Throwing Accuracy in the Vertical Direction During Prism Adaptation: Not Simply Timing of Ball Release

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Martin, Tod A., Bradley E. Greger, Scott A. Norris, and W. Thomas Thach. Throwing accuracy in the vertical direction during prism adaptation: not simply timing of ball release. J Neurophysiol 85: 2298–2302, 2001. In a previous study, others have hypothesized that the variance in vertical errors that occurs while throwing at visual targets is caused by changes in any of three throw parameters: hand location in space, hand translational velocity, and hand orientation. From an analysis of skilled throwers, those authors concluded that vertical error is best correlated with variance in hand orientation, which in turn is related to the timing of ball release. We used a vertical prism adaptation paradigm to investigate which of these throwing parameters subjects use when adapting to external perturbation. Our subjects showed no correlation between hand position or hand translational velocity and ball impact height in normal, over-practiced throwing. However, video-based motion analysis showed that modifications both of position and speed of the hand play an important role when subjects are forced to compensate for a vertically shifting prism perturbation during a dart-like throw (these factors contribute ~30% of the adaptation). We concluded that, during adaptation, more degrees of freedom and more sources of potential error are modified to achieve the gaze–throw recalibration required to hit the target than are employed in this type of throw during normal conditions.

INTRODUCTION

Overhand throwing is a complex movement, comprised of several body joints/segments moving at high accelerations and velocities, that is critically dependent on movement timing (Atwater 1979). Given the complicated nature of the movement, humans become exceptionally accurate after they practice overhand throwing.

After studying high-low variability in overhand throws, Hore et al. (1996) hypothesized that three variables could account for the inaccuracies: hand location in space at ball release, hand translational velocity, and hand orientation at ball release. We used vertically shifting prisms to investigate how these variables correlate with ball hit location when subjects adapt to external perturbation.

Adapting to horizontally shifting prisms while throwing consists of making changes among all of the body angles comprising the gaze–throw angle (Martin et al. 1996b). In light of these findings, we asked whether a subject uses only one source of high-low inaccuracy (e.g., timing of ball release) (Hore et al. 1996) to adapt to the vertically shifting perturbation or if instead all three sources of variability are used to adapt the gaze–throw angle to the new calibration.

Portions of this work were presented previously (Martin and Thach 1996).

METHODS

Subjects

Subjects were adult unpaid volunteers who had no history of neurologic injury and were naïve to the experiments. We recorded data from eight subjects (mean age 23.0 ± 5.9 yr, range 18–32; 4 female and 4 male). All were right-handed and threw with their dominant arm. All had participated in recreational softball or baseball but none was highly trained. All gave informed consent.

Task

Seated subjects threw 2-cm-diameter plastic balls (~10 g) at a target centered at shoulder level at a distance of 2.5 m. All throws began with the subjects holding the ball, their upper arm vertical by their sides, and their lower arm and hand horizontal. Subjects were instructed to lift their arm and throw at the target in one smooth motion, to keep their arm in a vertical plane passing through the arm/hand at rest, and to keep their back against the back of the chair. The target board was a 23 × 36 grid of 5 × 5 cm squares on a large Plexiglas board. Each square was divided into four quadrants and ball hit location was called out and recorded by an observer as falling into one of these quadrants in any given square, which resulted in a resolution of 2.5 cm. The target was a 3 × 3 square area in the middle of the board.

After ~10 warm-up throws, subjects threw at the target before, during, and after wearing prism eyeglasses (50 throws for each condition). When donning prisms, subjects viewed the target binocularly through 30-diopter (~17.2°) Fresnel Press-On Optics plastic lenses (Wilson Ophthalmic, Mustang, OK) mounted base-up on safety glasses (which shifted the visual world downward). During all throws, subjects were instructed to throw “where you see the target” and to not look down at their hands. Subjects were not instructed about how fast to throw.

Hit locations were plotted sequentially by trial number (abscissa)
versus vertical displacement (in cm) from an imaginary horizontal line passing through the target center (ordinate); hits below the target were plotted as negative values and hits above the target were plotted as positive values. The adaptive process was modeled by fitting an exponential decay curve to the data, a technique that was described previously (Martin et al. 1996a). The time constant of the curve fit served as a measure of the rate of adaptation [the number of trials required to achieve ~67% of the adaptation; adaptation coefficient (AC)]. The baseline performance of each subject was evaluated by calculating the standard deviation of the baseline throws [performance coefficient (PC)].

### Kinematics

We used video analysis to measure throw kinematics. Reflective markers were placed on the shoulder, elbow, wrist, and fifth metacarpal–phalangeal joints of each subject’s arm and on the front and back of each subject’s head (Fig. 1A). The balls thrown by the subjects were reflective. Subjects were videotaped from the side at 60 fields (30 frames) per second while making 50 throws each before, during, and after wearing prisms. The video was digitized and analyzed using a Peak Performance Motion Analysis System. The positions and angles of the shoulder, elbow, wrist, and head were measured. Angles were defined in a manner similar to that of Hore et al. (1996) (see Fig. 1A). Shoulder, elbow, and wrist angles were measured.

### Table 1. Throwing performance, prism adaptation, and correlation coefficients

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age, years</th>
<th>Baseline, cm ± SD</th>
<th>Prisms, cm</th>
<th>Adapted, cm</th>
<th>Negative Aftereffect, cm</th>
<th>AC, throws</th>
<th>Hand Height</th>
<th>Hand Translational Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prisms, r</td>
<td>After, r</td>
</tr>
<tr>
<td>DB</td>
<td>M</td>
<td>20</td>
<td>1.4 ± 8.3</td>
<td>−53.8</td>
<td>−8.0</td>
<td>31.8</td>
<td>11.30</td>
<td>0.36**</td>
<td>0.22</td>
</tr>
<tr>
<td>RC</td>
<td>F</td>
<td>18</td>
<td>0.9 ± 9.1</td>
<td>−30.1</td>
<td>−1.3</td>
<td>30.1</td>
<td>9.67</td>
<td>0.21</td>
<td>0.18</td>
</tr>
<tr>
<td>JC</td>
<td>M</td>
<td>32</td>
<td>0.9 ± 6.1</td>
<td>−19.1</td>
<td>−4.7</td>
<td>19.1</td>
<td>1.37</td>
<td>0.31*</td>
<td>0.62**</td>
</tr>
<tr>
<td>GE</td>
<td>F</td>
<td>24</td>
<td>−7.8 ± 11.0</td>
<td>−37.7</td>
<td>−19.9</td>
<td>9.7</td>
<td>1.50</td>
<td>0.58**</td>
<td>0.27</td>
</tr>
<tr>
<td>JF</td>
<td>M</td>
<td>32</td>
<td>1.2 ± 6.3</td>
<td>−25.0</td>
<td>−1.3</td>
<td>15.7</td>
<td>0.93</td>
<td>−0.07</td>
<td>0.27</td>
</tr>
<tr>
<td>SN</td>
<td>M</td>
<td>18</td>
<td>−2.0 ± 10.2</td>
<td>−36.8</td>
<td>−6.4</td>
<td>46.1</td>
<td>2.07</td>
<td>0.45**</td>
<td>0.57**</td>
</tr>
<tr>
<td>MP</td>
<td>F</td>
<td>19</td>
<td>−12.2 ± 12.6</td>
<td>−43.6</td>
<td>−4.7</td>
<td>14.8</td>
<td>1.74</td>
<td>0.46**</td>
<td>0.40*</td>
</tr>
<tr>
<td>JT</td>
<td>F</td>
<td>21</td>
<td>−3.5 ± 11.7</td>
<td>−36.0</td>
<td>1.3</td>
<td>19.1</td>
<td>6.67</td>
<td>0.48**</td>
<td>0.56**</td>
</tr>
</tbody>
</table>

The standard deviation of the subject’s 50 throws before donning prisms (Baseline) serves as the performance coefficient (PC). The average of the first three throws after donning prisms (Prisms) serves as an indication of the initial deviation of the subject. The average of the last three throws after donning prisms (Adapted) approximates the location to which the subject had adapted after 50 throws while wearing prisms. The average of the first three throws after doffing prisms (Negative Aftereffect) is a measure of the stored adaptation. The time constant of the exponential decay function fitting the throws made while wearing prisms serves as the adaptation coefficient (AC), a measure of the rate of adaptation. The correlation coefficients (r) for hand height and hand translational velocity at ball release versus ball impact height are listed. Separate values are calculated for throws made while the subject was adapting to prisms and while the subject was un-adapting. Statistically significant values are bold; asterisks indicate level of significance (*P < 0.05; **P < 0.001).
wrist angles were defined as zero when the arm was hanging vertically at rest. These angles became positive with flexion at the shoulder and elbow and extension at the wrist. Time of ball release was selected by choosing the first field of videotape in which the ball was completely free of the hand. The degree of planarity of the throw was determined by measuring the apparent change in length of the forearm during the movement. Planarity of the throw is important in the kinematic analysis because movements outside the parasagittal plane (in this case) introduce error in the position measurements. An apparent change of length of <10% has been proven to be acceptable for analyzing more sensitive measurements of limb movement (Bastian et al. 1996; Hoy et al. 1985); all of our subjects fell far below this measure. Finally, our system was adequate for measuring hand translational velocity and hand height at ball release, but hand orientation at ball release was beyond the quantitative assessment of our system because of the slow sampling speed (60 fields/s) and its importance can only be inferred.

RESULTS

Adaptation of throwing while wearing vertically shifting prisms

Kinematic data for a single throw that hit the target center are shown in Fig. 1, B and C (subject SN) and are typical of control subjects’ throws. The head and shoulder positions (Fig. 1B) and angles (Fig. 1C) remained relatively constant throughout the throw. Across subjects, release usually occurred at or before the zero-crossing of the wrist angle.

The vertical displacements of the hit locations for this subject before, during, and after prism use are plotted in Fig. 2A. Throws before donning prisms fell close to the baseline. The first throw after donning prisms fell ~60 cm below the baseline and subsequent throws fell closer to the target middle. The first throw after the subject removed the prisms was ~60 cm above the target (negative after-effect). The adaptation coefficients for this subject are 2.07 throws with prisms and 13.20 throws after prisms.

Figure 2B shows each throw’s average across all of the subjects in the study (mean ± SD). The adaptation coefficients for these averaged throws are 2.12 throws with prisms and 8.31 throws after prisms. The basic prism adaptation results of each subject are listed in Table 1.

Subjects were not instructed how fast to throw. The average throw velocity across subjects during control throws was 6.9 ± 1.7 m/s (range 2.7–9.8 m/s).

Hand height correlates with height of ball impact

Figure 3 shows that subject SN varied hand height with prismatic condition. In Fig. 3A, a stick figure of the subject’s last throw before donning prisms (light gray) is superimposed on the first throw while wearing prisms (top) and the first throw after doffing prisms (bottom). The wrist paths of the last four baseline throws, the first four throws when donning prisms, and the first four throws after doffing prisms are plotted in Fig. 3B. When donning prisms, the subject first threw with the wrist beginning at the same position as the last baseline throw but proceeded more downward through ball release (Fig. 3B, vertical ticks). The wrist positions during the subsequent three throws were also below the wrist path of the baseline throws. After doffing the prisms, the subject threw with a wrist position showing a negative aftereffect.

Hand height was measured at a fixed distance in front of the subject to remove the confounding factor of timing of release. Figure 3C shows ball impact height plotted against hand height measured 20 cm in front of subject SN’s sternum. All throws made while donning prisms (empty circles) and after doffing prisms (shaded circles) are plotted. The subject showed a significant correlation between the values of ball impact height and hand height during prism adaptation [r = 0.45; P(r = 0) < 0.001] and during un-adaptation after doffing prisms [r = 0.57; P(r = 0) < 0.001]. Six of eight subjects showed significant
correlations between hand height and ball impact height during prism adaptation; four of eight subjects showed significant correlations between the same variables during un-adaptation (Table 1). All significant correlations were of the predicted and appropriate sign. No subjects showed a significant correlation between hand height and ball impact height during control throws.

Hand translational velocity correlates with height of ball impact in half of subjects

In Fig. 3D, hand translational velocity is plotted against throw number during one subject’s adaptation (subject SN). There is a gradual increase in hand translational velocity, which mimicks the trend seen in the subject’s prism adaptation throws (see Fig. 2A). The subject showed significant correla-
tion between ball impact height and hand translational velocity during prism adaptation \( [r = 0.40; P(r = 0) < 0.05] \) but not during un-adaptation \( [r = 0.26; P(r = 0) = 0.066] \). Four of eight subjects showed significant correlations between hand translational velocity and ball impact height during prism adaptation; five of eight subjects showed significant correlations between the same variables during un-adaptation (Table 1). All significant correlations were of the predicted and appropriate sign. Only subject GE showed a significant correlation between hand translational velocity and ball impact height during control throws.

**Discussion**

The current study design (e.g., throw numbers, range of errors) was similar to that of Hore et al. (1996) but differed in the velocity of the throws. Thus, because our throwing paradigm involved a slower throw (~8 m/s in our study vs. 14 m/s for Hore; our study involved a more “dart-like” throw), our results cannot be directly compared. However, the behavior of our subjects during baseline throws was consistent with that seen in the study of Hore et al. (1996). Most subjects showed no correlation between hand translational velocity or hand height and ball impact height when throwing before donning prisms. However, our subjects showed a statistically significant correlation between these variables and ball impact height when they were required to adapt to vertically shifting prisms. During prism adaptation, six of eight subjects showed significant correlation between hand height and ball impact height and four of eight subjects showed significant correlation between hand translational velocity and ball impact height.

Among the 10 subjects of Hore et al. (1996), none showed a statistically significant correlation between the height of the hand 20 cm in front of the sternum and ball impact height. In addition, it is unclear how many subjects had a significant correlation between hand translational velocity and ball impact height, although they state that “variations in hand translational speed, and therefore ball flight time, were not a major factor in the present experiments” (Hore et al. 1996, p. 1022). The results of their studies suggest that only hand orientation at ball release and, more specifically, timing of ball release correlate with high-low inaccuracy.

Several calculations show the significance of the changes in hand height and hand translational velocity in our study. For subject SN, both variables were correlated with ball impact height. The difference in ball impact height for this subject’s first and last throws while wearing prisms was ~50 cm. The height of the subject’s hand 20 cm in front of the sternum was 15.9 cm for the first throw and 20.4 cm for the last throw while wearing prisms, which accounts for 4.5 cm of the total 50 cm adaptation. The ball’s forward translational velocity after release was 6.76 m/s for the first throw and 7.94 m/s for the last throw. If we assume that the ball was released 0.5 m in front of the sternum, then the ball traveled 2.0 m to the target. A velocity of 6.76 m/s results in a flight time of 296 ms for the first throw and 252 ms for the last throw. During this time, the ball will fall \( \frac{1}{2} gt^2 \) because of gravity. These values are 42.9 cm for the first throw and 31.1 cm for the last throw, which results in the last throw falling 11.8 cm less than the first throw.

Thus differences in ball impact height caused by height of the hand (4.5 cm) and hand translational velocity (11.8 cm) account for 16.3 cm (or 32%) of the 50 cm adaptation. On average, for subjects for whom these two variables were statistically significant, they accounted for 9.7 and 21.2%, respectively, of the total adaptation of each subject. The third variable, hand orientation during ball release (or timing of ball release), accounts for the remainder (and majority) of the adaptation.

Our data show that all three of these sources of control of high-low inaccuracy are involved when adapting gaze-throw recalibration to vertically shifting prisms. Although it would not be surprising if hand height or hand translational velocity correlated with ball impact height when a subject was asked to throw first at a target straight ahead, then 30 cm below the target and 30 cm above the target, Hore et al. (1996) demonstrated that hand translational velocity and hand height do not correlate with throw inaccuracy over ranges of ~30 cm during normal throwing; our results confirm theirs. Furthermore, our results show that the conclusions of Hore et al. (1996) accurately describe the kinematics of normal, over-practiced throwing. Nonetheless, when an individual faces a novel perturbation and has to adjust, finding a motor solution may involve many or all degrees of freedom.

Prablanc et al. (1975) noted, when studying the sensorimotor and perceptual loci of prism adaptation, that “it is probably more fruitful to consider prism adaptation as a process aimed at resolving the visuomotor conflict by using any available cue rather than as a process relying on a single specific mechanism.” Our results show that the motor system uses any and all available sources of gaze-throw recalibration during adaptation to vertically shifting prisms.

On a suggestion from R. Held, N. Daw and T. Wiesel developed this task for teaching.

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**References**


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