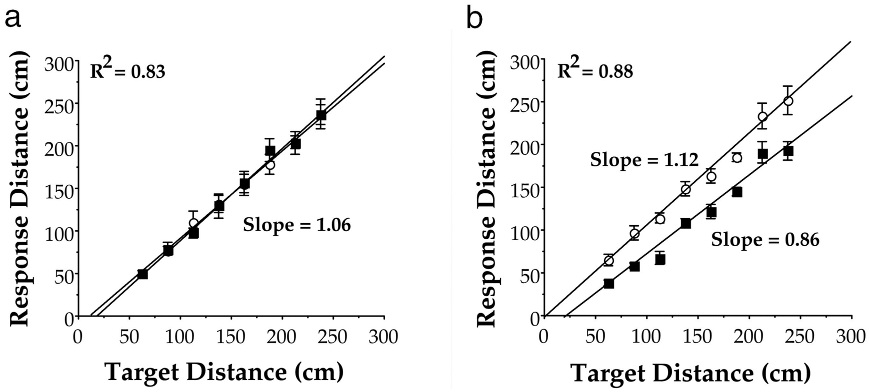

Figure 6. Results of Experiment 2. Responses were collected into 8 bins and a mean response distance was computed for each bin. Mean response distances are plotted as a function of mean target distances. Error bars are *SE*s. Regression lines were fitted to the means using simple regression. Figure 6a shows the postcalibration results with calibrated eye height (EH) values. Figure 5b shows the postcalibration results with perturbed EH values. Open circles are EH small. Filled squares are EH large.

icant (R^2 = .83, $F(3, 116)$ = 183.2, $p < .001$). Slopes were not significantly different from each other, $t(1,116)$ = 0.16, p = .87. Also, intercepts were not significantly different from each other ($p > .9$). The mean slope was 1.06, and the mean intercept was −15.03.

Next, we tested postcalibration performance with the perturbed EH. For those who were calibrated to large EH, we compared their postcalibration trials when EH was small with the group who were calibrated to small EH but tested with EH large. Now, we predicted a slope difference between the two groups. Increasing EH makes you undershoot, decreasing it makes you overshoot. The regression was significant (R^2 = .88, $F(3, 116)$ = 282.7, $p <$ .001). Slopes were 0.86 (when calibrated with small EH and tested with large EH) and 1.12 (when calibrated with large EH and tested with small EH) and were significantly different from one another, $t(1,116)$ = 9.8, $p < .001$. Intercepts were not different from one another ($p > .07$). The mean intercept was −13.4.

Summary of Experiments 1 and 2. In Experiments 1 and 2, we isolated the use of IPD scaled and EH scaled information, respectively, and tested the effect of changes in the size of the respective perceptual unit when performance was not recalibrated to the changed unit by feedback. We found, as predicted by the mapping theory, that increase in the perceptual unit yielded a decrease in the slope of the distance function whereas decreases in the perceptual units yielded an increase in the slope of the function.

The problem of combining different units. When vision is used to guide targeted reaching, walking, or throwing, units of visually perceived distance must be scaled to the unit of action. How are multiple sources of visual information or cues about distance (e.g., elevation and vergence) related to a given unit of action? Philbeck, Loomis, and Beall (1997) suggested that the various cues are first combined into a single representation of perceived distance. The unit of this single perceptual quantity would then be mapped to the unit of action by calibration. How should the different sources of information be combined? This problem falls into the domain of cue combination where the leading theory is "weak fusion" (Landy, Malony, Johnston, & Young, 1995). (See, e.g., Ernst & Banks, 2002; Hillis, Watt, Landy, & Banks, 2004; R. A. Jacobs (1999, 2002); Knill & Saunders, 2003; Landy & Kojima, 2001; Landy, Banks, & Knill, 2011; Oruç, Maloney, & Landy, 2003; Rosas, Wagemans, Ernst, & Wichmann, 2005; Trommershäuser, Körding, & Landy, 2011; and Young, Landy, & Maloney, 1993.) The weak fusion approach addressed the problem of cue combination but not the problem of units. Cue combination is described as a weighted averaging process where the weights are a function of the reliability (that is, inverse to the variability) of the cue. This fails when the problem is to combine information involving different units. When the units are different, each source of metric information returns a different value for the same actual target distance. For an observer seated at a table with EH = 24 cm and IPD = 6 cm, a target at a distance of 48 cm will be specified by elevation to be 2 units distant and by vergence to be 8 units distant.[5] How should these two measures be combined? A weighted average of 8 and 2 will not return a useful result. The units must be calibrated to a single unit.

The ultimate problem is that the size of the units of perceptual information can change. For instance, as already noted, EH units change frequently. A real advantage of multiple sources of metric information with multiple associated units is that a change in unit might be recalibrated without use of feedback information. If an altered perceptual unit has to be recalibrated using feedback information, then a targeted action has to be performed on the basis of uncalibrated information, that is, the changed unit. This could be risky or dangerous. It would be better if recalibration could be achieved without having to perform an action. If the mapping from perceptual to action units was calibrated before a change in one of the perceptual units, then the other unchanged perceptual units would remain calibrated to the action unit. This still-calibrated perceptual unit could be used to recalibrate the changed perceptual unit without having to perform an action to obtain feedback. A change in a perceptual unit would be revealed by a mismatch in specified distances. The problem, however, would be to determine

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[5] This second number is an approximation that removes geometrical detail not important to this discussion.

which unit had changed to become uncalibrated and which unit remained calibrated. The mapping theory of calibration is a dynamical theory and includes a dynamical solution. Some units are more stable than others. Some units change frequently over time and others do not. The theory proposes that more stable units should be used preferentially to calibrate less stable units. Ultimately, a dominance hierarchy among units is proposed in terms of their relative temporal stabilities. More stable perceptual units are hypothesized to calibrate less stable units and not the reverse.[6]

In particular, the IPD units that scale vergence information are stable, certainly for adult perceivers. In contrast, the EH units that scale elevation information are less stable. They change frequently. Thus, under conditions where both sources of information are available, the mapping theory predicts that changes in EH should be spontaneously calibrated by IPD but that the reverse should not occur. That is, changes in IPD should not be spontaneously calibrated by EH. Thus, if performance using both sources of information is calibrated to be accurate and then, EH is changed, then performance should remain accurate. However, if IPD were then changed, then performance should become inaccurate in proportion to the change in the IPD unit. We tested this prediction in Experiment 3.

Experiment 3

In Experiment 3, we investigated the effects of changes in the size of a perceptual unit when more than one source of information about metric distance was available. If the respective perceptual units are calibrated to allow accurate performance of targeted actions and then, the size of the unit associated with one of the sources of information is changed, will that unit be recalibrated by the other previously calibrated unit to allow accurate performance to continue? The problem is that, when a perceptual unit is perturbed, an observer might detect that a change has occurred, yet not be able to determine which perceptual unit was perturbed. (In Experiment 3, when the IPD was altered, participants spontaneously exclaimed that the table surface had become closer or farther, meaning that the EH had decreased or increased accordingly, when in fact, it had not. It was the IPD, not the EH that had changed.)

The mapping among embodied units theory of calibration predicts that a dominance hierarchy among perceptual units determines which units are used to recalibrate other units. The hierarchy is theorized to be determined by the relative temporal stability of perceptual units. Units that are more stable and thus change less often should be used to recalibrate units that are less stable.

In respect to the two perceptual units tested in these experiments, IPD is the more stable unit, and EH is the less stable. EH changes frequently, for instance, with changes in posture from sitting to standing or vice versa, whereas IPD changes rarely in adults. Thus, the theory predicts that IPD should be used to recalibrate changes in EH but that EH should not be used to recalibrate changes in IPD. Thus, if both sources of information are available and performance is calibrated to allow accurate targeting, then a change in the EH unit should fail to affect the continued accuracy of performance because that change would be recalibrated using the accurately calibrated IPD unit. The slope of the distance function should remain unaltered by the change in the EH unit. However, if the IPD unit were to be changed, then the performance and the slope of the distance function should change. We tested this in Experiment 3.

Method

Participants. Twelve participants (7 males, 5 females) took part in the experiment and were remunerated at a rate of $10/hr for their time. All participants had normal or corrected-to-normal vision and had adequate stereovision, as tested by the Stereo Test (Stereo Optical). 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 Experiments 1 and 2. A participant sat with his or her head resting on the chin rest and goggles and viewed the textured board through the telestereoscope. Interpupillary distance could be changed as in Experiment 1 using the telestereoscope. Eye height could be changed as in Experiment 2 by changing the height of the textured board. Participants used the cord and pulley to make their responses.

Procedure. As in Experiment 1, participants were first tested to be sure their stereovision was good. If it was, then the procedure was almost identical to that used in Experiment 2. The only difference was that IPD was altered as well as EH.

Four different conditions were completed by each participant. All participants completed 20 calibration trials. Group A participants were calibrated to the small EH with the IPD small, whereas Group B were calibrated to large EH with the IPD large. During these 20 trials, participants were given feedback, using the same method as in the two previous experiments. All participants then completed an additional 30 trials postcalibration (with no feedback). First, both groups completed 10 trials with IPD and EH the same as during calibration. Then, Group A completed 10 trials with EH changed from small to large and IPD remaining unchanged (small), and Group B completed 10 trials with EH changed from large to small and IPD also remaining unchanged (large). Finally, Group A completed 10 trials with EH still large, and IPD now changed from small to large. Group B completed 10 trials with EH still small, and IPD now changed from large to small. Between conditions, participants wore a blindfold while the experimenters changed the texture element panels as in Experiment 2 and, where required, altered the height of the board and size of the IPD. Data analysis was performed as in the previous two experiments except that there were now three sets of conditions to be compared.

Results

As shown in Figure 7, the results were as predicted by the mapping theory. Postcalibration targeting performance is shown in Figure 7a with the calibrated EH and IPD values. As predicted, there was no difference between EH and IPD large and EH and IPD small, because each was calibrated for accurate performance. Postcalibration performance is shown in Figure 7b with the perturbed EH values (and IPD unchanged). As predicted, neither slopes nor intercepts were affected by the perturbations to the EH

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[6] Note that the reliability of a *cue* is not relevant to this problem. What is important is the reliability of the *unit*. The reliability of a cue is not the same as the reliability of a unit.

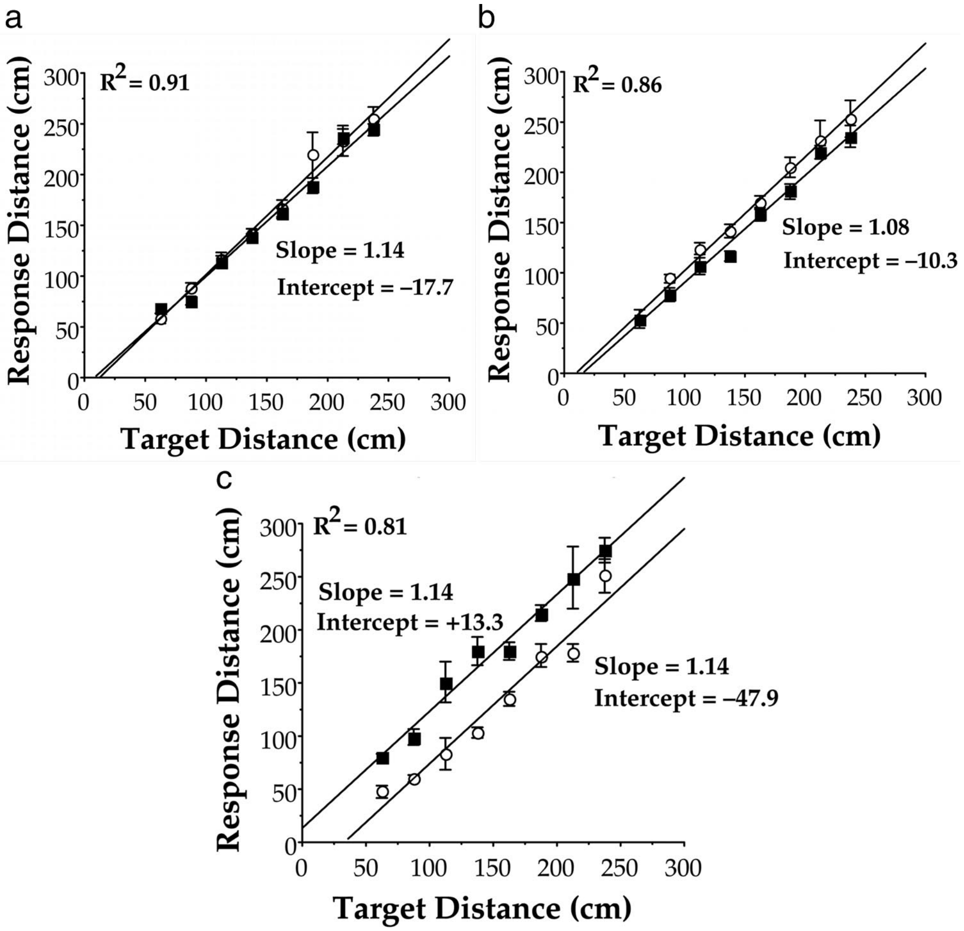

Figure 7. Results of Experiment 3. Responses were collected into 8 bins and a mean response distance was computed for each bin. Mean response distances are plotted as a function of mean target distances. Error bars are *SE*s. Regression lines were fitted to the means using simple regression. Figure 7a shows the postcalibration results with calibrated interpupillary distance (IPD) and eye height (EH) values. Open circles are IPD and EH large. Filled squares are IPD and EH small. Figure 7b shows the postcalibration results with perturbed EH values. Open circles are EH large. Filled squares are EH small. Figure 7c shows the postcalibration results with perturbed IPD values. Open circles are IPD large. Filled squares are IPD small.

units. They were the same for EH changed from small to large, on the one hand, and for EH changed from large to small, on the other hand. Finally, when IPD was perturbed, performance was affected as predicted. When IPD was changed from small to large, targeted responses reliably undershot the target distances. When IPD was changed from large to small, targeted responses reliably overshot the target distances. However, as shown in Figure 7c, these changes yielded significant changes in the intercepts of the distance functions and not the slopes as expected.

As in the previous experiments, we used multiple regressions to test for differences of slopes, intercepts, or both, comparing postcalibration trials between groups in the successive conditions.

First, we examined postcalibration performance with the calibrated EH and IPD. For those who were calibrated to large EH and IPD, we compared their postcalibration trials when EH and IPD were large with the group who were calibrated to small EH and IPD and tested with both EH and IPD small. We predicted there should be no slope or intercept differences between groups. This is indeed what we found. The regression was significant (R^2 = .91, $F(3, 116) = 411.0$, $p < .001$). Slopes were not significantly different from one another ($p > .6$). Also, intercepts were not significantly different from each other ($p > .8$). The mean slope was 1.14, and the mean intercept was −17.7.

Next, we compared the postcalibration performance between groups in the condition where we changed EH but not IPD. So, for those that were calibrated to large EH and IPD, we compared their postcalibration trials when EH was small (and IPD large) with the group who were calibrated to small EH and IPD, when tested with large EH (and IPD small). We expected that IPD would recalibrate the changed EHs, and because IPD was not changed from calibrated values, we should find no differences between groups in either slope or intercept. This is indeed what we found. The regression was significant (R^2 = .86, $F(3, 116) = 234.2$, $p < .001$). Slopes were not significantly different from one another ($p > .3$). Also, intercepts were not significantly different from each other ($p > .7$). The mean slope was 1.08, and the mean intercept was −10.3.

Finally, we compared the postcalibration performance between groups in the condition where IPD was changed. So, for those that were calibrated to large EH and IPD, we compared their postcalibration trials when IPD was changed to small (and EH was also small) with the group who were calibrated to small EH and IPD, tested with IPD changed to large (and EH was also large). We expected that EH would not recalibrate the changed IPD, and because IPD was changed from calibrated values, we should find significant differences between groups. This is indeed what we found. However, we expected differences in slopes, and we obtained large differences in intercepts. The regression was significant ($R^2 = .81$, $F(3, 116) = 165.2$, $p < .001$). Slopes were not significantly different from one another ($p > .4$). The mean slope was 1.14. Intercepts were significantly different from one another, $t(1,116) = 3.3$; $p < .002$. The intercept for IPD changed from small to large and was −47.9. The intercept for IPD changed from large to small and was 13.3.

General Discussion

Cue combination has been a major focus for theories in space perception. Remarkably, despite space perception's extremely long history as a topic of study, including discussions of cue combination, the role of embodied units of perceptual information in the perception of metric properties of the environment has not been considered. Units of perception necessarily entail a process of calibration as part of perception. There are related reasons for this. Calibration is required because perceptual units are different in size and must be calibrated to one another. The units are embodied (i.e., 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 dynamics. Perception of metric distance using vergence information entails an IPD unit, which changes in size slowly over the course of development and then remains stably unchanging during adulthood. In contrast, perception of metric distance using elevation information entails an EH unit, and this changes frequently throughout one's life with change in posture or change in surfaces of support (e.g., floor to table). Logically, different units of perception will be changing at different times. What is the effect on relevant actions of such changes in perceptual units?

If an altered unit is not recalibrated, then the mapping theory predicts that a change in the slope of the distance function should occur. The distance function relates actual target distances to the distances of targeted responses. An uncalibrated decrease in perceptual unit should yield an increase in slope, meaning targeted actions overshoot actual target distances. An uncalibrated increase in perceptual units should yield a decrease in slope, meaning targeted actions undershoot actual target distances. We tested these predictions in Experiments 1 and 2. In Experiment 1, we investigated changes in IPD units of vergence information. In Experiment 2, we investigated changes in EH units of elevation information. In each experiment, we first calibrated the mapping from the respective perceptual unit to the unit of targeted action to yield accurate performance. One group of participants was calibrated using a small perceptual unit. A second group was calibrated using a large perceptual unit. Both groups exhibited accurate targeting performance once calibrated. Next, the size of the perceptual unit was changed. The small unit was made large. As a result, the slope of the distance function decreased as predicted. Participants undershot the targets. The large unit was made small. As a result, the slope of the distance function increased as predicted. Participants overshot the targets. Thus, the predictions of the mapping theory were confirmed.

Normally, perceptual units are recalibrated after such changes in the size of the units, so that the targeted action remains accurate. This recalibration can be achieved using feedback information. However, to yield feedback information, that process requires that the targeted action be performed initially without calibrated information. This might better be avoided as costly (requiring attentive online visual guidance) or hazardous (requiring error prone actions). If more than one source of metric information is available, including an unperturbed calibrated unit, then that unit might be used to calibrate the altered perceptual unit without the need for feedback information.

The question is, How do units of perception interact to achieve such calibration? This brings us properly to the domain of cue combination. As we have noted, all existing theories of cue combination fail to address this problem.[7] The solution requires calibration among units. Just as perceptual units must be calibrated to a unit of action so must multiple units of perception be calibrated to one another. If multiple sources of metric information are available, accurate calibration with feedback will simultaneously calibrate each perceptual unit to the unit of action. In this way, all the perceptual units will be calibrated to one another. Returning to the example described in the introduction (EH = 24 cm and IPD = 6 cm, target distance = 48 cm), the target is specified by elevation to be at a distance of 2 EH units and by vergence to be at a distance of 8 IPD units. 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 $2 \times \text{EH} = \text{AL}$ and the IPD units would be calibrated as $8 \times \text{IPD} = \text{AL}$. Implicitly, EH units would also be calibrated to IPD units as $\text{EH} = 4 \times \text{IPD}$.

The interesting problem arises when one of the units is changed in size after accurate calibration based on feedback. For instance, in our example, EH might be doubled to 48 cm. Now, the target would be specified by elevation to be at a distance of 1 EH unit. (Before the change in unit, it had been calibrated as at a distance of 2 EH units.) The specification by vergence would be unchanged (i.e., still 8 IPD units). When a unit changes in size like this, the perceiver can detect that such a change has occurred. In this case, the 4-to-1 relation between IPD and EH would be violated, and this would reveal that a change in unit had occurred. However, the perceiver is unlikely to be able to determine which unit has changed. A case in point was found in the course of testing participants in Experiment 3. When the IPD was changed in size, participants spontaneously reported that a change in the EH of the table surface had occurred. So, how should units of perception

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[7] Landy et al. (1995) discussed cue promotion as a process that uses metric cues to upgrade nonmetric cues to be metric. This aspect of the weak fusion theory does not address the combination of different metric units or the cross calibration of multiple metric units. The "intrinsic constraint" theory is a more recent alternative theory to weak fusion (Domini & Caudek, 2003, 2011; Domini, Caudek, & Tasinari, 2006). This theory also does not address the problem of units, although calibration based on feedback has been addressed (Foster, Fantoni, Caudek, & Domini, 2011).

interact to yield adaptive recalibration in response to a change in size of a perceptual unit?

In recognition of the dynamics associated with embodied units, the mapping theory hypothesizes a dominance hierarchy among the units of perception where relative dominance is determined by the relative temporal stability of the unit. Units that do not change often should be used to calibrate units that do change often because the former are more likely to remain accurate and the latter not. Thus, IPD should be used to recalibrate changes in EH, but not the reverse. This hypothesis was tested and confirmed in Experiment 3.

In a general sense, calibration involves two measurements of the same physical quantity (Rosen, 1978). The two measurements each entail different units. The units must be appropriately scaled or mapped to one another. As should be clear at this point, this occurs in two ways in perception–action. In the first, feedback is used to calibrate a mapping from perceptual units to action units. The action yields the second measurement. When the units are inappropriately related or mapped, the targeted action results in either over- or undershooting. Feedback information reveals this and allows the mapping between the units to be adjusted accordingly. In this case, there is actually a third measurement (assuming the action to be the second) that yields feedback information. However, this information need only be ordinal (not necessarily metric or involving units). This was studied in Experiments 1 and 2. The second way in which calibration occurs is when there are two perceptual units corresponding to two different sources of information. In this case, one of the two measures must be assumed (or known) to be correct, and the units of the other measurement are then scaled in respect to the units of the correct measurement. This process was studied in Experiment 3.

We had tested the effect of changes in both IPD and EH in Experiments 1 and 2, respectively, when each source of information was isolated. In each case, we found that change in the size of the unit of perception yielded proportional changes in the targeted action, so that the targets were systematically over- or undershot accordingly. This same result was obtained for both vergence (with change of IPD) in Experiment 1 and elevation (with change of EH) in Experiment 2.

In Experiment 3, both sources of information were available simultaneously. Now, the same changes in EH failed to yield any change in the targeted action. Performance continued to be relatively accurate. This result confirmed the mapping theory. The theory predicted that vergence information, with unchanged (and accurately calibrated) IPD, would be used to recalibrate the changed EH, and it was. Next, however, we changed the IPD and obtained a proportional change in the targeted action. When the IPD was increased, the targeted action undershot the targets. When the IPD was decreased, the targeted action overshot the targets. This result also was predicted by the mapping theory because the IPD is the more stable unit. It changes infrequently in adults while EH changes often. Thus, IPD was predicted to recalibrate changed EH, but EH was not predicted to recalibrate IPD.

How did the perceptual units interact to yield the results observed in this last condition? Before the IPD unit was altered, the IPD and EH units were calibrated to the unit of action and to one another. So, for instance, if IPD = 6 cm and EH = 30 cm, then a target at a distance of 60 cm would have been specified by vergence as at a distance of 10 IPD units and by elevation as at a distance of 2 EH units. The two units would have been calibrated to be related to one another as EH = 5 × IPD. Next, if the IPD unit were decreased to 5 cm, then the target (still at 60 cm) would be specified by vergence to be at a distance of 12 IPD units. Because the IPD unit was originally calibrated as 6 cm (and the new value was not recalibrated), this means that the target distance was now effectively specified by vergence as at a distance of 12 × 6 cm = 72 cm. Elevation would still specify the target distance as 2 EH units. Thus, the relation between EH and IPD units would be recalibrated using the changed IPD unit, despite its not having been recalibrated and thus, being inaccurate. The new relation would be EH = 6 × IPD. Because IPD was originally calibrated at 6 cm, EH would now effectively be recalibrated as 6 × 6 cm = 36 cm, that is, larger than its previous value of 30 cm. This is exactly what happened in Experiment 3. When the IPD was decreased in size, participants spontaneously remarked that the surface had been lowered and was farther away. As determined by the dominance hierarchy, IPD was used preferentially to recalibrate EH even though it was the IPD unit that had been changed and was now uncalibrated. The result was that the EH unit was miscalibrated, and performance was systematically inaccurate.

With a 20% decrease in the size of the IPD unit, the response distances should increase by about 20%. With a 20% increase, they should decrease by about 20%. This is essentially what we found in Experiment 3. However, the mapping theory predicted a slope change, and the results yielded a significant change in intercept. Looking at Figure 7c, one can see that the farthest mean departed substantially from the trend obvious in the remaining 7 means. If Figure 7c is compared with Figure 4b, one can see that the latter means well overlap those in Figure 4b, that is, they do exhibit the expected slope change. We do not know why that last mean, representing the farthest response distances (all falling into that last bin), departed from this trend to yield the intercept change in lieu of the expected slope change. The bottom line is that the direction and size of the changes that occurred as a result of the perturbations to the IPD unit were as predicted by the mapping theory.

The mapping theory introduces three important new components to a theory of perception and calibration. The first, and most significant, is embodied units of perception and of action. We here have demonstrated the importance of embodied perceptual units to an understanding of calibration. Embodiment introduces dynamics, and dynamics is clearly essential to calibration as shown both in the current studies and in the extensive research on calibration. Embodied units are dynamic meaning, in part, that they change. Different units change with different characteristic frequencies that inform the way in which the units interact as we have shown. The second important new component introduced by the mapping theory is a dominance hierarchy among different units of perception. The hierarchy is determined by the relative temporal stability of the units. It governs the interactions among the units, determining when a perturbation to a unit is usefully recalibrated by other units and when recalibration would require feedback from targeted actions to be accurate. Changes in the size of the IPD for an adult should be extremely rare, but if and when they occur, the performance of accurate targeted actions must require feedback to recalibrate the change. Such feedback is effective as shown in Experiments 1 and 3. Change in the size of the EH unit is frequent, but when it occurs, the new EH unit is recalibrated spontaneously by vergence information (if it is available) as shown in Experiment 3. The third new component introduced by the mapping theory is the mapping between embodied units of perception and embodied units of action. It is this mapping that is calibrated by feedback from targeted actions. The mapping allows calibration to intercalibrate units associated with multiple available sources of metric information. This interrelation among units subsequently reveals if and when a unit has changed (although it does not reveal which unit has changed). The dominance hierarchy then allows an adaptive response that spontaneously recalibrates the changed unit. In sum, the mapping theory is simultaneously concrete and abstract, including embodied units, dynamics, and mappings. These are the elements required for a flexible and powerful theory sufficient to capture all the complex phenomena entailed in targeted action guided by perception of metric properties and calibration of those actions.

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