Journal of Experimental Psychology:
Human Perception and Performance
2014, Vol. 40, No. 1, 404–415

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0096-1523/14/$12.00 DOI: 10.1037/a0033795

Calibration Is Action Specific But Perturbation of Perceptual Units Is Not

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G. P. Bingham and C. C. Pagano (1998, The necessity of a perception/action approach to definite distance perception: Monocular distance perception to guide reaching. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 145–168) argued that metric space perception should be investigated using relevant action measures because calibration is an intrinsic component of perception/action that yields accurate targeted actions. They described calibration as a mapping from embodied units of perception to embodied units of action. This mapping theory yields a number of predictions. We tested two of them. The first prediction is that calibration should be action specific because what is calibrated is a mapping from perceptual units to a unit of action. Thus, calibration does not generalize to other actions. This prediction is consistent with the "action-specific approach" to calibration (D. R. Proffitt, 2008, An action specific approach to spatial perception. In R. L. Klatzky, B. MacWhinney, & M. Behrmann (Eds.), *Embodiment, ego-space and action* (pp. 179–202). New York, NY: Psychology Press.). The second prediction is that a change in perceptual units should generalize to all relevant actions that are guided using that perceptual information. The same perceptual units can be mapped to different actions. Change in the unit affects all relevant actions. This prediction is consistent with the "general purpose perception approach" (J. M. Loomis & J. W. Philbeck, 2008, Measuring spatial perception with spatial updating and action. In R. L. Klatzky, B. MacWhinney, & M. Behrmann (Eds.), *Embodiment, ego-space and action* (pp. 1–43). New York, NY: Psychology Press). In Experiment 1, two targeted actions, throwing and extended reaching were tested to determine if they were comparable in precision and in response to distorted calibration. They were. Comparing these actions, the first prediction was tested in Experiment 2 and confirmed. The second prediction was tested in Experiment 3 and confirmed. The action-specific and general purpose perception approaches each fail to predict the alternative results predicted by the other. Both sets of results were predicted by the mapping among embodied units theory of calibration.

Keywords: calibration, embodied perceptual units, perception/action, reaching, throwing

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In the mid-1990s, perception researchers studying space perception confronted a puzzling situation. Most of the large number of studies investigating perception of metric distance, size and/or shape were finding performance that was inaccurate and imprecise. These results were puzzling because space perception is used to guide actions, and as a rule, actions are reasonably effective and accurate. Baseball 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). How are these and countless other accurate (open loop) actions possible if the space perception that must support and enable them is so poor?

Bingham and Pagano (1998) addressed this situation (see also Bingham, Coats, & Mon-Williams, 2007) by arguing as follows:

> If action is what perception is for, then space perception should be tested in the context of relevant action.
>
> Perception/action entails an intrinsic component that had been missing in previous judgment studies, namely, calibration. Calibration is required to yield metrically accurate responses.
>
> Optical information is angular so the linear dimension in perceived distance or size is provided by embodied perceptual units that are intrinsically associated with specific optical variables; for instance, Inter-Pupillary Distance (IPD) scales vergence angles in binocular vision and Eye Height (EH) scales the angle of elevation; see extended explanation of what these units are and how they work in the introductory section of Experiment 3.
>
> Calibration is required (a) because perception drifts without calibration as shown, for instance, by Bingham and Pagano (1998) and Vindras and Viviani (1998) and (b) because embodied units of perceptual information must be mapped to embodied units of action. See also Bingham and Romack (1999) and discussion by Fajen (2007).

This article was published Online First August 12, 2013.

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This research was supported by a grant from the National Eye Institute R01 EY011741-08, awarded to Geoffrey P. Bingham.

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The Mapping Among Embodied Units Theory of Calibration that was developed by Bingham and Pagano (1998) entailed 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:

> Calibration of one action does not generalize to another action involving a different unit of action. It is the mapping from units of perception to units of action that is calibrated. Change of action (and the associated unit) renders the calibration ineffective.
>
> Perturbation of embodied units of perception should generalize, on the other hand, to different actions. Different actions are performed using the same perceptual information (and thus, perceptual units). If those units are perturbed, then all of the relevant actions would similarly be perturbed.

A recent book on embodied approaches to perception and action (Klatzky, MacWhinney, & Behrmann, 2008) featured two competing and contradictory approaches to calibration. The "action-specific approach" hypothesizes that perception (including calibration) is specific to action (Proffitt, 2008; Witt, Proffitt, & Epstein, 2010). The alternative "general purpose perception approach" hypothesizes that perception is independent of action (Loomis & Philbeck, 2008). The "mapping among embodied units theory" is a third approach that makes predictions consistent with aspects of both of the other approaches.

First, the action-specific approach predicts that calibration will be action specific. This means that if an action (e.g., targeted throwing), guided using distance perception, is calibrated, then that calibration will not generalize to other actions (e.g., targeted walking) that are also guided using distance perception. The reason is that the perception itself is assumed to be specific to the action. What is perceived is assumed to be, not just distance as such, but instead "distance for reaching" or "distance for throwing," where the perceived property is assumed by the theory to be different in each case and thus, independent. The "mapping theory of calibration" also predicts that calibration will be specific to the calibrated action. The reason, however, is that the specific mapping is assumed to be calibrated. This is important because the mapping theory of calibration entails perceptual units that are assumed to be used in common to guide different actions. The use, however, requires that the perceptual units be mapped to the relevant action units, and it is that mapping that is assumed to be calibrated. Nevertheless, the theory predicts action specificity of calibration just as does the action-specific approach.

Second, the general purpose perception approach predicts that perception generalizes across actions that are guided in common by that perception, for instance, perceived distance. So, a change in the perception is predicted to affect all the relevant actions, that is, to generalize across actions. The mapping theory of calibration also predicts that a change in the relevant unit of perception will generalize to affect all actions using that unit of perception. The reason is that the same perceptual unit can be mapped to different units of action. Although it is the mapping that is calibrated, according to this theory and the mapping is specific to the unit of action, the perceptual unit is not assumed to be specific to a particular action. Thus, a perturbation to the perceptual unit is predicted to affect the different actions to which the perceptual unit is mapped.

Previous studies have found evidence to support the hypothesis that calibration is specific to calibrated actions; however, that evidence is problematic. First, studies that have used verbal judgments to provide such evidence (e.g., Witt et al., 2010) confound hypotheses about calibration with the two-visual system hypothesis. In the early 1990s, Milner and Goodale advanced the two visual systems theory with the suggestion that one visual system (namely, the object recognition or ventral stream) might be relatively insensitive to metric properties of space, whereas the other (the perception/action or dorsal stream) should be sensitive to metric properties and thus, potentially be more accurate (Goodale & Milner, 1992; Milner & Goodale, 1995). Because they also hypothesized that only the ventral stream would entail awareness, visual judgments were assumed to invoke the ventral stream. In the space perception literature, verbal judgments have been contrasted frequently with appropriate action measures. In the context of the two visual system theory, many studies have found dissociations between verbal judgments and action measures, and these results have been used to support the hypothesis of two distinct visual systems. (see Norman (2002) for review.) For instance, Pagano and Bingham (1998) simultaneously tested both verbal judgment of target distance and a reach to the same target in each trial. Each reach yielded haptic feedback about both the actual target distance and errors in perceived distance that could be used to calibrate responses in subsequent trials. Lag 1, 2, and 3 correlations between errors in reaching and in verbal judgments were computed with the finding of no correlation between the two types of responses. Nevertheless, errors decreased over trials, and performance improved in both accuracy and precision. Still, the pattern of errors was consistently different for the two response types. Clearly, the verbal judgments and the action response measure were dissociated as frequently found in other studies. Thus, use of verbal judgments to test action specificity of perception is inappropriate because it confounds issues of calibration with the two visual system hypothesis. Pagano and Bingham (1998) discussed this confluence of issues at length.

Second, earlier studies (e.g., Rieser, Pick, Ashmead, & Garing, 1995) had used action measures (not verbal judgments) to demonstrate a failure of calibration to generalize from one action to another. However, this and other similar studies used targeted locomotion as one of two actions that failed to share calibration. The problem with this, as pointed out by Bingham and Pagano (1998), is that targeted locomotion is a special case. It exhibits a symmetry that is not characteristic of most other actions. In targeted locomotion, the units of perception are the same as the units of action. This difference is evident in the methodology of studies that either did or did not involve targeted locomotion. Most calibration studies using targeted locomotion do not include explicit terminal feedback (or "Knowledge of Results"), whereas studies using, for instance, targeted reaching (e.g., Mon-Williams & Bingham, 2007; the current studies), braking (Fajen, 2005a, 2005b, 2005c), catching (Jacobs & Michaels, 2006), or throwing (van der Kamp, Bennett, Savelsbergh, & Davids, 1999) do. Fajen (2007) showed explicitly that terminal feedback is not required for recalibration of targeted locomotion. To recalibrate visually guided locomotion, a relation between speed of locomotion and speed of resulting optic flow is manipulated. Rieser et al. manipulated this

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relation by putting a treadmill, on which participants walked, on a trailer and pulling it with a tractor at speeds either slower or faster than the speed of walking on the treadmill. (The fast tractor speed is similar in effect to that experienced on the moving sidewalks commonly found in airports.) Another way to achieve the same effect was used in a recent study by White, Shockley, and Riley (2013), who manipulated the optic flow using computer graphic displays viewed by participants in a head-mounted display while walking on a treadmill. Participants viewed (virtual) target cones at two distances, near and far, on the floor of a hallway. As they approached the nearer set of cones, they judged the distance between the two sets of cones. When they reached the nearer set, the far set disappeared. They then walked the distance perceived between the cones and hit a button once they judged they had reached the farther set of cones. Targeting trials were preceded by calibration trials during which participants walked with, for instance, speeded optic flow.

Targeted locomotion is a special case because the units of perception are the same as the units of action. Bingham and Pagano (1998) suggested that stride length was both the embodied perceptual unit, intrinsically coupled with optic flow, and the embodied unit of targeted walking. White et al. (2013) have now shown that the relevant unit in each case is not stride length, but instead metabolic energy. They used a Douglas airbag to measure energy usage as they manipulated either speed of optic flow, speed of locomotion (that is, step frequency), or the slope of the treadmill. (Walking up a slope increases energy usage per unit distance traversed.) Targeted walking distances in all cases were invariant with the energy. This result provides support for the action-specific approach. However, it also shows the symmetry between units of perception and units of action in targeted locomotion. The units are the same, which is not true of other actions like reaching or throwing, where the units of perception are different from the units of action and terminal feedback is required to recalibrate the mapping between these different units. The difference in symmetry is thus confounded with the difference in action in studies purporting to show that calibration fails to generalize between targeted locomotion and other targeted actions. Thus, in the current study, we used targeted reaching and targeted throwing (and not targeted locomotion) to investigate whether calibration would generalize between actions, or not. Both of these actions required terminal feedback to calibrate subsequent performance.

The key element of the mapping theory of calibration is its focus on various embodied units of perception and their interrelations as well as the required mapping to embodied units of action. In this theory, it is the mapping between units that is calibrated. For this reason, calibration is predicted to be specific to the unit of action involved in the mapping, and thus, to the relevant action. However, different mappings can relate the same unit of perception to different actions. If that perceptual unit is perturbed, then logically the perturbation must affect all relevant mappings, and thus, actions. We will test the first prediction in Experiment 2 where we compare two actions, targeted throwing and an extended type of targeted reaching. In Experiment 1, we perform baseline testing of the two actions to determine whether they are comparable in precision and in their respective responses to distorted feedback during calibration. Having found that the two actions are comparable as required, we then predict, in Experiment 2, that calibration of throwing will not generalize to extended reaching and that calibration of extended reaching will not generalize to throwing. In Experiment 3, we will test the second prediction. Two different sources of visual distance information will be made available to participants to be used to perceive target distances. Each source will entail a different perceptual unit, namely, IPD for binocular vergence and EH for (monocular) elevation information. The size of both units will be perturbed in the same way with the prediction that this perturbation will generalize to both actions, that is, both extended reaching and throwing. The results of Experiment 2 are consistent with the action-specific approach, but not the general purpose perception approach. The results of Experiment 3 are consistent with the general purpose perception approach, but not the action-specific approach. Both sets of results are consistent with the mapping among embodied units theory of calibration.

Experiment 1: Comparing Actions—Throwing and Extended Reaching

The goal of this experiment was to test if the two actions we selected, namely extended reaching and throwing, were suitable to be used as response measures. For throwing, a 5-cm diameter Velcro covered ball was thrown to land at the perceived distance of a visible target. For extended reaching, a marker on a cord extended between two pulleys was moved to the perceived distance of a visible target by repeated reaching to pull the cord through the pulleys. There are several intrinsic differences between the two actions. Extended reaching was a one-dimensional action, that is, it only varied along the horizontal distance in depth, because the other two dimensions were fixed by the pulleys. In contrast, throwing required three-dimensional control, that is, although only distance along the depth-dimension was measured, when a participant was throwing, he or she needed to control the release angle, which affected distance along the depth as well as other dimensions. Additionally, in extended reaching, a participant was able to make fine adjustments of positioning. However, in throwing, once the ball was released, the thrower was no longer able to adjust the action. Last, because the extended reaching was a novel but potentially easier task (requiring only one-dimensional control), whereas throwing was a natural action at which participants were more experienced but was potentially more difficult to control, it was necessary to test how well participants were able to perform these actions and whether the actions exhibited the same levels of precision and finally, whether they responded comparably to distorted feedback used during calibration.

To test the two actions we provided the participants with full visual information in a lit environment in which the extended surface of support, on which targets were placed, was well specified by bright texture elements. Both extended reaching and throwing were tested before calibration, during calibration with veridical feedback and postcalibration. In addition, we gave participants distorted or false feedback that mis-represented the actual target distance by +15 cm or −15 cm. After this, we tested them again postcalibration. If the two actions were comparably responsive to calibration, then with accurate calibration, participants should be able to perform throws and extended reaches accurately, showing only comparable random errors. False calibration should yield a systematic error of approximately ±15 cm in each action. We required the actions to be comparable in these respects to be suitable for testing generalization of calibration and changes in perceptual units.

Methods

Participants. Eight participants (half male) 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 using the Stereo Fly (Stereo Optical Co.).

Apparatus. Participants sat at one end of a 5-m-long, 1-m-wide table that was covered in black felt. They sat on the left side of the end. They were seated in an adjustable height chair and asked to rest their chin on the chin rest that was attached to the table. This was used to keep eye-height at 53 cm above the viewing surface throughout the experiment. A large black curtain was hung from the ceiling along the center of the table, extending along the 5-m length. This allowed participants to see targets positioned along the visible textured surface on the left perception side where they sat, but not to be able to see the right "action" half of the table along which they made their responses, either by throwing or by positioning the marker on the pulley. The visible support surface was black with phosphorescent 1- and 2-inch square and circular texture elements that were distributed randomly along a long board (400 cm long and 30 cm wide) placed on the tabletop. On each trial, a target was placed at a distance from the observer on this surface. The target was a phosphorescent X mounted on a black square wooden block with sides of 5.5 cm. The range of distances that the target was placed throughout the experiment was between 50 and 350 cm.

The "action" side of the table was occluded by the curtain so that participants were unable to see the result of their actions. Thus, actions were performed open-loop. A tape measure was attached along each side of the table running the entire length. See Figure 1 for an illustration of the setup.

Two actions were tested in this experiment: extended reaching and throwing. To test extended reaching, two identical pulleys (7-cm radii) were attached to the two ends of the table, with a cord running around them, on the right action side of the table directly to the right of the participant with the cord just below shoulder height. Attached to the cord was a marker, which could be moved smoothly by pulling the cord. The participant was unable to see this marker and could only feel it with the hand at the beginning of a trial. Thus, positioning of the marker was performed open loop. During extended reaching, a participant would first place his or her hand around the curtain to grasp the cord and marker and then send the marker toward the target distance by reaching to pull the cord. The participant repeated this action, grabbing only the cord, as many times as needed to place the marker at the distance of the target on the perception side of the table. We removed the pulleys to test throwing. A small plastic ball (5 cm in diameter) was handed to the participant each trial. The participants were told to throw the ball to land at the distance of the target viewed on the perception side of the table. This ball was covered in black Velcro so that it would stick to the felt-covered tabletop upon contact without rolling. The surface of the table on the action side was also padded so that the ball made little sound on contact with the surface. Hence, participants were unable to see or hear the result of their throwing. Again, the action was performed open loop.

Procedure. After the participant had read and signed consent forms approved by the Institutional Review Board at Indiana University, participants were seated in a chair that was adjusted in height so that they could comfortably place their chin on the chin

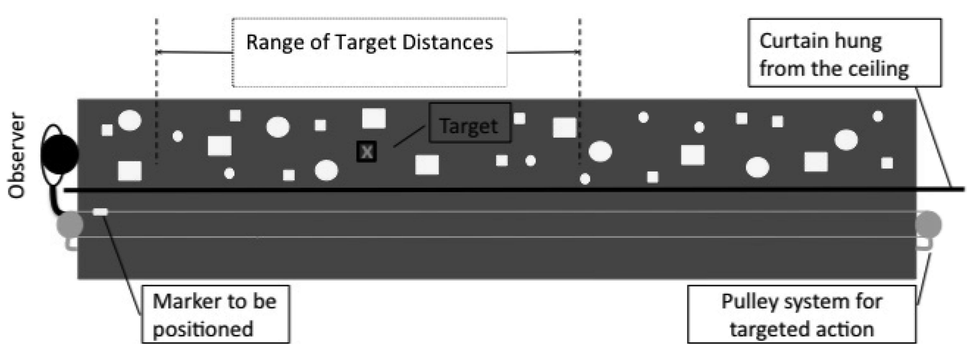

Figure 1. Apparatus used in the experiments. The observer sat at the end of the table on the perception side to the left of a curtain that extended along the length of the table. Responses were made on the action side to the right of the observer. Extended reaching responses were performed using the pulley system on the action side to move a marker to the distance of the target seen on the perception side. Throwing responses were performed by tossing a Velcro-covered ball on the action side to land at the distance of the target on the perception side. The curtain occluded the observer's view of the action responses that, therefore, were performed open-loop. Terminal feedback was provided during calibration trials by an experimenter on the action side who extended a visible rod under the curtain to appear on the perception side relative to the target. The range was 50–350 cm in Experiment 1 and 50–250 cm in Experiments 2 and 3. In Experiments 1 and 2, the observer placed his or her head on a chin rest attached to the table. In Experiment 3, a new type of telestereoscope that included chin and forehead rests replaced the chin rest. The telestereoscope was used in Experiment 3 to change the observer's interpupillary distance. Finally, the surface on the perception side could be rapidly raised or lowered to change the observer's eye height. This was used in Experiment 3. This illustration was not drawn to scale. Actual texture elements were more dense than shown. See Figure 5.

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rest at the end of the perception side of the table. The participant was then asked to close his or her eyes while the target was placed at a distance by one of the experimenters using the tape measure attached to the edge of the table. Distances within the range tested were selected randomly. During the extended reaching task, participants were asked to reach around the curtain to grasp the cord and marker with their right hand. The participant's task was to send the marker out by repeatedly reaching and pulling the cord until the marker matched the distance of the target viewed on the perception side of the curtain. Once the participant had finished adjusting the marker, he or she closed his or her eyes and alerted a second experimenter standing next to the pulleys on the action side of the table, who then measured and recorded the distance of the marker using the tape measure attached to the edge of the table. In the throwing task, a participant first closed his or her eyes and held out his or her right hand so the experimenter could place the Velcro-wrapped ball in the palm. After the experimenter on the perception side placed a target on the visible surface, the participant opened his or her eyes and threw the ball to land on the action side of the table at the distance of the target on the perception side. Then, the participant closed his or her eyes while the experimenter on the action side measured and recorded the throwing distance and handed the ball back to the participant for the next trial. Sometimes participants felt, immediately after releasing the ball, that the throw was inaccurate. In this case, they were allowed to perform the throw again. This happened in approximately 5% of throwing trials. During the experiment, participants only opened their eyes when they were viewing the targets and performing the actions. Experimenters reminded them when they should have their eyes open or closed.

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 to show the participant the distance to which he or she had placed the ball or marker to provide visual feedback to the participant for calibration. The rod could be seen on the perception side relative to the target to reveal positioning error. Target distances were uniformly, but randomly, chosen to cover the range of distances (50−350 cm) for each participant.

All participants first were given accurate calibration of both extended reaching and throwing. Trials were blocked by action. The order of extended reaching and throwing blocks was counterbalanced across participants. Then participants were given false calibration. For half of them, the feedback was always 15 cm shorter than their actual responses, that is, undercalibration (which should have led participants to overshoot by 15 cm during post-calibration trials). For the other half, the feedback was always 15 cm farther than their actual responses, that is, overcalibration. False calibration was applied to both actions in blocked trials with order counterbalanced across participants. Participants were randomly assigned to receive over- or under-calibration treatment. Specifically, for each action, the conditions were: precalibration (6 trials), accurate calibration (10 trials), post (accurate) calibration (15 trials), all for one action, then the other, then over/undercalibration (10 trials), post (over/under) calibration (15 trials), again all for one action, then the other. All participants completed the first three conditions, and then half were overcalibrated and the other half undercalibrated.

Data analysis. Performance error was calculated by subtracting target distance from response distance for each trial. Using performance error as the dependent variable, independent-sample *t* tests were used to test if participants' average reaching and throwing post (accurate) calibration were accurate, that is, different from zero. Paired-sample *t* tests were used to compare performance post (accurate) calibration and post false calibration (using absolute error to combine data from participants treated to either over or under calibration).

Results

The goal of this experiment was to test, under full viewing conditions, whether the two selected actions, namely, throwing and extended reaching, were comparable. Our results showed that this was indeed true and that both actions responded alike to calibration.

Before calibration, response distances were shorter than target distances for both actions. Specifically, in extended reaching, the mean error (defined as response distance minus target distance) was −10.8 cm (SD = 29.2 cm) and for throwing, it was −19.7 cm (SD = 27.2 cm). After calibration with veridical visual feedback, both actions became more accurate and precise, with mean throwing error reduced to −5.4 cm (SD = 20.6 cm) and mean extended reaching error reduced to + 2.1 cm (SD = 21.0). For both actions, participants' average performance errors after accurate calibration were not significantly different from zero, $t_{\text{reaching}}(7) = 0.6$, $p = .6$, $t_{\text{throwing}}(7) = -1.4$, $p = .2$, two-tailed. This showed that both actions could be calibrated effectively with visual feedback.

Additionally, the two actions responded alike in direct proportion to distorted calibration. In this experiment, the visual feedback was either 15 cm farther (overcalibration) or 15 cm shorter (undercalibration) than the actual response distance during false calibration. Mean errors are plotted in Figure 2 for throwing and extended reaching with accurate-calibration, overcalibration and undercalibration. Compared with post (accurate) calibration errors for each action, errors for undercalibration exhibited overshoot by approximately 16 cm in both throwing and extended reaching. Errors for overcalibration exhibited undershoot by approximately 14 cm in extended reaching and 18 cm in throwing. Ignoring the direction of error, the magnitude of error introduced by false calibration was significantly larger than the magnitude of error after accurate calibration for extended reaching, $t(7) = -3.0$, $p < .04$, one-tailed and for throwing, $t(7) = -3.6$, $p < .02$, one-tailed. There was also no change in precision for either reaching or throwing, with standard deviations for both actions of approximately 21 cm. Therefore, both actions were responsive to calibration in like manner and were hence appropriate to be used as experimental tasks in Experiments 2 and 3.

Experiment 2: Does Calibration Generalize Between Actions?

In Experiment 1, we found that both extended reaching and throwing respond to calibration in the same way. Next we tested whether calibrating one action affects the performance of another action. To do this, we first tested baseline performance of extended reaching and throwing without feedback. We tested both actions

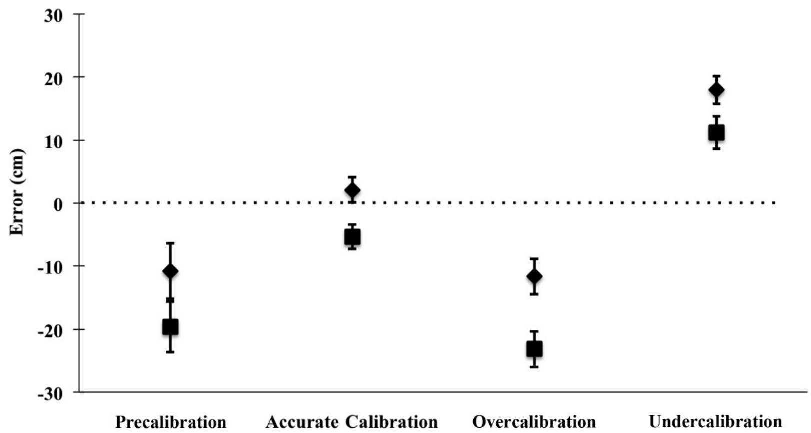

Figure 2. Response errors in extended reaching (diamonds) and throwing (squares) before calibration, after accurate calibration, after overcalibration by 15 cm and after undercalibration by 15 cm. Error bars represent ±1 *SE*.

precalibration. We then calibrated one of the actions by providing false feedback to induce a constant overshoot of approximately 15 cm. Finally, postcalibration responses for both actions were measured. If calibration generalized between actions, falsely calibrating one action should show an effect of overshooting in both actions; if calibration does not generalize between actions, falsely calibrating one action should not affect the other action; that is, the constant error should only be seen in the action that was falsely calibrated.

Methods

Participants. Sixteen participants (half male) took part in the experiment and were remunerated at a rate of $10/hour for their time. All participants had normal or corrected to normal vision and adequate stereovision, as tested by the Stereo Test (Stereo Optical Co.).

Apparatus. The apparatus was the same as that in Experiment 1, except that in this experiment, three perceptual targets of different sizes were used. The perceptual targets were phosphorescent Xs mounted on three black wooden squares, with sides equal to 5.5, 9, and 11 cm. On each trial, one of these targets was randomly selected to control for the effect of image size.

Procedure. The procedure was similar to that in Experiment 1 with some modifications. First, the perceptual targets were placed between 50 and 250 cm from the participant on the perception side. In Experiment 1 responses became more variable as target distance increased. We reduced the range of target distances to obtain more consistent responses. Second, in this experiment, participants completed five different conditions. All participants completed 20 precalibration trials: 10 extended reaching and 10 throwing trials. Then eight participants completed 20 calibration trials of extended reaching and the other eight completed 20 calibration trials of throwing. During these trials, all participants were given false feedback. A rod was pushed under the curtain by the experimenter on the action side 15 cm closer to the participant than the actual response distance. All participants then completed a further 20 postcalibration trials: 10 reaching and 10 throwing. During pre- and postcalibration trials, the order of actions (tested in blocked trials) was counterbalanced. As in Experiment 1, participants had their eyes open only when they were performing the actions. Between calibration and postcalibration conditions, the textured surface of support was rotated 180° (that is, end to end) so the participants could not use the pattern of texture elements as landmarks to aid their perception of distance. During calibration they were advised not to try to use the texture elements to aid performance.

Data analysis. Performance error was calculated by subtracting target distance from response distance for each trial. All analyses were performed on error scores. Using performance error as the dependent variable, we first performed two mixed-design ANOVAs comparing the two actions in respect to the actions that were calibrated, one analysis on precalibration responses, and a second analysis on postcalibration responses.

Second, we examined the levels of variability as measured by standard deviations. We computed a standard deviation for each participant's error scores postcalibration and performed a repeated-measures ANOVA to compare performance of calibrated and noncalibrated actions. We also report between-subjects variability as the standard deviation in each condition of the mean error scores for participants.

Finally, we used false feedback that should yield a consistent 15-cm overshoot so that we could clearly recognize effective calibration. We tested each condition (that is, each action as a function of the calibrated action both pre- or postcalibration) using an independent or group *t* test (two-tailed) to test difference from 15 cm. Strictly, all that can be predicted of uncalibrated performance is that it should be variable. However, it is consistent with this expectation that uncalibrated performance should not reliably exhibit a 15-cm overshoot. Therefore, we expected all effectively uncalibrated conditions to yield a statistically significant difference from +15 cm, whereas the two calibrated conditions should not. Predicting that such a test should fail to reach statistical significance is usually discouraged; however, here we also expect the conditions that fail to reach significance to exhibit lower variance as we will have also tested.

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Results

This experiment was designed to determine whether calibration is action specific. To achieve this, we provided false calibration (that is, visual feedback that was always 15 cm shorter than the actual response distance) to one of the actions and compared performance in each action before and after calibration. Our results showed that the effect of the false calibration was only reflected in performance of the calibrated action and not in that of the action that had not been calibrated.

We used mixed-design ANOVA to test precalibration and postcalibration errors, separately, with action-calibrated as a between-subjects factor and action-performed as a repeated measures factor in each of the two analyses. No factors were expected to be significant in the first analysis. The interaction was predicted to be significant in the second analysis. In the ANOVA on precalibration errors, the action-calibrated was significant, $F(1, 158) = 6.2$, $p < .02$; effect size was 0.04. The means for the two groups of participants (that is, those for whom extended reaching or throwing *would be* calibrated) were −3.2 and −12.8, respectively. Essentially, these represented individual differences in the uncalibrated precalibration performance. The means that for throwing and extended reaching, errors were −8.4 and −7.6, respectively, and thus, were essentially the same. In the ANOVA on postcalibration errors, neither main effect was significant ($p > .2$), but the interaction was significant, $F(1, 158) = 23.3$, $p < .001$; effect size was 0.15. As shown in Figure 3, postcalibration means for the two actions calibrated with false feedback were ≈15 cm as expected, whereas those for the two actions not calibrated were near 0. For participants whose extended reaching was calibrated, we performed a paired t test to compare postcalibration throwing and extended reaching errors. (The latter had been calibrated and the former not.) The result was significant, $t(79) = 3.8$, $p < .001$. Likewise, for participants whose throwing was calibrated, the result was significant, $t(79) = -3.0$, $p < .005$.

As shown in Figure 4, the postcalibration variability was less for the calibrated actions than the other noncalibrated actions, and the variability for those other actions was comparable to the variability for all actions precalibration. We computed a standard deviation for each participant's error scores postcalibration and performed a repeated-measures ANOVA to compare performance of calibrated and noncalibrated actions. The result was significant, $F(1, 15) = 5.0$, $p < .05$; effect size was 0.25. The mean *SD* was 21.1 for noncalibrated actions and 16.0 for calibrated actions. The same analysis, performed on precalibration errors, was not significant ($p > .8$). The mean *SD* was 22.7 for actions that were not to be calibrated and 21.8 for actions that were to be calibrated; that is, both were the same as for the noncalibrated actions postcalibration. Next, we also evaluated between-subjects variability by computing the standard deviation in each condition of the mean error scores for participants. For the conditions, the standard deviations were as follows in pre- to postcalibration. When throwing was calibrated, extended reaching was 26.0 and then 37.9 (variability increased), whereas throwing was 28.0 and then 14.4 (variability decreased). When extended reaching was calibrated, extended reaching was 34.5 and then 27.7 (variability decreased), and throwing was 39.1 and then 36.1 (variability decreased slightly, but was still high).

Finally, we used an independent or group t test (two-tailed) to test difference from +15 cm in each condition. We predicted that all conditions that were uncalibrated (or where calibration was ineffective) would yield a significant difference. Only the calibrated conditions should fail to yield a significant difference in this case, because the false feedback should have yielded overshoot by +15 cm. All conditions, except two, yielded significant results, $p < .002$ or better. The two that failed to reach significance (and

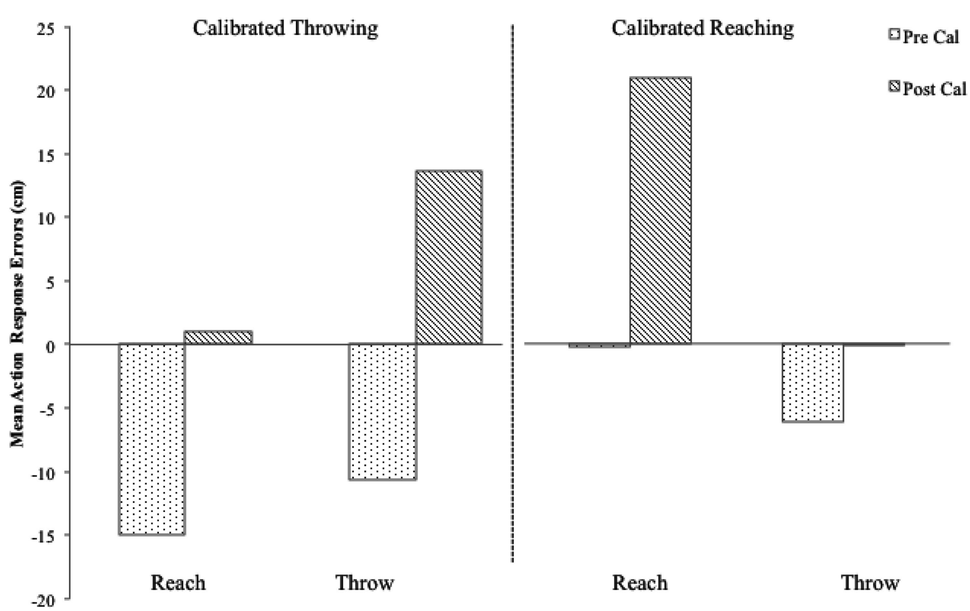

Figure 3. Mean errors for extended reaching and throwing both precalibration (light bars) and postcalibration (dark bars). (Left) Results when throwing was calibrated. (Right) Results when extended reaching was calibrated.

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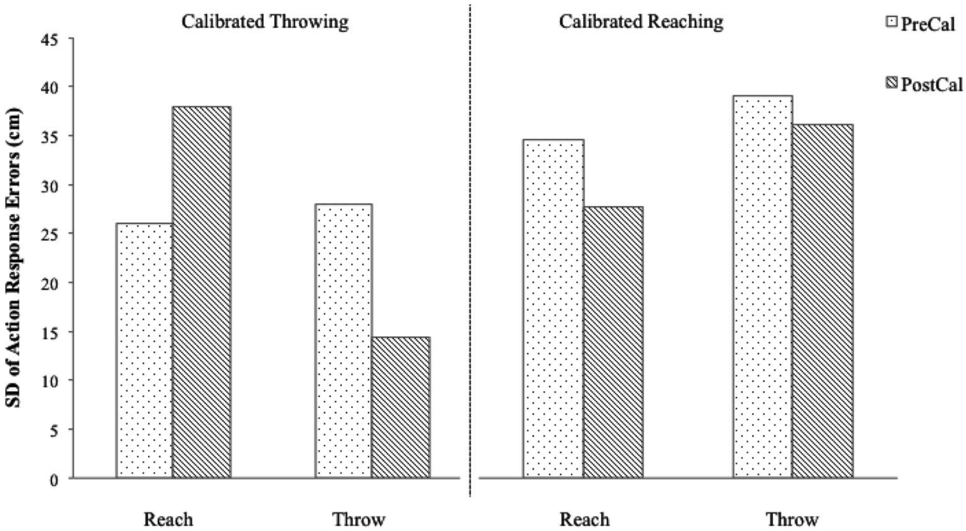

Figure 4. Standard deviations for extended reaching and throwing both precalibration (light bars) and postcalibration (dark bars). (Left) Results when throwing was calibrated. (Right) Results when extended reaching was calibrated.

therefore, were $p > .05$) were both postcalibration, namely, extended reaching when extended reaching was calibrated and throwing when throwing was calibrated. When this result was combined with the finding that the reliability of the performance only increased in the same two calibrated conditions that failed to reach significance in the group *t* test, we concluded that only those two conditions exhibit the effect of calibration.

In short, calibration only affected the calibrated actions and did not generalize to other actions. Calibration is action specific.

Experiment 3: Does Change of Perceptual Units Generalize Across Actions?

The goal of this experiment was to determine whether the effect of a change in units of perceptual information about distance generalizes across actions. We first calibrated each of two actions, extended reaching and throwing, using accurate feedback. Each of the two actions was tested postcalibration. Then, the perceptual units were altered without recalibrating the actions. Instead, each action was simply tested again with the expectation of a change in response distances caused by the change in perceptual units. We predicted that the change in perceptual units would generalize across actions.

We manipulated two perceptual units, each coupled with one of two different sources of visual information about distance: EH units scale the angle of elevation and IPD units scale the vergence angle. The EH unit is defined as the perpendicular distance between the eyes and the surface of support. The IPD unit is defined as the distance between the two eyes. Purely optical information is angular. The linear dimension required to specify metric distance is missing. However, the geometry of viewing couples a linear scaler with optical angular values to yield metric visual information about linear extents (that is for instance, distance or size). For instance, 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, for instance, 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 $\varphi = 45°$, that 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 accurately to the target at a distance of 40 cm. However, if the EH unit is then increased by 25% to 50 cm (by lowering the table) 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. The same type of analysis applies to information specified in binocular vergence angles.

In this experiment, we first calibrated both extended reaching and throwing with both sources of information available and then tested performance of each action postcalibration. Next, we increased the EH and the IPD, each by 25%. Without recalibration, we again tested extended reaching and throwing and response distances were expected to be systematically shorter than responses immediately preceding the change in the size of the perceptual units.

Method

Participants. Twelve participants (four women and eight men) completed this experiment and were remunerated at a rate of $10 per hr for their time. All of them had normal or corrected to normal vision and adequate stereovision, as tested by the Stereo Test (Stereo Optical Co.).

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Apparatus. The experimental setup was similar to that in Experiment 1, except that participants rested their heads on the chin and forehead rest of a telestereoscope, which was used to adjust the IPD optically. See Anderson and Bingham (2010) for description and explanation of this new type of telestereoscope. See Figure 5 for illustration. Additionally, the previously described textured board attached to the table top on the perception side of the table was adjustable and could be easily raised or lowered to produce changes of the EH. Targets used in this experiment were the same as those in Experiment 2.

Procedure. This experiment was conducted in the dark. The telesteroscope was first set to decrease the IPD by 8 mm (relative to the normal IPD), and the adjustable surface of support was positioned to fix the EH at 40 cm. All participants were calibrated and tested performing each of the two actions. They first performed 20 trials of extended reaching or 20 trials of throwing with veridical visual feedback provided by the experimenter pushing a glow-in-the-dark rod through the curtain indicating where the marker or ball had been placed relative to the visual target. Immediately after calibrating one of the two actions, in the next 10 trials, participants performed that calibrated action under the same viewing conditions, but postcalibration (that is, without feedback). These trials were always conducted immediately after the calibrations trials for the same action. Order of testing reaching or throwing was counterbalanced across participants. Then the experimenters reset the telestereoscope to increase the IPD by 16 mm (that is, to 8 mm larger than normal) and lowered the textured surface to an EH of 50 cm. This yielded comparable amounts of change in the IPD and the EH. Given that the average IPD in adults was 65 mm, a 16-mm change from the calibrated condition to the perturbed condition yielded a 25% increase. Also, as compared with the calibrated condition with an EH of 40 cm, the new EH of 50 cm was again a 25% increase. Thus, both perceptual units were increased by 25%. The experimenters were trained to reset the perceptual units quickly and surreptitiously, and participants were asked to keep their eyes closed in between trials such that participants were unaware of this manipulation. Without further calibration, participants performed extended reaching and throwing with the new set of perceptual units, 10 trials of each action with order again counterbalanced across participants.

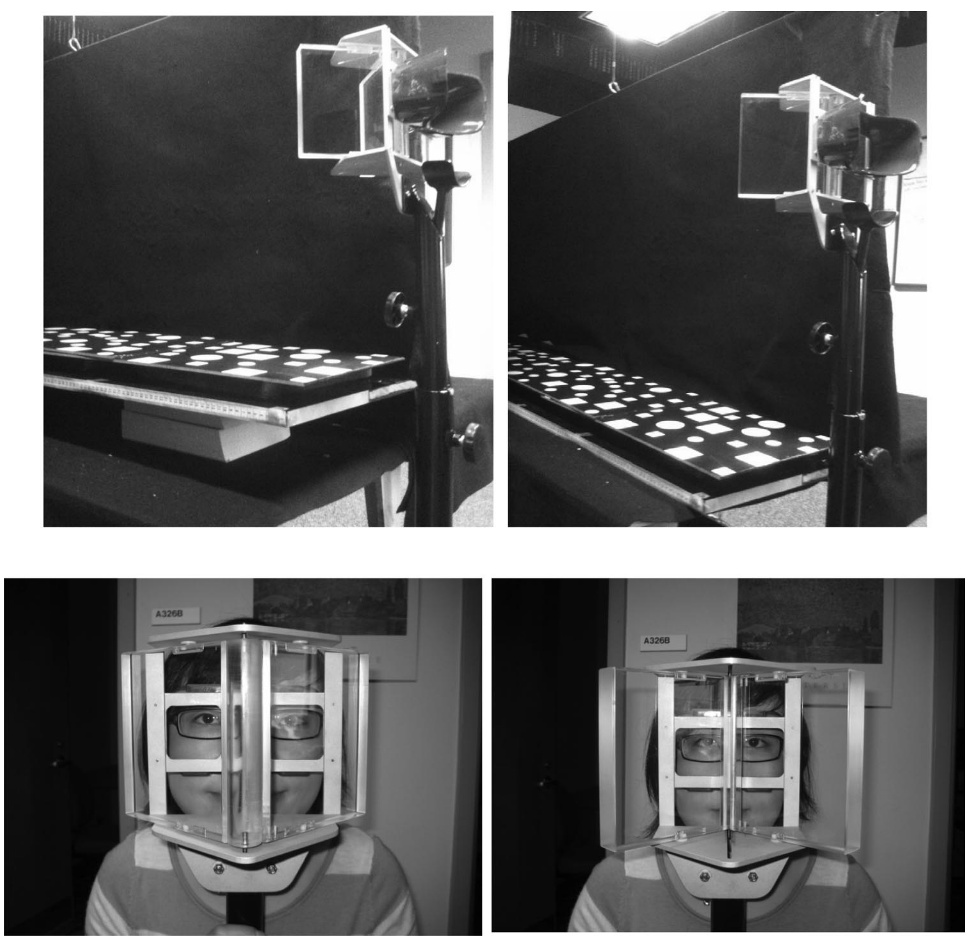

Figure 5. The top two pictures illustrate the change in EH by raising or lowering the textured support surface. The new telestereoscope is also shown. The bottom two pictures illustrate change in IPD both greater than and less than normal produced using the new telestereoscope. See Anderson and Bingham (2010) for full description and explanation.

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Data analysis. For each action, response errors (defined as response distance minus target distance) before and after the change of perceptual units were compared using a paired-samples *t* test. Response errors were also analyzed using a repeated-measures ANOVA with the following factors (and levels): action (reaching, throwing) and perceptual unit (original-calibrated, enlarged-uncalibrated).

Results

To determine how action responses were affected by the increase in the size of perceptual units without recalibration, we compared throwing and extended reaching responses performed with the original, calibrated perceptual units to those performed with enlarged units, both cases having followed a single block of calibration trials for each action with the originally sized units. Trials with response errors more than two standard deviations away from the mean in each condition were considered outliers (approximately 6%) and were removed from the analysis.

Our results showed that calibrating perceptual units to action responses produced accurate responses. Specifically, after calibrating the first set of perceptual units (EH = 40 cm and IPD = −8 mm), the mean error for throwing was −0.9 cm (SD = 14.2 cm) and for extended reaching, it was −5.5 cm (SD = 16.1 cm). When both perceptual units were increased, without recalibration, participants undershot as expected: the mean error for throwing was −27.3 cm (SD = 18.56 cm) and for extended reaching, it was −34.9 cm (SD = 16.4 cm) (Figure 6). Paired-sample *t* tests showed that the decrease in response distances for both actions was significant, with $t(11) = 9.7, p < .001$ for throwing and $t(11) = 11.4, p < .001$ for extended reaching.

A repeated-measures ANOVA showed that response error was significantly affected only by the change in perceptual units, $F(1, 11) = 318.8, p < .001$, effect size was 0.6. Neither the action nor the interaction were significant: action: $F(1, 11) = 1.6, p > .3$; action by perceptual units interaction: $F(1, 11) = 0.4, p > .6$. Figure 6 shows mean response errors in throwing and extended reaching with both original and changed perceptual units. These results show that a change in perceptual units generalized in its effect across actions.

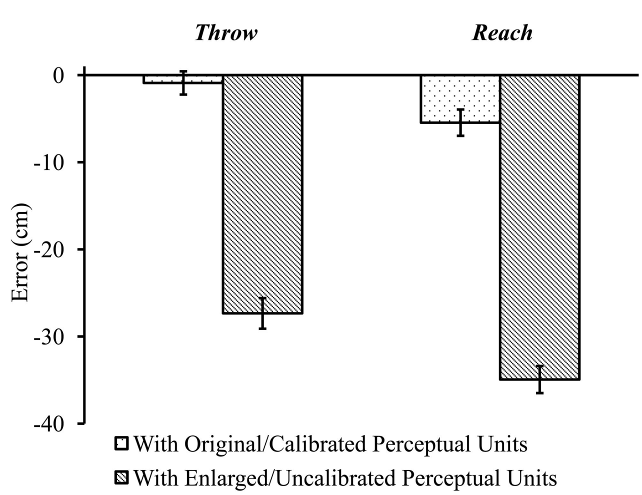

Figure 6. Error means for throwing and extended reaching before and after a 25% increase in the size of the perceptual units. Error bar represents ±1 *SE*.

General Discussion

The goal of these experiments was to test two predictions of the mapping among embodied units theory of calibration. To test these predictions, we used targeted feedforward actions that required terminal feedback for calibration. In Experiment 1, we tested both actions in response to the same distorted feedback to ensure that the actions were comparable in precision and in response to the feedback. They were. The first prediction was that calibration of one action should not generalize to another action. To test this, two groups of participants in Experiment 2 each performed both actions before calibration. Then, one action was calibrated for one group and the other action for the other group, using the same distorted feedback in both cases, namely, 15-cm undercalibration. This was expected to produce 15-cm overshoot in performance of the calibrated actions postcalibration. It did. The central question was whether this effect would generalize for each group to the action that was not calibrated (when tested after the other action had been calibrated). The result was that it did not. Calibration did not generalize to other actions beyond the action calibrated. In addition to having been predicted by the mapping theory, this result was consistent with expectations of the action-specific approach, but not the general purpose perception approach.

However, a second prediction of the mapping theory was that a change in the size of the relevant units of perception would generalize to different actions (in which that information is used). This prediction of the mapping theory was also consistent with the general purpose perception approach, but not the action-specific approach. We tested this prediction in Experiment 3 by providing participants with two sources of visual information about target distance, each involving a different perceptual unit. Elevation angles are scaled by EH and vergence angles are scaled by IPD. Performance of both throwing and extended reaching was calibrated, with given sizes of each of the two perceptual units. Accurate feedback was provided for calibration. Performance was tested postcalibration and was found to be accurate as expected for each of the two actions. Then both of the perceptual units were increased in size by 25%, and both actions were tested again without additional calibration. The result was that targeted throws and targeted extended reaches both reliably undershot the targets, as expected given the increase in the size of the perceptual units. The effect generalized across relevant actions.

Thus, two predictions of the mapping theory of calibration were confirmed. The key aspect of the mapping theory is embodied units of perception and action. The focus on embodied units of perception and the dynamics of their relations to one another and to embodied units of action is new and important. This focus allows us to resolve current debates in the calibration literature while bringing new problems to the attention of researchers. Is perception action specific or general? The answer is necessarily both. On the one hand, it is specific because a mapping is required from embodied units of perception to embodied units of action. Calibration tunes this mapping, and the mapping is specific to the action that returns feedback information used for calibration. On the other hand, embodied units of perception are general to the

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different actions to which they are mapped. A change in a unit naturally affects all the relevant actions. Indeed, the fact that units of perception are embodied means that they can and do change. In Experiment 3, two different perceptual units, EH and IPD, were changed in the same way after the relevant actions had been calibrated. Both were increased by 25%. What would happen if they were changed in different ways, for instance, one increased and the other decreased, or one changed and the other not? Would calibration remain stable? Would one perceptual unit dominate to determine targeting responses or would responses instead reflect some weighted average as suggested by "cue combination theories"? Surprisingly, these possibilities have not been previously considered or investigated, although Coats, Pan, and Bingham (2014) have now ventured to do so following the work herein reported. The role of dynamics in interactions among sources of perceptual information has not previously been featured, but it naturally is when the questions are raised in the context of calibration. A substantial literature exists of investigations revealing the dynamical properties of calibration, for instance, the lag in response to terminal feedback or the stability of calibration once terminal feedback is made unavailable. See, for instance, Bingham (2005); Bingham, Bradley, Bailey, and Vinner (2001); Bingham et al., (2007); Bingham, Pan, and Mon-Williams (2014); Bingham and Pagano (1998); Bingham and Romack (1999); Coats, Bingham, and Mon-Williams (2008); Hu, Eagleson, and Goodale (1999); Lee, Crabtree, Norman, and Bingham (2008); Mon-Williams and Bingham (2007); and Vindras and Viviani (1998). Calibration is akin to learning and as such, it naturally involves dynamics. However, dynamics has not been featured in the longstanding debates among proponents of different cue combination theories. Once interactions among embodied units of perception is considered in the larger context of the calibration of perceptually guided actions, dynamics naturally becomes an intrinsic part of the problem domain. Much future work will be required to pursue the many issues that arise in the context the mapping among embodied units theory of calibration.

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Received September 4, 2012
Revision received March 25, 2013
Accepted June 12, 2013 ■

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