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Calibrating Reach Distance to Visual Targets

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The authors investigated the calibration of reach distance by gradually distorting the haptic feedback obtained when participants grasped visible target objects. The authors found that the modified relationship between visually specified distance and reach distance could be captured by a straight-line mapping function. Thus, the relation could be described using 2 parameters: bias and slope. The authors investigated whether calibration generalized across reach space with respect to changes in bias and slope. In Experiment 1, the authors showed that both bias and slope recalibrate. In Experiment 2, they tested the symmetries of reach space with respect to changes in bias. They discovered that reach space is asymmetric, with the bias shifting inward more readily than outward. The authors measured how rapidly the system calibrated and the stability of calibration once feedback was removed. In Experiment 3, they showed that bias and slope can be calibrated independently of one another. In Experiment 4, the authors showed that these calibration effects are not cognitively penetrable.

Keywords: calibration, prehension, vision, haptic, distance perception

It is a matter of common observation that people are extremely adept when reaching-to-grasp objects. The exquisite control demonstrated by many adult humans belies the inherent difficulties involved in this task. It is, perhaps, only the clumsy grasp of the neonate or the poor control shown in conditions such as cerebral palsy that highlights the complexities of this everyday behavior. Skilled reach-to-grasp movements (*prehension*) require the human nervous system to localize accurately the position of the target object together with the position of the hand and use this information to generate the appropriate movement of the hand in space and time. It has been well established that adult humans can reach and grasp an object with high accuracy and precision, even when a view of the hand is prevented (*vision-open-loop*) during the movement (e.g., Loftus, Murphy, McKenna, & Mon-Williams, 2004). This finding suggests that humans are proficient in gauging the location of an object relative to the hand and in coordinating appropriate movements accordingly. Indeed, Tresilian, Mon-Williams, & Kelly (1999) reported that in a visually rich environment, participants could accurately and precisely align the end of a pointing stick with targets placed up to 100 cm away in a vision-open-loop pointing task. Nevertheless, a plethora of studies have found that distance perception is not necessarily stable, with vision-open-loop pointing becoming progressively inaccurate and imprecise over time (i.e., distance perception drifts). Although the relative amount of instability depends on the nature of the available visual information (e.g., binocular vision yields less rapid decline than does monocular vision), drift appears somewhat inevitable. It appears that the reports of accurate distance perception are at odds with studies showing drift in target localization over time. The apparent conflict can be reconciled by the fact that reports of inaccurate distance perception have come from situations in which participants received no feedback about the outcome of their movement (i.e., they remained in a visual-open-loop environment throughout the experiment). In line with this, a number of research studies have demonstrated that reaches increasingly drift from visually targeted locations as feedback information is removed (Bingham, Zaal, Robin, & Shull, 2000; Vindras & Viviani, 1998; Wann & Ibrahim, 1992; Wickelgren, McConnell, & Bingham, 2000). These observations paint a picture of a nervous system that continually needs to adapt its behavior because it is subject to biological noise. The process of adaptation as a way of producing environmentally geared behavior is well captured by the term *calibration*.

In visually guided reaching, the hand contacts an object, and the resulting feedback (haptic and/or visual) can provide an error signal for calibration, thus ensuring the accuracy of subsequent reaches. In a large number of studies, researchers have used prisms to demonstrate calibration of pointing direction to a visual target (e.g., Bingham & Romack, 1999; Dolezal, 1982; von Helmholtz, 1894/1962; Welch, 1978; Welch, Bridgeman, Anand, & Browman, 1993). Bedford (1989) investigated whether providing distorted feedback regarding directional pointing accuracy at one position would generalize to other locations. To further study the calibration process, Bedford (1989) provided feedback at two separate locations with opposite distortions so as to either compress the space (placing the two directions closer to one another) or expand the space (placing the directions farther apart). Finally, Bedford (1989) provided distorted feedback at three locations to explore the nature of the function relating pointing direction and visually specified direction. The results from her studies showed that the distorted feedback generalized (i.e., participants altered

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their behavior when pointing at target directions in which no feedback information had been provided).

Bedford (1989) first considered whether the changed relationship between visual direction and pointing direction could be mapped in terms of a point-to-point lookup table. In this case, alteration of the relationship would generalize only to a subset of directions in a small neighborhood of a given direction, a pattern reminiscent of a neural tuning function and suggestive of population coding. Neural network models have been developed that use such value-dependent reinforcement learning to capture hypothesized nonlinear alterations of motor function (Rucci, Edelman, & Wray, 1999; Salganicoff, Rucci, & Bajcsy, 1996). Nonetheless, Bedford's (1989) finding that a local response was not produced meant that these models did not describe well the calibration process. Instead, Bedford (1989) found that the changed relationship between visual direction and pointing direction could be captured by a straight-line mapping function. Thus, the relation between visually specified direction and pointing direction could be described using two parameters: bias and slope. Bedford (1989) found that the calibration of direction could involve shifts in bias and/or slope.

The calibration of reaching distance has been investigated less frequently than has pointing direction, and such investigations have occurred only recently. Bingham and Pagano (1998) investigated the calibration of reaching in response to different perturbations of visual information about distance (including viewing with one eye and with a reduced visual field). They found that reach distance became progressively less accurate when calibration was prevented, and drift was increased when the quality of the visual information was degraded. Importantly, Bingham and Pagano (1998) found that accurate performance could be regained by the provision of calibration information even when the quality of the visual information was poor. A number of other studies have indicated the need for feedback information in skilled movement (Bingham, Bradley, Bailey, & Vinner, 2001; Bingham, Zaal, et al., 2000; Loftus et al., 2004; Bingham, Coats, & Mon-Williams, 2007; Wickelgren, McConnell, & Bingham, 2000). The need for calibration is well illustrated by the moving sidewalks present in airports. Rapid calibration is required on the sidewalk for the gauging of one's actions when preparing to step off the sidewalk and, once again, in preparing one's step for the next moving sidewalk (Durgin et al., 2005; Reiser, Pick, Ashmead, & Garting, 1995). Bingham, Vinner, and Shull (2000) studied calibration of reach in virtual environments. Participants viewed virtual spherical targets at either 60% or 80% of their maximum reach distance. The targets appeared either in empty surrounds or on a visible textured surface and were viewed with either monocular or binocular vision. On each trial, participants would place an unseen handheld stylus at the perceived target location. Following the initial recording of the reaches to the near virtual target, researchers placed a physical sphere coincident with the near virtual sphere to provide haptic feedback. The haptic sphere was moved 1 cm closer than the visual sphere after every block of reaches (near and far) until it had traveled 7 cm over eight blocks. The participants were not informed about this experimental manipulation. The results showed that participants altered their reach distances by approximately 7 cm, but post hoc questioning revealed that they were unaware of the experimental manipulation. Bingham, and Shull (2001) replicated the Bingham, Vinner, and Shull (2000) study in all respects except that targets at three distances were tested (60%, 75%, and 90% of maximum reach) and veridical visual feedback was provided for the far target in addition to the distorted haptic feedback provided for the near target. This study showed that participants tracked the two feedback objects to yield a straight-line distance function that altered in both slope and bias. Once more, participants were unaware that the haptic feedback had been manipulated. Typically, participants in both studies would complain that they had a persistent tendency to overreach the target and that they could not prevent this tendency. A few participants suggested that "something was going on" but were unable to identify the actual manipulation.

The results of these experiments provide clear evidence that, in the absence of cognitive awareness, manipulating haptic or visual feedback can cause changes in reach distance. On the other hand, it is known that virtual environments perturb perception, in general, and distance perception, in particular (Bingham et al., 2001; Loomis, Blascovich, & Beall, 1999; Wann, Mon-Williams, McIntosh, Smyth, & Milner, 2001). Thus, results obtained in virtual environments might not be representative of normal reaching behavior. Moreover, a number of research questions were not addressed by these earlier experiments in virtual environments.

We, therefore, set out to explore the calibration of visually guided reaching in a normal environment using unperturbed optics and full vision conditions. Following the work of Bedford (1989), we explored the relationship between visually specified distance (*V*) and reach distance (*D*) using straight-line functions of the following form:

$$D = a + bV, \tag{1}$$

where a and b are constants. Accurate reaching requires the bias (*a*) of the relationship to be 0 and the slope (*b*) to be 1. Our general approach was discovering whether such a function was adequate at capturing the calibration process (the fact that Bedford, 1989, found it useful for direction did not necessarily mean that it would be successful for distance). But, in fact, this function captured well the relationship. Our primary questions, therefore, related to whether we could change the bias and slope and, if so, whether they could change separately. For example, if a participant received feedback that they were undershooting the target by 4 cm at one location, would they increase reach distance at all locations across the workspace (i.e., would the bias shift)? If participants received feedback that they were overshooting near targets but undershooting far targets, would they compress their reaching responses between these locations (i.e., would the slope shift)?

Specifically, we addressed nine research questions regarding calibration. First (a), Could we change the nature of the function relating visually specified distance to reach distance by distorting the feedback provided at the end of the movement? If the answer to this first question is positive, the following questions arise: (b) Does calibration at a given distance generalize when reaches to other distances are tested? (c) Is observation of changes in the bias of the relationship possible? (d) Is observation of changes in the slope of the relationship possible? (e) How rapidly does the system respond to altered feedback information, that is, what is the adaptation time course? (f) Are there limitations on the magnitude of the change? (g) Does a modified relationship stay constant or revert to its original form? (h) Are there asymmetries of calibration across the workspace? (i) Is a change in the relationship between visually specified distance and reach distance necessarily accompanied with cognitive awareness?

Experiment 1

We first set out to replicate the experiments that had been performed in virtual environments. In the first condition, participants reached to grasp virtual cylindrical targets located at three distances. We moved a haptic target at the near distance gradually closer to provide distorted haptic feedback. In the second condition, we added veridical visual feedback to the far target.

Method

Participants. Ten graduate and 10 undergraduate students at Indiana University participated in each of two experimental conditions ($N = 20$ participants). In the haptic feedback condition, 6 participants were women and 14 participants were men. In the haptic and visual feedback condition, 5 participants were women and 15 participants were men. All participants had normal or corrected–to-normal vision and normal motor abilities. We gave participants $10 per hour to defray any costs associated with attending the laboratory.

Apparatus. The apparatus is shown in Figure 1. Participants sat near the corner of an L-shaped table so that one surface of the table lay in their sagittal plane and the other arm of the table was in the coronal plane to their left. A semisilvered mirror (which reflected 60% of the light and transmitted 40% of the light) extended across the corner of the L so that it was 45° to the line of sight. The mirror was 33.7 cm × 24.3 cm. It was in a black wooden frame supported on a rod that extended upward from the table on the inside of the corner of the L. The mirror was placed so that the center was at average eye height. We adjusted each participant's eye height to the mirror height by changing the seat height. A wooden surface 38 cm × 80 cm was placed over each arm of the L at 20 cm below eye height. Each of these surfaces was cut diagonally to fit against the bottom of the mirror at the front and back, respectively. Targets were placed on the table surface extending to the left of the participant (i.e., in front of the mirror). These targets were viewed in the mirror as if located on the surface behind the mirror extending away from the participant. The two table support surfaces could be seen simultaneously in the semisilvered mirror, and the surfaces were positioned so that they appeared exactly coincident. Likewise, cylindrical target objects could be placed on the two surfaces so that they appeared coincident and so that they gave the impression that there was a single object. The illusion was absolutely convincing. Target cylinders were hardwood, 7 cm in height, 7 cm in diameter, and painted matte black. The target placed in front of the mirror was covered with bright dots 1 cm in diameter, whereas the target placed behind the mirror was only black. A black panel was fixed to the back of the mirror by a screw at the upper left corner of the mirror so that the panel also rested on a nail on the bottom right corner of the mirror. A string attached to the right upper corner of the panel extended up over a pulley so that when the experimenter, who was standing on the inside of the L, pulled the string, the panel rotated around the screw up and away from the mirror, giving the participant a simultaneous view of the image in the mirror and the coincident scene behind the mirror. With the panel up, the participant could see his or her hand behind the mirror grasping a virtual object. This method is how visual feedback could be provided. With the panel in the down position, the scene behind the mirror was occluded.

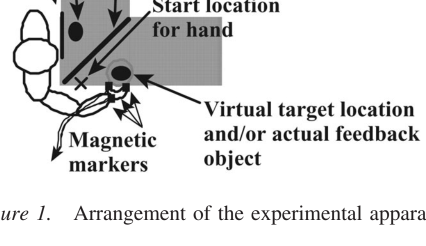

Figure 1. Arrangement of the experimental apparatus.

Reach kinematics were measured using a three-marker Ascension Mini-bird (Ascension Technology Corporation, Burlington, VT) magnetic measurement system. Movements were sampled at 60 Hz. We calibrated the measurement volume, checking loci every 2 cm in a three-dimensional grid over the reach space. Measurements were reliable and accurate within 1 mm. Using double-sided tape, markers 1.1 cm × 0.8 cm × 0.8 cm were placed on the nail of the index finger and thumb and on the first knuckle of the right hand. The wires were gathered around both the wrist and the forearm with Velcro bands. The emitter for the measurement system was placed immediately below the wooden table centered in the reach space. The area that included the L-shaped table and the participant was enclosed by thick, black velveteen drapes that were sound attenuating. The Mini-bird control boxes and computers were outside the drapes. The table was draped with black felt that extended to the floor. An occluding black panel, with an upper edge that rose diagonally to the left, was placed at the front edge of the table in front of the participant so that it would occlude their view of the surface and targets in front of the mirror. The diagonal upper edge of this panel allowed a view of the bottom edge of the mirror. The right edge of the mirror was immediately in front of the participant's right shoulder.

Procedure. Participants read and signed consent forms and then were fitted with the markers. The participants looked down a ruler at the required eye height while the height of the chair was adjusted and while the task and procedure were described. Each reach started with the thumb and index finger of the right hand placed together and resting within view at the bottom right corner of the mirror. The occluding panel was in place behind the mirror so that the hand could not be seen once the reach unfolded. Participants were allowed to practice reaching-to-grasp a purely virtual target and also a physical object. Participants understood that they would be reaching to targets at three different distances and that they would never contact an object at the far two distances but would be contacting an object at the near distance. In the condition in which the participant received visual feedback for the far object, the occluding panel was raised after the reach was completed, and we allowed the participant to see his or her hand grasping the virtual object. This technique also was demonstrated during instruction.

Targets were placed at one of three distances: 22 cm, 28 cm, and 34 cm. Reaches were tested in blocks of trials in which all three distances occurred in a random order. Every two blocks, the haptic feedback object at the near distance was moved 1 cm closer to the participant. Sixteen blocks of trials were tested. In the first condition, only (progressively distorted) haptic feedback was provided for the near object. In the second condition, (correct) visual feedback was also provided to the far object.

The participant wore occluding plastic work glasses between trials while the experimenter silently placed target objects. The participant opened his or her eyes and placed his or her hand at the start location. Mini-bird sampling was started, and the participant was told to reach. Reaches were performed at a normal speed. If experimenters were to give visual feedback, they then raised the occluder behind the mirror.

Participants were instructed that they should always reach to where they saw the target object and if they missed the actual object at the near distance, they should adjust to grasp that object. They were told that if they experienced any difficulty at any point, they should tell the experimenter. Once the haptic feedback object was displaced from the virtual object by 4–5 cm, participants often mentioned that they were having some difficulty. In this situation, the instruction of "always reach to the seen location" was repeated. At the end of the experiment, participants were debriefed and asked if they noticed anything odd and, if so, what they thought was happening.

Results and Discussion

In Condition 1 (haptic feedback at near) and Condition 2 (haptic feedback at near and visual feedback at far), reaches tracked the near haptic feedback target as shown in Figure 2. In Condition 1, reaches to the medium and far virtual targets calibrated with changes over time of about 38%. In Condition 2, the change at the far target was only 10%. The correct visual feedback prevented calibration at the far target from the distorted haptic feedback at the near target. Nevertheless, reaches to the medium target did calibrate with a change over time of 33%. Analyses of the slopes and biases of the distance functions revealed that a slope near 1 was preserved in the first condition, and only the bias changed. In the second condition, both the slope and the bias changed.

The analyses proceeded in two stages. First, we analyzed changes in reach distance for each of the target distances over blocks of trials. Here, we studied the adaptation time course of the changes at each distance or position in reach space. Second, we analyzed changes in the distance functions relating visually specified distance to reach magnitude, examining changes in slope and bias.

To evaluate reach distance, various measures can be taken along a reach-to-grasp trajectory, including the points at which peak speed, maximum grasp aperture (MGA), terminal grasp aperture (TGA), and final grasp aperture (FGA) occur. The *MGA* describes when the fingers achieve their maximum opening in preparation for the grasp. The *FGA* is when the fingers are finally in contact with the target object. The *TGA* is when the hand has stopped moving (that is, reach speed drops to 0), but the fingers have yet to close down to achieve the final grasp of the object (Bingham, Coats, & Mon-Williams, 2007). We used the distance of the hand at the point of TGA as a measure of reach distance. This measure correlated with the distance of FGA, with $r^2 = .99$ and a slope of 1 in both conditions of Experiment 1. It correlated with the distance of MGA, with $r^2 \approx .90$ and a slope of about 0.90 (see Bingham, Coats, & Mon-Williams, 2007, for extended analysis and comparison of these measures).

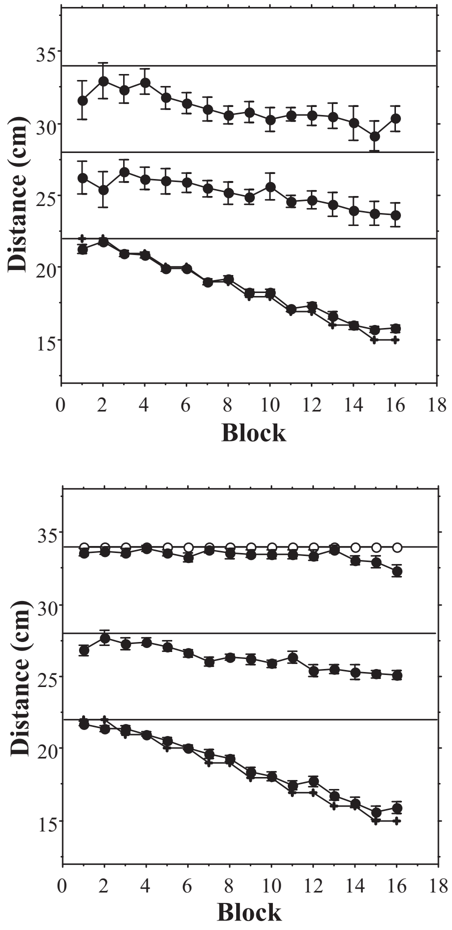

Figure 2. Time series of the reach distance means in Experiment 1. Horizontal lines represent the distances of the visual (virtual) targets. Crosses represent the successive positions of the actual feedback target. The top panel is the haptic feedback–only condition. The bottom panel is the haptic and visual feedback condition. The open circles represent the visual feedback target. Error bars represent standard errors.

Reach distance tracked the distance of the near haptic feedback object in both conditions. Reaches to the virtual targets at the other two distances progressively adapted, but the changes over time were smaller than were the distances in which feedback was provided. To evaluate the changes over time at each of the three virtual target distances, we computed the slope of the relation between the distance of the haptic feedback object and trial block and then divided this slope into slopes computed for reach distances. The results are shown in Table 1. In both conditions, the change over time at the near target distance was 88% (note that the thickness of the blocks meant that this allowed participants to successfully grasp the block). In the visual feedback condition, the change over time at the far target (to which visual feedback was given) was only 10%. The changes over time, otherwise, were

Table 1
Results of Linear Fits to Mean Reach Distances in Experiment 1

Variable	Only haptic feedback	Haptic and visual feedback
Near TGA distance		
Slope	−.43	−.43
r^2	.98	.98
Gain (%)	88	88
Medium TGA distance		
Slope	−.18	−.16
r^2	.84	.87
Gain (%)	37	33
Far TGA distance		
Slope	−.19	−.05
r^2	.75	.45
Gain	39	10
Haptic target		
Slope	−.49	
r^2	.99	

Note. Fits were performed for each of three distances in two conditions. Also shown is a fit to the progressively displaced haptic feedback target. This slope was divided into the others for determination of the relative changes over time (labeled "gain").

between 30% and 40%, that is, intermediate between the two extremes.

We tested possible slope differences by performing a separate multiple regression for each target distance, regressing trial number as a continuous variable and feedback condition as a categorical variable (coded as ±1) and an interaction vector on reach distances (Pedhazur, 1982). For the far target distance, the regression was statistically significant, $F(3, 316) = 45.5$, $r^2 = .30$, $p < .001$, and all three factors were statistically significant: trial number (partial $F = 23.9$, $p < .001$), feedback condition (partial $F = 7.0$, $p < .001$), and the interaction (partial $F = 7.5$, $p < .001$). The statistically significant interaction reflected a difference in slopes. For the medium distance, the regression was statistically significant, $F(3, 316) = 26.4$, $r^2 = .20$, $p < .001$, and only trial number (partial $F = 53.2$, $p < .001$) and feedback condition (partial $F = 5.1$, $p < .05$) were statistically significant. There was no difference in slope. For the near distance, the regression was statistically significant, $F(3, 316) = 563.2$, $r^2 = .84$, $p < .001$, and only trial number (partial $F = 1{,}685.4$, $p < .001$) was statistically significant.

Next, we analyzed the distance functions in each feedback condition using the mean reach distances for each of the three targets in each block of trials. The distance functions for the haptic feedback–only condition are shown in Figure 3. The bias was progressively changed by the distorted haptic feedback, but the slope remained near 1. As shown in Figure 4, the inclusion of correct visual feedback at a second distance yielded changes in both the slopes and biases of the distance functions.

Experiment 2

The first experiments successfully replicated the results of the earlier virtual environment experiments (Bingham & Shull, 2001; Bingham, Vinner, & Shull, 2000). Experiment 1 demonstrated that reaches performed under full vision conditions calibrated in response to distorted haptic feedback information. The calibration generalized to distances across reach space, although the changes over time (at about 35%) were somewhat less than those found previously in the virtual environment. Alternatively, the changes over time were constant. The exponential decrements in the changes over time found in the virtual environment were not in evidence. We performed regression to compute slopes for each participant at each target distance, and we tested for polynomial fits without success. We tested the overall means in a similar fashion, and only linear trends were significant. The final dissociation between visually specified reach distance and reach magnitude was 4–5 cm. This dissociation was somewhat less than that found previously in the virtual environment; however, given the strictly linear trends with no decrement in changes over time, we cannot treat this as the maximum possible dissociation.

The designs used in Experiment 1 were limited in certain respects. First, we noted how well the reaches to the near haptic target tracked that target despite the smaller changes at the other targets. To better test the effect of calibration at the near distance where feedback was provided and to investigate the stability of

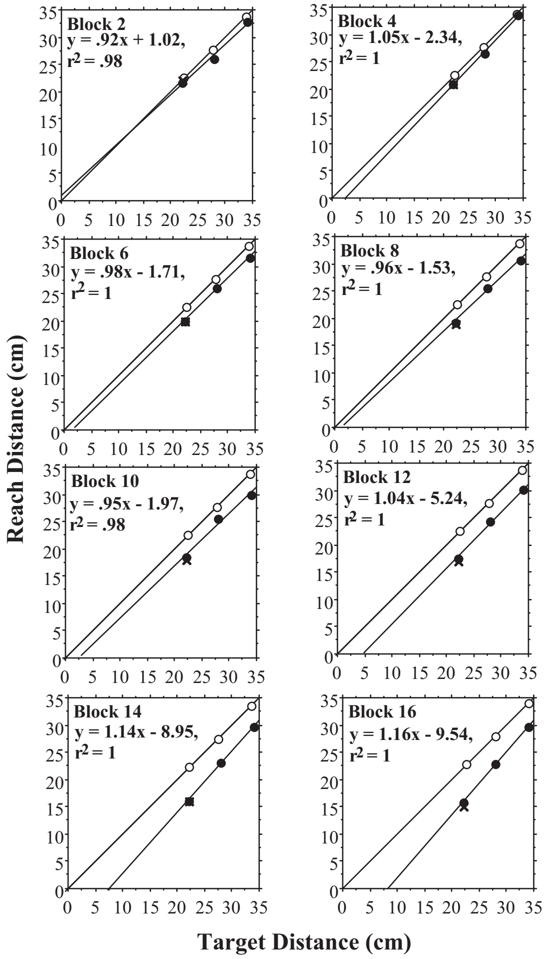

Figure 3. Haptic target–only condition: Empirical distance functions for reach means of even blocks. Also shown for each block are results of simple regressions on the three means. Filled circles represent reach mean distances; open circles represent visual target distances; crosses represent haptic feedback target distance.

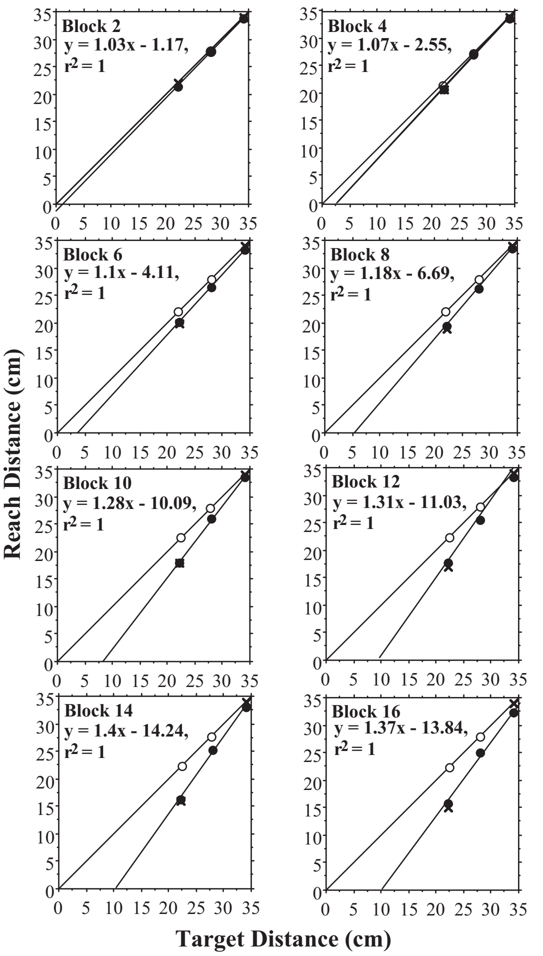

Figure 4. Haptic and visual target condition: Empirical distance functions for reach means of even blocks. Also shown for each block are results of simple regressions on the three means. Filled circles represent reach mean distances; open circles represent visual target distances; crosses represent haptic and visual feedback target distances.

calibration after feedback was removed, we added additional blocks of trials without feedback. We refer to these blocks as *snapback blocks* in contrast to feedback blocks. As long as the actual feedback target was present, it seemed that the reaches to that distance exhibited nearly complete calibration in contrast to the more modest changes (≈30%–40%) exhibited at the other distances. The question was whether reaches would snap back to the same levels as the nonfeedback distances once the feedback object was removed. We also wished to investigate whether the level of calibration would remain stable once feedback was removed or whether reaches would tend to drift back to the initial distances.

Second, we wished to investigate the symmetries of reach space in respect to calibration. Can reach distances be calibrated to farther distances as well as to closer distances? Does feedback to a far object generalize in the same way as feedback to a near object? These questions are inspired, in part, by the fact that near positions are perceived both visually and proprioceptively with greater precision than are far positions in reach space (van Beers, Sittig, & van der Gon, 1998; Tresilian et al., 1999). We used 4 groups of different participants to address these issues. In Experiment 2, we tested responses to distorted haptic feedback only at a single distance.

Method

Participants. Forty graduate and undergraduate students at Indiana University participated in one of four experimental conditions (10 participants per condition). In the near-out and far-out feedback conditions, 5 of the participants were women and 5 were men. In the near-in feedback condition, 6 participants were women and 4 were men. In the far-in feedback condition, 8 participants were women and 2 were men. All participants had normal or corrected-to-normal vision and normal motor abilities. We gave participants $10 per hour to defray any costs associated with attending the laboratory.

Apparatus and procedure. The apparatus was the same as that used in Experiment 1. The procedure was different in the following ways. First, only distorted haptic feedback was tested (i.e., there was no visual feedback). Second, 4 groups were tested in which feedback was provided to either the near or the far target distance and, in both cases, the feedback object was moved progressively closer or farther, respectively. As in Experiment 1, the feedback object was moved 1 cm every two blocks of trials. Third, 14 blocks were tested with progressively distorted feedback followed immediately by 6 blocks of snapback trials without feedback. Preceding the first trial of Block 15, participants were told that they should no longer expect to grasp the actual feedback object. In all other respects, the procedure was the same as that used in Experiment 1. Each participant performed 60 trials.

Results and Discussion

Reaches tracked the haptic feedback targets in each of the four conditions, that is, when the actual target was contacted near or far and moving closer or farther (Figure 5). Nevertheless, the generalization of this feedback across other reach distances varied depending on the locus of the feedback and its direction of change. The changes were greater when reach distance moved closer than when it moved farther. The changes also were greater when the feedback was provided to the near target as opposed to the far target. The calibration changes at the nonfeedback distances remained stable during the snapback trials and, when the feedback objects were no longer present, the reaches to the locations of the feedback targets snapped back to reflect the same levels of change. The calibration was consistent at all distances, and it was stable over blocks of snapback trials. At the end, as shown in Figure 6, calibration altered the biases of the distance functions without changing their slopes (all of which remained near 1).

Once more, we first analyzed changes in reach distance occurring over blocks of trials, examining the generalization of changes over different reach distances. We began analysis with the feedback blocks, Blocks 1–14. We performed simple regressions on the data for each condition and target distance, regressing block number on the mean reach distances. As in Experiment 1, we used the resulting slopes to compute the relative changes over time. The results are shown in Table 2. We used reach distances at the medium targets to compare across conditions because we used both near and far targets to provide feedback in the different conditions. To compare the magnitudes of changes for feedback moving closer versus farther, we used the difference between reach and target distances, changing the sign of the latter data to align the directions. For feedback moving closer, we used reach-target, and for moving farther, we used target-reach. We performed a multiple regression on these distances with block (Blocks 1–14) as a continuous independent variable and with feedback distance (near vs. far, coded as ±1) and feedback direction (closer vs. farther, coded as ±1) as categorical independent variables, together with vectors, coding the three two-way and single three-way interactions.[1] The result was significant, $F(7, 552) = 83.2$, $p < .001$, and accounted for 47% of the variance. We repeated the analysis after having hierarchically removed nonsignificant factors (Pedhazur, 1982). The result was statistically significant, $F(4, 555) = 124.9$, $r^2 = .47$, $p < .001$. The statistically significant factors were Block (partial $F = 137.6$, $p < .001$), Feedback Direction (partial $F = 137.6$, $p < .001$), Block × Feedback Distance interaction (partial $F = 6.1$, $p < .02$), and Block × Feedback Direction interaction (partial $F = 5.7$, $p < .02$). The main effect of feedback direction was a difference in bias of 1.7 cm. The two interactions represented differences in changes over time. The changes over time for feedback moving closer versus farther, respectively, were 43% versus 29%. The changes for feedback to the near versus far targets, respectively, were 41% versus 31%. The changes specific to each of the four conditions and three distances are shown in Table 2. All of these changes reflect strictly linear trends in feedback blocks. We attempted to fit both group data and individual participant data with polynomial trends without success. There were no decrements in calibration as the size of the distortion in the haptic feedback became large. Hence, we can only make inferences about the changes themselves and not about maximum possible dissociation magnitudes. Nevertheless, we next evaluated the size of the dissociation magnitudes obtained.

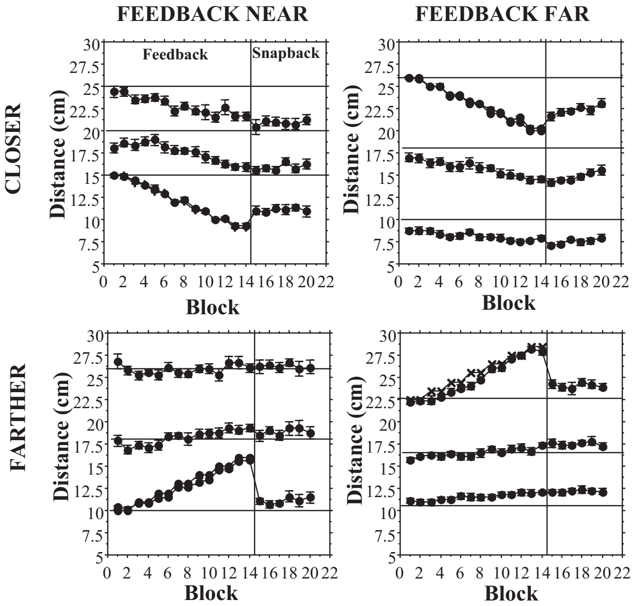

Figure 5. Time series of the reach distance means in Experiment 2. Horizontal lines represent the distances of the visual (virtual) targets. Crosses represent the successive positions of the actual feedback target. The vertical line is the transition from feedback blocks to snapback blocks (which included no feedback). The panels represent the four conditions. The open circles represent the visual feedback target. Error bars represent standard errors.

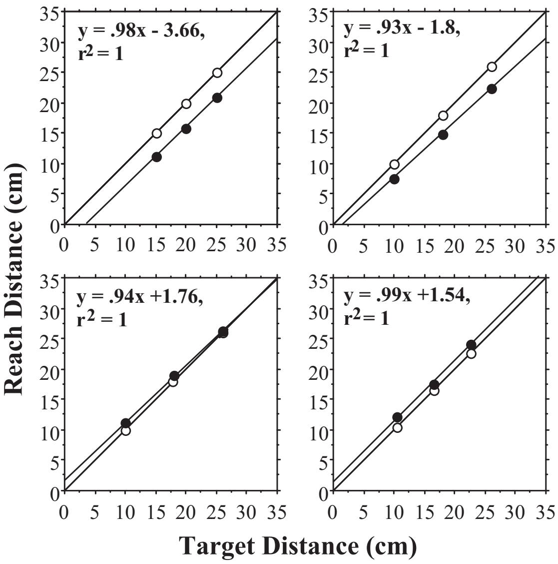

Figure 6. Empirical distance functions for reach means from snapback blocks computed across all six blocks in each condition of Experiment 2. Also shown are results of simple regressions on the three means. Filled circles represent reach mean distances; open circles represent visual target distances. Upper left panel is feedback to the near target moving closer. Upper right panel is feedback to the far target moving closer. Lower left panel is feedback to the near target moving farther. Lower right panel is feedback to the far target moving farther.

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[1] For all of the analyses of this type reported in this article, we obtained essentially the same results by performing mixed-design ANOVAs—in this case, for instance, with Block as a repeated-measures factor and Feedback Distance and Feedback Direction as between-subject factors. Of course, these analyses did not yield the parametric slope and intercept values given to us by the multiple regression analyses, which is why we report those. Finally, in this particular case, we also performed a separate simple regression on the data for each participant and then performed factorial ANOVAs on the r^2, slopes, and intercepts, with Feedback Distance and Feedback Direction as between-participant factors. No factor or interaction reached significance for the analysis on the r^2. The overall mean r^2 was .42, which was comparable to the r^2 for the multiple regression, and the significance, $p < .05$ or better, of most (70%) of these simple regressions replicated the significance of the Block factor. Main effects for feedback direction and feedback distance were tested by an ANOVA on intercepts from simple regressions. Feedback direction was significant, $F(1, 36) = 20.4$, $p < .001$, but feedback distance was not. This replicated the multiple regression result. We tested the Block × Feedback Distance and Block × Feedback Direction interactions by performing an ANOVA on slopes from simple regressions. Feedback direction was significant, $F(1, 36) = 8.1$, $p < .01$, and feedback distance was marginal ($p < .08$). This finding suggested that the direction in which the calibration was pulled was, perhaps, more significant than the distance at which feedback was applied.

Table 2
Results of Linear Fits to Mean Reach Distances in Experiment 2

Variable	Feedback near	Feedback far
	Moving closer	
Near distance		
Slope	−.48	−.08
r^2	.98	.76
Gain (%)	98	16
Medium distance		
Slope	−.23	−.19
r^2	.82	.93
Gain (%)	47	39
Far Distance		
Slope	−.22	−.46
r^2	.84	.98
Gain (%)	45	94
Snapback Distance		
Slope	−.26	−.26
r^2	.98	.96
Gain (%)	53	53
	Moving farther	
Near Distance		
Slope	−.45	−.08
r^2	.97	.89
Gain (%)	92	16
Medium Distance		
Slope	−.17	−.10
r^2	.80	.76
Gain (%)	35	20
Far Distance		
Slope	−.03	−.51
r^2	.07	.97
Gain (%)	6	104
Snapback Distance		
Slope	−.03	−.11
r^2	.52	.92
Gain (%)	6	22
Haptic target		
Slope	−.49	
r^2	.99	

Note. Fits were performed for each of three distances in feedback blocks of four conditions. Fits were also performed at the feedback distance using the first three feedback blocks and snapback blocks. Also shown is a fit to the progressively displaced haptic feedback target. This latter slope was divided into the others for determination of the relative changes over time (labeled "gain").

We performed the same analysis on the data from the snapback blocks to investigate (a) the absolute average magnitude of the changes between visually specified distance and reach magnitude and (b) the temporal stability of calibration. Did reach distances tend to drift back to initial levels once the distorted haptic feedback was removed? If so, this would appear as a main effect of block in this analysis. The multiple regression was statistically significant before, $F(7, 232) = 30.9$, $r^2 = .48$, $p < .001$, and after, $F(4, 235) = 53.5$, $r^2 = .48$, $p < .001$, nonsignificant factors were removed.[2] There was a main effect of feedback direction (partial $F = 12.3$, $p < .001$). The magnitude of the change between visually specified distance and reach magnitude was ±3.5 cm, yielding a range of variation of about 7 cm. There was no main effect for block, $p > .1$. However, two of the two-way interactions with block (Block × Feedback Distance, partial $F = 4.4$, $p < .05$, and Block × Feedback Direction, partial $F = 4.6$, $p < .05$) and the three-way interaction (Block × Feedback Distance × Feedback Direction, partial $F = 7.3$, $p < .01$) were statistically significant. Accordingly, we performed separate simple regressions of block number on distances for each of the four conditions. We found that only the feedback for moving closer condition was statistically significant, $F(1, 58) = 9.6$, $r^2 = .14$, $p < .01$). The remaining three conditions failed to reach statistical significance ($p > .2$ or greater). Therefore, we concluded that calibration was stable. This conclusion is important because it implies that there was no intrinsic or preferred distance to which reaches returned. The difference in effect magnitude between feedback and snapback trials, presumably, reflects different adaptation time courses. Thus, behavior on an individual trial is directly affected by feedback from the immediately preceding trials, but generic adaptation follows a slower time course.

Next we turned to analysis of the distance functions. We performed simple regressions on the mean reach distances for snapback blocks in each condition. To do this, we computed three distance means across blocks. The results are shown in Figure 6. To evaluate the effect of calibration on the slopes and biases of the functions, we performed a multiple regression on the data from the snapback blocks. We regressed the three target distances on the reach distances for the 10 participants and six blocks of data, also using feedback distance (±1) and feedback direction (±1) as categorical independent variables together with the three two-way interactions and the single three-way interaction. The result was statistically significant both before, $F(7, 711) = 1{,}432.3$, $r^2 = .93$, $p < .001$, and after, $F(3, 715) = 3{,}328.0$, $r^2 = .93$, $p < .001$, nonsignificant factors were removed.[3] Target distance was statistically significant, partial $F = 9{,}215.3$, $p < .001$. The overall mean distance function was as follows:

$$\text{Reach Distance} = .95 \times \text{Target Distance} - .32, \quad (2)$$

that is, the slope was near 1 and the bias was near 0. Feedback distance was statistically significant (partial $F = 39.1$, $p < .001$), but the difference in bias between feedback near and far was only 0.7 cm. Feedback direction was significant (partial $F = 1{,}650.7$, $p < .001$), and the difference in bias between feedback moving closer and farther was 4.8 cm. This value was consistent with that found in the stability analysis. None of the Target × Distance interactions reached statistical significance (ps $> .1$); thus, calibration in response to the single haptic feedback object yielded no changes in slopes, with the slopes remaining near 1. Calibration

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[2] Once again, we performed separate simple regressions on the data for each participant. An ANOVA performed on the r^2 yielded no significant factors. The mean r^2 was .34, and 83% of these separate regressions did not reach significance at the .05 level. This finding replicates the nonsignificance of the Block factor in the multiple regression. An ANOVA on intercepts tested main effects. Only feedback direction was significant, $F(1, 36) = 7.62$, $p < .005$. This finding replicated the multiple regression result. No factors were significant in an ANOVA on the slopes. So, again, our conclusions were verified by these subsidiary analyses.

[3] An ANOVA performed on slopes from simple regressions yielded no significant factors, and the mean slope was .93. When the ANOVA was performed on intercepts, both feedback distance, $F(1, 36) = 4.8$, $p < .04$, and feedback direction, $F(1, 36) = 62.9$, $p < .001$, were significant. Again, this replicated the results of the multiple regression analysis.

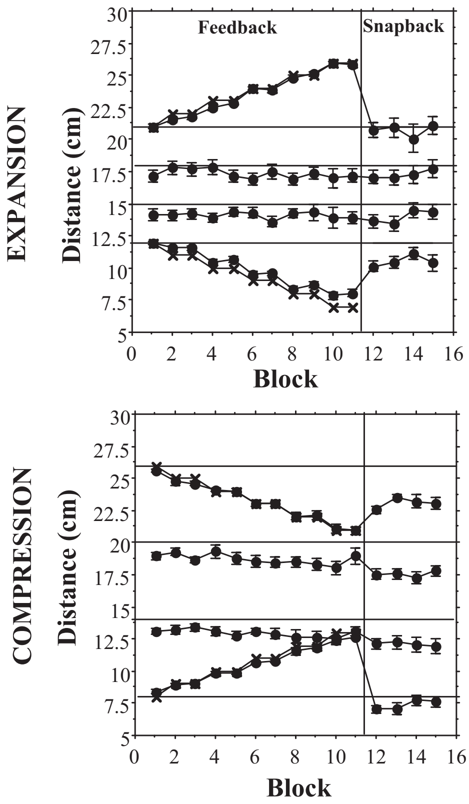

Figure 7. Time series of the reach distance means in Experiment 3. Horizontal lines represent the distances of the visual (virtual) targets. Crosses represent the successive positions of the actual feedback target. The vertical line is the transition from feedback blocks to snapback blocks (which included no feedback). Top panel: Expansion. Bottom panel: Compression. Error bars represent standard errors.

yielded only changes in bias up to about 5 cm, although greater change remains possible.

Experiment 3

To explore calibration of slope, we provided distorted haptic feedback at two distances, near and far, moving one in and the other out. We predicted that the near-in with far-out condition should yield expansion of reach space and that near-out with far-in should yield compression. We used two intervening distances to test generalization of the progressive changes in slope.

Method

Participants. Twenty graduate and undergraduate students at Indiana University participated in each of two experimental conditions (10 participants participated in one condition, and the remaining 10 participated in the other condition). In the compression condition, 8 participants were women and 2 were men. In the expansion condition, 6 participants were women and 4 were men. All participants had normal or corrected-to-normal vision and normal motor abilities. We gave participants $10 per hour to defray any costs associated with attending the laboratory.

Apparatus and procedure. The apparatus was the same as those used in Experiments 1 and 2. The procedure was different in the following ways. Targets at four distances were tested. The middle two distances only ever consisted of visually specified virtual targets. Near and far distances were associated with haptic feedback objects that were moved progressively in and out, respectively, for compression, and out and in, respectively, for expansion. We adjusted target distances between the two conditions to allow room for the respective displacements of the feedback targets. Eleven blocks of feedback trials were tested, followed by four blocks of snapback trials with no feedback. Each participant performed 60 trials.

Results and Discussion

As shown in Figure 7, reaches tracked the feedback objects in all cases with resultant calibration at the intervening nonfeedback distances. Analysis of snapback trials revealed that calibration of slope occurred for both expansion and compression. The calibration was stable over successive snapback blocks. The magnitude of change in slope was the same in both directions at about 13%.

We began analysis by testing the magnitudes of calibration at each distance and the temporal stability of these changes. We performed a mixed design analysis of variance (ANOVA) on data from snapback blocks. We tested differences between target distances and reach distances using condition (expand vs. compress) as a between-participants factor and distance (1–4) and block (1–4) as repeated measures factors. The Condition × Distance interaction was statistically significant, $F(3, 54) = 10.4$, $p < .001$, with a main effect obtained only for distance, $F(3, 54) = 34.3$, $p < .001$. Mean differences ranged from nearly 0 cm to 3 cm, depending on condition and distance, in such a way that they yielded the mean slope changes shown in Figure 8. There was no main effect for block nor were any of the interactions with block statistically significant ($p > .15$ or more in all cases). Therefore, the calibration was stable with no tendency for the slope to drift to an intrinsic or preferred value.

We next turned to analysis of the distance functions shown in Figure 8. We performed a multiple regression on reach distances from snapback blocks using target distance as a continuous independent variable and direction (expand vs. compress, coded as ±1) as a categorical independent variable together with an interaction

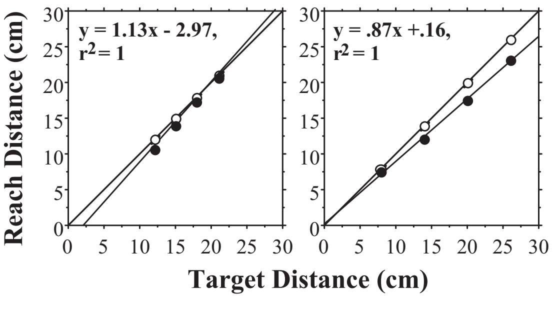

Figure 8. Empirical distance functions for reach means from snapback blocks computed across all four blocks in each condition of Experiment 3. Also shown are results of simple regressions on the four means. Filled circles represent reach mean distances; open circles represent visual target distances. Left panel: Expansion. Right panel: Compression.

vector. The result was statistically significant, $F(3, 316) = 936.3$, $p < .001$, and accounted for 90% of the variance. Target distance was statistically significant (partial $F = 2{,}072.1$, $p < .001$), and the mean distance function was

$$\text{Reach Distance} = 1.0 \times \text{Target Distance} - 1.4\ \text{cm}. \tag{3}$$

Nevertheless, direction was statistically significant (partial $F = 17.3$, $p < .001$), as was the interaction (partial $F = 33.1$, $p < .001$). The difference in bias was 3.14 cm (or ± 1.57 cm), and the difference in slope was 0.26 (or ± 0.13). Thus, calibration resulted in both bias and slope changes, as shown in Figure 8.

Experiment 4

Experiment 4 was a direct test of the role of awareness in these calibration experiments. Participants were told that the object they would grasp might be located incorrectly relative to the visible target object. We instructed them to move the object to the correct location (i.e., at the same place as that of the object they saw). Thus, the participants were made aware of the manipulation, and the question was whether this would prevent calibration from occurring.

Method

Participants. Ten graduate and undergraduate students at Indiana University participated in the single experimental condition. All participants had normal or corrected-to-normal vision and normal motor abilities. We gave participants $10 per hour to defray any costs associated with attending the laboratory.

Apparatus and procedure. The apparatus was the same as that used in Experiments 1–3. The procedure was different in the following ways. Participants were told that the object they would actually grasp might be located incorrectly relative to the target object that they would be seeing. We instructed them to move the object and place it in the correct location so that it would be at the same place as that of the object they saw. Only two target distances were tested (near = 20 cm, far = 26 cm), and haptic feedback was provided only to the near target. However, we determined the placement of the haptic feedback target using a uniform distribution of locations ± 4 cm around a mean location that was gradually displaced (just as in the near closer condition of Experiment 2; see Figure 9 for an illustration). The mean of the distribution began at the visually specified target distance and was moved 1 cm closer to the participant every two blocks of trials over a total of 22 blocks for a total displacement of 10 cm. Nevertheless, given the random variation in placement ±4 cm around this mean from one trial to the next, the feedback object jumped randomly in position by as much as 8 cm. We measured the final position at which participants placed this near target. In addition, we used the measured position of the FGA for reaches to the far, strictly virtual target.

Results and Discussion

The results replicated those of Experiment 2, showing that awareness plays no role in calibration. As shown in Figure 9, awareness did not prevent calibration from taking place. Unlike Experiment 2, however, the data were fit by an exponential trend that yielded an asymptote. The asymptote indicated that a limit of about 7 cm exists for shifting the bias.

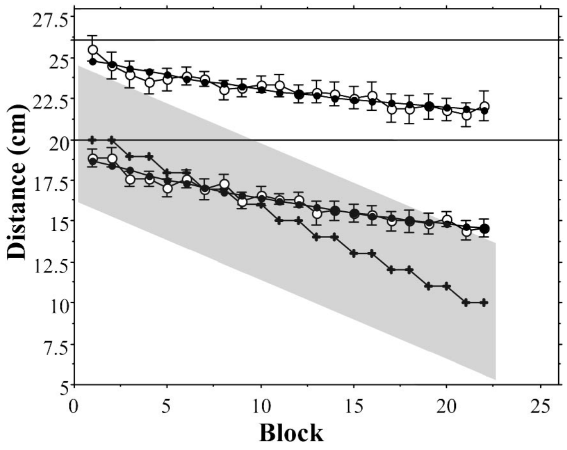

Figure 9. Time series of the distance means in Experiment 4. For the far target, the mean final grasp aperture (FGA) is shown, and for the near target, the mean placement of the actual haptic target is shown. Horizontal lines represent the distances of the visual (virtual) targets. Crosses represent the successive positions of the mean of the distribution for positioning of the actual feedback target. The gray area illustrates the region within which targets were placed. Open circles represent means; filled circles represent exponential functions fit to means. Error bars represent standard errors.

We subtracted target distances from reach distances to obtain displacement distances. We performed a multiple regression, regressing block number on displacement distance together with target distance as a categorical independent variable (coded as ±1) and an interaction vector. The result was significant, $F(3, 436) = 48.4$, $R^2 = .25$, $p < .001$, but the only significant factor was block number. (Note: Each participant experienced a different series of displacements of the haptic feedback object. A simple regression of block number on haptic feedback target distances yielded an R^2 of .64.) The change in calibration over time was 34%, and it was the same for reaches to the near and far target; that is, the slope yielded by the multiple regression (−0.168) divided by the slope for the distribution of haptic feedback object distances (−0.489) was .34.

Using a Quasi-Newton nonlinear estimation, an exponential function was fit either to the means shown in Figure 9 or to the collected data. The results were, essentially, the same. The resulting functions were as follows:

Near: $y = 6.5 \times e^{(-.053 \,*\, \text{block})} + 12.6$ (corrected $R^2 = .95$ for the means; corrected $R^2 = .34$ for the collected data).

Far: $y = 4.7 \times e^{(-.056 \,*\, \text{block})} + 20.4$ (corrected $R^2 = .89$ for the means; corrected $R^2 = .15$ for the collected data).

The asymptote for the near fit yielded a maximum calibration change of 7.5 cm at limit, and the asymptote for the far fit yielded a maximum change of 6.6 cm.

General Discussion

The experiments reported in this article investigated the calibration of reach distance. In previous studies, researchers have shown that reach distance can be calibrated in virtual reality systems. The results of Experiment 1 established that the calibration of reach distance is not unique to virtual environments and can be observed under normal viewing conditions. In Experiment 1, feedback information about hand–object contact was either haptic or visual in nature. It appeared that the two modalities provided equivalent information about contact; thus, only haptic information was used in Experiments 2, 3, and 4. In the introductory paragraphs, we highlighted nine research questions that we sought to address regarding the calibration process. We now consider these questions in turn.

The first question we considered was whether altering feedback at the end of the movement would change the nature of the function relating visually specified distance to reach magnitude. The results from all four experiments showed that distorted feedback is sufficient to change the relationship between reach distance and visually specified distance. These findings emphasize the importance of considering calibration when attempting to understand the control of prehension (and other skilled movements). In the introductory paragraphs, we highlighted the fact that reach distance lacks stability when the opportunity for calibration is restricted. This inherent instability is, perhaps, unsurprising considering that humans are noisy biological systems. Nevertheless, the instability of reach distance does not affect the accuracy and precision of everyday movements. The results reported in this article indicate that the high performance normally exhibited in prehension is a result of the system continually calibrating itself.

Our second question was whether calibration at a given distance generalizes when reaches to other distances are tested. In the first condition in Experiment 1, we provided feedback at a single distance. We found that the slope of the relation between reach distance and visually specified distance was preserved near 1, whereas the bias was changed progressively by the distorted feedback. This finding provided an answer to our third question as it demonstrated that the bias of the relationship can be changed by calibration.

Question 4 asked whether calibration can be associated with changes in the slope as well as the bias. The findings from Experiment 1 clearly indicate that providing distorted feedback at one target location can result in a change in the bias. Experiment 2 replicated this change in bias when one of three targets was subjected to distorted haptic feedback and, again, the bias changed progressively, whereas the slope remained near 1. In the second condition in Experiment 1, we provided feedback at two distances. It appears that the results of this experiment indicate a modification in slope as the reaches successfully tracked the slope changes. In Experiment 3, we provided distorted haptic feedback to near and far distances. To determine the calibration effect, we used two intermediate targets to test generalization of calibration in subsequent snapback blocks with no feedback. The result was that the slope changed. The results of Experiments 1–3 provide compelling evidence that changes in both bias and slope are possible and that these changes are relatively independent.

The fifth question concerned the temporal response characteristics of the reaching system. It is known that too rapid a response to feedback can yield instability and that the optimal temporal change is a function of the delay between feedback and the next response (e.g. Franklin, Powell, & Emami-Naeini, 1994; Jagacinski & Flach, 2003). Indeed, the results from Experiments 1–3 showed that reach distance changed about 30%–40% of the maximum distorted feedback over time. This finding is entirely consistent with a system that is flexible but that has stability. Our results indicate that the reaching system has the stability and flexibility that is expected when considering the exquisite skill shown in tasks such as prehension.

The sixth issue of interest was whether there are limitations on the magnitude of changes in the reach distance. In Experiment 2, we found that the size of the difference between visually specified distance and reach magnitude was ±3.5 cm, yielding a range of variation of about 7 cm. Nevertheless, there was no decrease in change as the size of the haptic feedback distortion became large. In Experiment 4, we explored only two target distances; thus, we were able to test a longer series of blocks of trials. The resulting asymptotes of the exponential fits indicated that the limit for change in bias is about 7 cm. If we infer this to be ±7 cm, then the range of possible change is 14 cm. In Experiment 3, we found that the maximum change in slope was about ±13%.

The seventh question that we attempted to answer related to whether a modified relationship between visually specified distance and reach magnitude would stay constant or revert to its original form. In Experiments 2 and 3, we included snapback blocks in the design, and we found that the calibration was stable. These results are important because they imply that there is no intrinsic or preferred distance to which reaches return.

The eighth question concerned the symmetries of reach space. In Experiment 2, we used targets at near and far distances, and we provided distorted haptic feedback suggesting that the target was either closer or farther than its visually specified distance. We found variations in the extent to which calibration occurred, depending on target location and the direction of the change. We found that the changes were greater when reach distance moved closer than when it moved farther. The changes also were greater when the feedback was provided to the near target rather than to the far target. In contrast, we found, in Experiment 3, that the changes in slope were equivalent whether reach space was being expanded or compressed. This difference in symmetry provides additional evidence that bias and slope are separate with respect to calibration. There are several possible reasons why direction asymmetries exist in the calibration of reach distance with respect to bias. The stiffness and inertia of the arm increase with distance from the body, thus incurring greater energy demands. It is also possible that the changes reflect the consequences of reaching to the wrong place: Reaching short is a relatively safe strategy, whereas reaching long increases the risk of colliding with an object.

The last issue that we wished to address (Question 9) was whether a change in the relationship between visually specified distance and reach distance was necessarily accompanied with (or affected by) cognitive awareness. In existing studies in virtual environments, researchers found that participants were unaware of changes in their reaching behavior either during or following calibration processes. These results were interesting, but an argument could be made that the novel experience of immersion in a virtual environment might mask awareness of other differences in experience. Nevertheless, the present experiments provided a compelling indication that the calibration of reach distance is not cognitively penetrable. The first three experiments reported here involved 80 participants, all of whom were asked to report any strange sensation during the experiment and all of whom were questioned after the experiment about their subjective experience. In line with the results reported for virtual environments, none of the participants could identify the experimental manipulation (i.e., that they were being provided with distorted haptic feedback). It might be argued that relying on subjective impression is inherently unreliable. Thus, in Experiment 4, we alerted participants to the possibility that the haptic feedback object might be misplaced, and we instructed them to place it correctly. Large (≤ 8 cm) changes in the displacement of this object from trial to trial made its potential misplacement obvious. Nevertheless, the mean positioning by participants replicated the previous results, showing progressive calibration in response to the change in the mean location of the feedback target. Once again, in debriefing, participants expressed no awareness of the calibration. Thus, it seems entirely reasonable that these calibration processes are beyond the realm of conscious awareness (in any meaningful sense).

In conclusion, the results from the experiments demonstrate that the relationship between visually specified distance and reach distance is altered through feedback mechanisms. We have found clear evidence that both the bias and the slope of the relationship are altered separately. These findings regarding reach distance reflect the findings of Bedford (1989) regarding pointing direction. Our findings indicate that these calibration processes are not associated with cognitive awareness. The results shed new light on the calibration processes underlying prehension. It is likely that a consideration of these processes will be necessary for making progress in understanding basic motor control and may hold the key to understanding neonatal development and the problems experienced by people with conditions such as cerebral palsy.

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