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Eye Movements and the Selection of Optical Information for Catching

Eric L. Amazeen, Polemnia G. Amazeen, and Peter J. Beek

Faculty of Human Movement Sciences
Vrije Universiteit
Amsterdam, The Netherlands

The direction of gaze during a single-ball throwing and catching task was analyzed to generate hypotheses regarding the optical information that participants used. Five intermediate and 5 expert jugglers threw and caught a single ball continuously with 1 hand while wearing a head-mounted eye tracker to monitor their direction of gaze. Participants were instructed to throw the ball at 3 self-paced frequencies: preferred, one half of preferred, and twice preferred. Analysis of the digital eye tracker data along with the video recording of the ball and hand revealed that all participants viewed the ball at or around the ball's zenith. Intermediates varied only the mean phase of viewing across frequencies. Experts, however, varied the initiation of viewing, the point of minimum gaze to ball distance, the mean viewing phase, and the mean time between viewing and catching across frequencies. Both groups initiated the final downward movement of the hand toward the catch 89 msec after the ball's zenith. The implications of these results for the optical information for catching and expertise in a perceptual–motor task are discussed.

Controlling an interceptive act such as catching requires the availability of some form of information, usually optical. The most common way to investigate the optical information for catching starts with a formal expression of a potentially informative optical variable. For example, the inverse relative rate of optical expansion, tau, for an object approaching at a constant velocity, can specify the time remaining until contact with the point of observation without specifying size, distance, or closing velocity (Lee, 1976). The effectiveness of this variable has been tested by presenting

Requests for reprints should be sent to Eric Amazeen, Department of Psychology, Arizona State University, Tempe, AZ 85287. E-mail: eric.amazeen@asu.edu

observers with variations in tau (or tau-like quantities) and evaluating increases or decrements in catching performance (e.g., Bootsma & Oudejans, 1993; Savelsbergh, Whiting, & Bootsma, 1991; Savelsbergh, Whiting, Pijpers, & Van Santvoord, 1993). This approach, however, has remained limited in its ability to explain fully the role of optical information in controlling an interceptive act (Van Santvoord & Beek, 1994; Wann, 1996).

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We took a different approach in this experiment, which is based on the observation that, in many interceptive acts, one tends to use only a portion of the available information. In catching, for example, one tends not to track the approaching object along its entire trajectory to the point of interception (see discussion by Abernethy, 1991). Experiments have shown that individuals are able to catch a ball, or juggle more than one ball, successfully even when the ball(s) cannot be viewed along the entire trajectory (Amazeen, Amazeen, Post, & Beek, 1999; Austin, 1976; Savelsbergh et al., 1993; Sharp & Whiting, 1974; Van Santvoord & Beek, 1994; Whiting, 1968, 1970; Whiting, Gill, & Stephenson, 1970; Whiting & Sharp, 1974). In such cases, the individual attends selectively to some optical transformation to obtain the most relevant information at the most appropriate time. Therefore, identifying the portion of the ball's trajectory to which the individual attends should provide clues about the optical information for catching.

Amazeen et al. (1999) investigated the constraints that participants invoke in selecting optical information during a rhythmic throwing-and-catching task. Two existing hypotheses were contrasted and tested. The first was that individuals selected information at a particular time relative to the catch (Sharp & Whiting, 1974, 1975; Whiting & Sharp, 1974). The second was that individuals selected information from a particular phase of the ball's trajectory, such as the zenith (Austin, 1976; Todd, 1981; Van Santvoord & Beek, 1994; Watson, Banks, von Hofsten, & Royden, 1992). Participants in Amazeen et al.'s study wore liquid-crystal occlusion goggles that limited viewing to specific amounts of time at specific intervals. The task was to throw and catch a single ball continuously for 1 min with one hand in whatever manner was most comfortable. An analysis of the phasing and timing of the viewing indicated that individuals selected information at a particular time relative to the catch, 361 msec.[1] Participants often chose to view the ball before it reached its zenith. This observation, along with the observation that participants appeared to time the movement of the hand to the time of

[1]This value was incorrectly reported as 365 msec by Amazeen et al. (1999).

the ball's zenith, led Amazeen et al. to conclude that participants were using optical information about the time of the ball's zenith.

We used a similar procedure in this experiment, except that the artificial constraints on viewing that were imposed by the liquid-crystal goggles were replaced by a head-mounted eye tracker. Experiments investigating the direction of gaze during other interceptive acts have shown that individuals exhibit gaze patterns specific to a particular task. In tasks such as returning a badminton serve (Abernethy & Russell, 1987) or a tennis serve (Goulet, Bard, & Fleury, 1989), participants directed their gaze to the racquet and the body of the server rather than to the ball in flight. In other tasks, such as hitting a baseball (Shank & Haywood, 1987) or returning a volleyball serve (Vickers & Adolphe, 1997), individuals directed their gaze toward the ball during the early portion of its flight trajectory. Similarly, the pattern of gaze across the ball's trajectory during a rhythmic throwing-and-catching task (in which the participant controls both the movements of the ball and gaze) should provide insight into the physical variables and associated optical transformations that are selected and used in catching.

Research on the direction of gaze during an interceptive act has sought to identify differences as a function of expertise. Differences have been investigated in the contexts of sports such as badminton and squash (Abernethy, 1991; Abernethy & Russell, 1987), baseball (Shank & Haywood, 1987), cricket (Abernethy & Russell, 1984), ice hockey (Bard & Fleury, 1981), lawn tennis (Jones & Miles, 1978), tennis (Goulet et al., 1989), and volleyball (Vickers & Adolphe, 1997). One pervasive finding is that experts tend to use earlier optical information than do novices or intermediates. Often, this means that experts are directing their gaze at the individual launching the object, whereas novices and intermediates wait to direct their gaze at the object in flight. Differences as a function of expertise have been equated with the education of attention (E. J. Gibson, 1969; J. J. Gibson, 1979/1986), information-processing capabilities (Goulet et al., 1989), and cognitive and perceptual skills (Starkes, 1987). In each case, it would be assumed that experts would exhibit gaze patterns that better reveal the optical information for catching.

Overview

This experiment was designed to investigate the pattern of gaze during catching. Instead of limiting or constraining the visibility, participants wore a head-mounted eye tracker to monitor when and where the line of gaze was directed at the ball. Participants were instructed to throw at three frequencies—preferred, one half of preferred, and twice preferred—in order to distinguish between the times and phases of viewing. Both expert and intermediate jugglers were used to test whether the observed patterns varied with experience. Analyses of the hand's trajectory were conducted to examine if the selection criteria were related to the kinematic portrait of the hand.

METHOD

Participants

Ten jugglers participated in this study. Five of the jugglers were intermediate jugglers, and 5 were expert jugglers.[2] All of the participants could maintain a three-ball juggle comfortably for 1 min. Experts were defined as jugglers who could juggle five or more balls. One of the intermediate jugglers could juggle four balls and made regular attempts at juggling five. Nine of the participants were men, and 1 intermediate participant was a woman.

Apparatus

Participants were videotaped while they threw and caught a white ball (a juggling "stage ball") that was 7.3 cm in diameter and 130 g. A video camera was mounted on the floor 4 m in front of the participant. The frame rate of the video camera was 50 Hz, resulting in a temporal resolution of 20 msec. To avoid any unnecessary distraction of the participant, and to maximize the contrast on the head-mounted video camera, the floor-mounted camera was situated behind a hole in a black wall. The walls behind and to the sides of the participant were covered in black to maximize contrast on the floor-mounted video camera.

The participant's direction of gaze was monitored with an EyeCatcher head-mounted eye-tracking system (H. A. Mooij Holding B. V., Oegstgeest, The Netherlands). The eye-tracking system consisted of an eye tracker (Series 4000 Eye Tracker, Applied Science Laboratories, Bedford, MA) mounted onto a lightweight helmet. In addition to the eye tracker itself, the helmet was fitted with a head-mounted video camera (ELMO CCD Color Camera, Model MP481, 90° lens).

The lighting in the room was carefully controlled to ensure sufficient contrast on the ball for the video analysis while minimizing the amount of light entering the eyes for the eye tracker. This was accomplished by lighting the ball from the two sides perpendicular to the observer's line of sight. Lights were placed behind screens that had narrow slits cut out. This resulted in a range of about 25 cm, front to back, in which the ball would be appropriately lit without excessive light entering the eyes. Moving out of this range resulted in errors in the eye tracker, video analysis, or both.

Procedure

Participants threw and caught a single ball continuously with their right hand in whatever manner was most comfortable. The trial length was 1 min, and a success-

[2]Contrary to expectations, professional jugglers who can juggle three balls blindfolded report that it is more difficult to throw one ball continuously without vision than it is to juggle three balls without vision. We expected, therefore, that both groups would use optical information when rhythmically throwing and catching a single ball.

ful trial was defined as one during which the participant maintained continuous throwing and catching for the entire minute without dropping or fumbling the ball. The experiment consisted of six successful trials, two trials at each of three frequencies. Data were collected on two trials to ensure that clean data (i.e., no errors on the videotape or from the eye tracker) would be available, although only one of the two trials was analyzed. There were a number of trials with lost data, but at least one clean trial was available from each participant in each condition. Participants were responsible for selecting the frequencies of throwing and catching. In the first condition, the participant was instructed to throw the ball at his or her most comfortable, or preferred, frequency. After completing two successful trials at this frequency, participants completed two trials each at one half and twice their preferred frequency, in a random order.

Data Reduction and Analysis

The horizontal and vertical positions of the ball and wrist on the videotape from the floor-mounted camera and the horizontal and vertical positions of the ball on the videotape from the head-mounted camera were digitally recorded from each frame of the videotapes for the first 20 sec of each trial. In the case of an error in either the video recording or the digital output from the eye tracker, the data from the second successful trial were analyzed.

The vertical-position time series of the ball and wrist from the floor-mounted camera were analyzed to determine the moments (in milliseconds) of each throw, catch, and zenith of the ball as well as the moments (in milliseconds) when the wrist was accelerated or decelerated in the vertical direction (this measure refers to the location of the wrist, not the wrist angle). The phase angle of the ball at sample i, θ_i (rad), was calculated as

$$\theta_i = \arctan(\dot{y}_i / y_i), \qquad (1)$$

where y_i and $\dot{y}_i$ are the vertical position and the time derivative of vertical position, respectively, at sample i normalized to be more symmetric around zero in the phase plane by subtracting the mean value of the series from each sample and then dividing each sample into the maximum for that series. The ball's zenith occurs at $\theta_i = 0$. A time series of the angular frequency of the ball, ω_i (rad), was computed using the time-derivative of θ_i. The mean ω_i for each trial, ω_{ave}, was used as the measure of ball frequency. The zenith of the ball's trajectory on each cycle was defined as the moment of maximal vertical position. The moment of the ball's maximal upward velocity on each cycle defined the moment of the throw, and the frame following the maximal downward velocity of the ball on each cycle defined the moment of the catch.

The vertical- and horizontal-position time series of the ball from the head-mounted camera were analyzed along with the digital output of the eye tracker to determine the position of the direction of gaze relative to the ball while the ball was in sight. A ball was defined as in sight on a particular sample when more than half of the ball was in the field of view of the camera. With more than half of the ball in the field of view of the camera, both the position of the ball's center and its width could be determined. The position of the direction of gaze relative to the position of the ball, in units of ball width, was calculated for each sample in which the ball was in sight.

RESULTS

Ball Frequency and Flight Time

Ball frequency and flight time were analyzed to determine if the manipulation of instructed frequency had the desired effect. A mixed analysis of variance (ANOVA) of ω_{ave} as a function of expertise and instructed frequency was conducted. As expected, there was a significant main effect of instructed frequency on the observed angular frequency of ball throwing, ω_{ave}, $F(2, 16) = 53.36$, $p < .0001$. The mean preferred angular frequency was 5.78 rad/sec. The mean ω_{ave} for participants instructed to throw at one half of their preferred frequency was 4.89 rad/sec, and the mean ω_{ave} for participants instructed to throw at twice their preferred frequency was 8.62 rad/sec. There was neither a main effect of expertise, $F(1, 8) = 0.07$, $p > .79$, nor a significant interaction between the two variables, $F(2, 16) = 1.31$, $p > .3$.

Because participants can decrease ω_{ave} by either increasing the ball's flight time (time from throw to catch), increasing the amount of time that the ball is held in the hand, or both, we conducted a mixed ANOVA of the mean flight time per trial as a function of expertise and instructed frequency. As was expected, increasing ω_{ave} resulted in a decrease in the flight time per cycle, $F(2, 16) = 143.36$, $p < .0001$. There was also a main effect of expertise showing that experts tended to use longer flight times than intermediates, $F(1, 8) = 6.20$, $p < .05$. The decrease with expertise in the ratio of the time spent holding the ball to the total cycle time has also been documented in the three-ball cascade juggle (Beek & Van Santvoord, 1992). There was no significant interaction between the two variables, $F(2, 16) = 3.08$, $p > .05$.

Viewing Phase and Time

To test if the participants were electing to view the ball at a particular phase along the ball's trajectory, we calculated the ball's phase, θ, at each sample in which the participant's line of gaze intersected the ball and then averaged these time differences for each trial, resulting in a measure of the mean viewing phase. We then conducted a mixed ANOVA of the mean viewing phase as a function of expertise and instructed frequency. A phase of 0 indicates that participants were viewing the ball at the zenith of its trajectory, a negative phase indicates that they were viewing the ball after its zenith, and a positive phase indicates that they were viewing the ball rising up toward the zenith. The results depicted in Figure 1 show that there was a significant main effect of expertise such that the experts tended to view the ball at an earlier phase than the intermediates, $F(1, 8) = 5.58, p < .05$. There was also a main effect of instructed frequency such that participants tended to view the ball earlier in its cycle as frequency increased, $F(2, 16) = 3.86, p < .05$. There was no interaction between the two variables, $F(2, 16) = 1.49, p > .25$.

To test if participants had elected to view the ball at a particular time relative to the catch, we subtracted the time of each sample in which the line of gaze intersected the ball from the time of the subsequent catch; the mean was taken on each trial as a measure of the mean time between viewing and catching. Positive intervals indicate that the ball was viewed prior to the catch. The mean time between viewing and catching across participants and conditions was 364 msec, which is very close to the 361 msec found by Amazeen et al. (1999). The results for each condition are depicted in Figure 2. A mixed ANOVA of the time between viewing and catching as a function of expertise and instructed frequency was conducted. There was a significant main effect of expertise such that the experts tended to view the ball earlier in time relative to the catch than the intermediates, $F(1, 8) = 15.03, p < .005$. This is a similar effect to that reported earlier, in the phase analy-

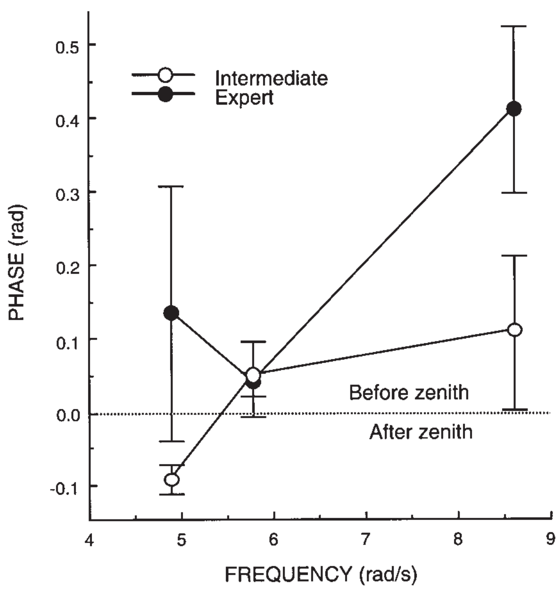

FIGURE 1 Mean phase of the ball at which the participants elected to view the ball as a function of angular frequency for experts and intermediates. Vertical lines represent the standard error of the mean.

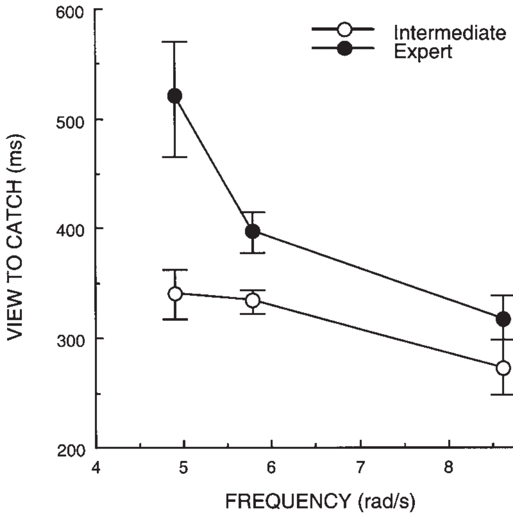

FIGURE 2 Mean time interval between viewing and catching the ball as a function of angular frequency for experts and intermediates. Vertical lines represent the standard error of the mean.

sis. There was also a significant main effect of instructed frequency such that participants tended to view the ball later in time relative to the catch with increased frequency, $F(2, 16) = 13.96, p < .0005$. However, the interaction between these two variables was also significant, $F(2, 16) = 4.18, p < .05$, revealing that the main effect of instructed frequency was shown only for the experts who decreased the time between viewing and catching from 525 msec at the lowest frequency to 315 msec at the highest frequency, $F(2, 16) = 16, p < .001$; the intermediates did not vary this time interval significantly from their mean of 315 msec across frequencies, $F(2, 16) = 2.15, p > .15$.

The distance of the line of gaze from the ball, in units of ball width, is shown across all phases of the ball's trajectory in Figure 3, Panel A. At each of the three instructed frequencies there is a fast approach of the gaze and ball beginning at about 2 rad until the region of minimum distance is reached at or around the ball's zenith, 0 rad. Shortly after the ball's zenith, the gaze and ball recede as the ball falls toward the hand. Whereas the previous analyses treated the viewing of the ball as a single point in time, Figure 3 depicts the pattern of viewing across the entire trajectory. Inspection of this figure reveals that, although participants coordinate the ball and gaze so that their gaze is brought into the region closest to the ball at an earlier phase with increased frequency, the ball and gaze begin to recede at about the same phase, –0.5 rad, at each frequency.

To test the hypothesis that participants varied the phase at which viewing was initiated, but not terminated, across frequencies, we calculated the region of mini-

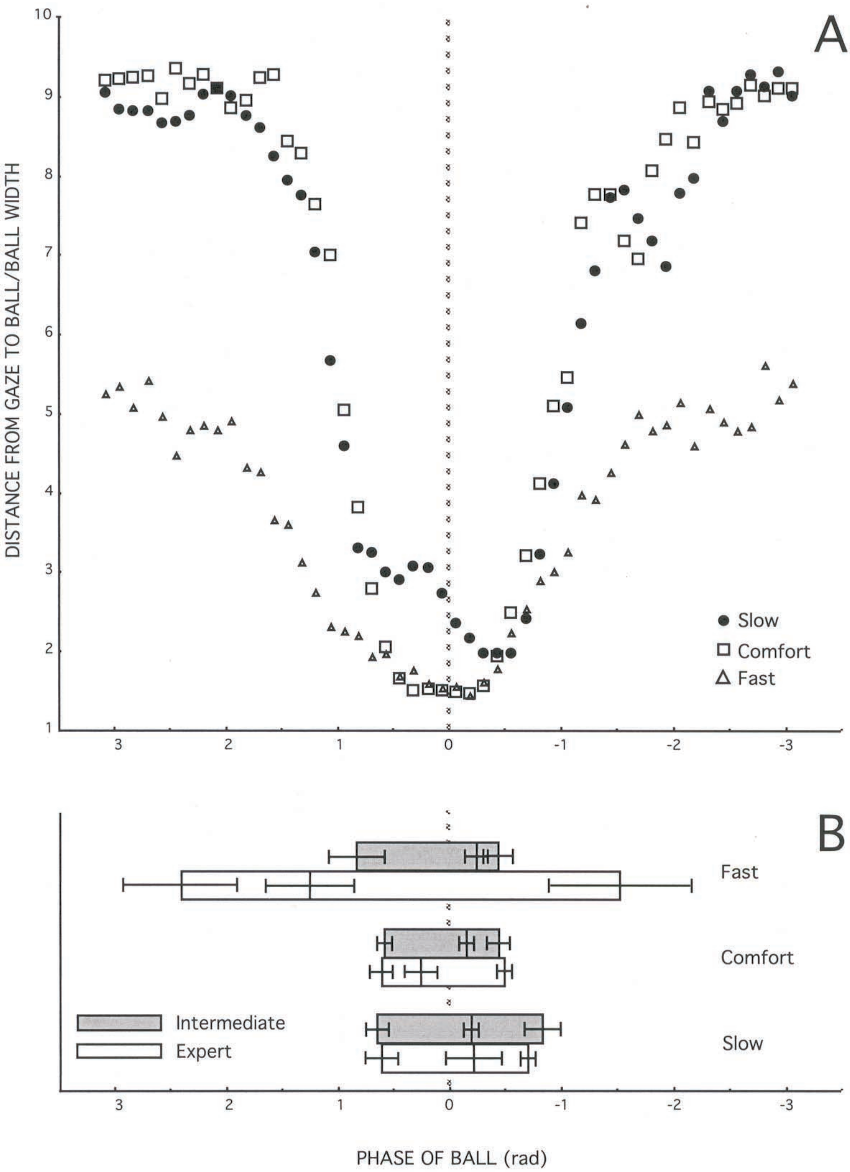

FIGURE 3 Panel A depicts the distance from the line of gaze to the ball, in units of ball width, as a function of the phase of the ball at each of the three frequencies. Panel B depicts the mean range of phases over which the gaze was within 1 width of the ball from the minimum gaze to ball distance on that trial. The vertical line inside each bar indicates the phase of minimum gaze to ball distance. Horizontal lines represent the standard error of the mean. Results are shown for intermediates and experts.

mum viewing distance for each trial. We calculated this region by finding the minimum viewing distance per trial and then determining the range of phases over which the distance from the gaze to the ball was less than 1.0 ball width greater than the minimum distance on that trial. The beginning and end phases of this region of minimum viewing distance, along with the phase of minimum viewing distance, are depicted in Figure 3, Panel B, for intermediates and experts at each level of instructed frequency.

We conducted three mixed ANOVAs, one each on the beginning and end phases of the region of minimum viewing distance and one on the phase of minimum viewing distance. The mixed ANOVA of the beginning phase of the region of minimum viewing as a function of expertise and instructed frequency revealed a significant interaction, $F(2, 16) = 8.53, p < .005$, which reflects the fact that the beginning phase was earlier with increased frequency for the experts, $F(2, 8) = 14.77, p < .005$, but that it did not change for the intermediates, $F(2, 8) = 0.84, p > .05$. The mixed ANOVA of the end phase of the region of minimum viewing as a function of expertise and instructed frequency, on the other hand, revealed no significant main effects of expertise, $F(1, 8) = 1.80, p > .05$, or of instructed frequency, $F(1, 16) = 2.38, p > .05$, and no significant interaction, $F(2, 16) = 3.29, p > .05$. Finally, the mixed ANOVA of the phase of minimum viewing distance as a function of expertise and instructed frequency revealed a significant interaction, $F(2, 16) = 7.17, p < .01$. This interaction reflects the fact that the phase of minimum viewing distance was earlier with increased frequency for the experts, $F(2, 8) = 7.27, p < .05$, but that it did not change for the intermediates, $F(2, 8) = 0.14, p > .05$. Experts, therefore, varied both the phase of minimum viewing distance and the initiation of viewing but not the termination of viewing across frequencies. Intermediates, on the other hand, exhibited no variations in these variables across conditions.

Timing the Deceleration of the Hand

A typical portion of the hand's trajectory is depicted in Figure 4. Following the release of the ball, the hand continues upward, reaches its maximum height, and then begins to move downward. Shortly thereafter, the hand is accelerated upward, resulting in a slowing of the downward velocity and, as indicated in Figure 4, a reversal of direction. Finally, the hand is decelerated in order to move downward toward the catch. This dip or inflection in the hand's trajectory has been shown to be related to a physical variable along the ball's trajectory (Amazeen et al., 1999). Specifically, it was shown that participants generally initiated this final deceleration 82 msec after the zenith. We hypothesized that the participants selected optical information about the timing of the ball's zenith and used this information to time this final phase of the hand's motion.

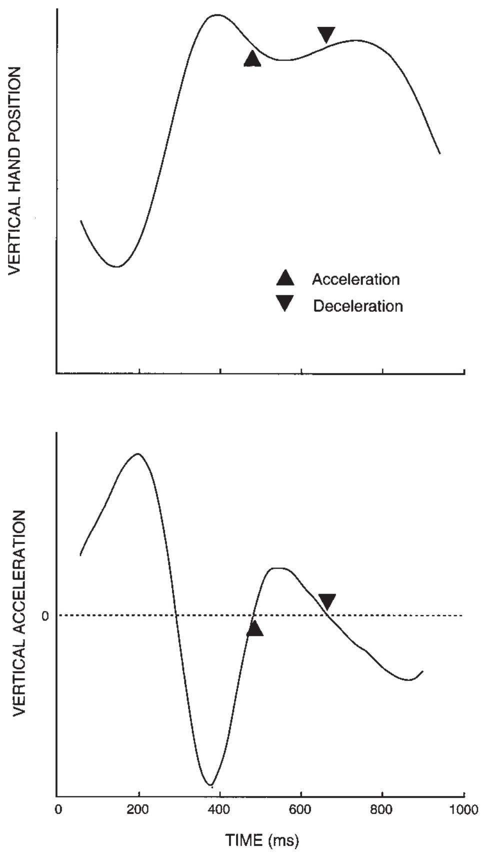

FIGURE 4 Sample cycle of the hand's vertical position (top panel) and acceleration (bottom panel). The throw occurred toward the beginning of the cycle when the hand was moving upward with its maximal acceleration. After the throw, the hand continued to move upward to its maximum position. Shortly after passing through its maximum position, the hand's downward motion was broken by an inflection where it was accelerated briefly upward again (i.e., acceleration > 0). Following this inflection, the hand decelerated in order to move down toward the catch (i.e., acceleration < 0).

The interval between the ball's zenith and the deceleration of the hand was calculated for each cycle and then averaged across cycles in a trial. The overall mean time between the ball's zenith and the deceleration of the hand across participants and conditions was 89 msec. The standard errors of the mean for the slow, preferred, and fast frequencies were 15.42, 15.35, and 16.71, respectively, for the intermediates and 14.46, 16.16, and 29.09 for the experts. We conducted a mixed ANOVA of the time between the ball's zenith and the final deceleration of the hand as a function of expertise and instructed frequency. There were no significant main effects of expertise, $F(1, 8) = 0.04, p > .8$, or of instructed frequency, $F(2, 16) = 1.04, p > .35$, neither was there a significant interaction between the two variables, $F(2, 16) = 0.38, p > .65$. Participants exhibited no statistically significant differences across conditions in the time intervals between the ball's zenith and the initiation of the final deceleration of the hand.

DISCUSSION

Five expert and 5 intermediate jugglers threw and caught a single ball continuously with one hand while wearing a head-mounted eye tracker to monitor their direction of gaze. Although participants were allowed to keep their line of gaze on the ball through its entire trajectory, they elected to bring their line of gaze into the region of the ball for only a portion of the ball's trajectory. The results from the eye tracker identify the physical variables along the ball's flight path to which the participants might have been attending. Identifying these physical variables should provide clues about the optical information used in catching (Bootsma, Fayt, Zaal, & Laurent, 1997). In this discussion, we explore the hypotheses regarding the optical information for catching that may be generated from these results.

Optical Information for Catching

The direction of gaze relative to the ball was used as an indicator of the participants' direction of attention. The patterns of gaze were analyzed as a function of both the phase of the ball and the flight time of the ball (specifically, the time until the catch). Consistent with the results of Amazeen et al. (1999), the mean phase at which the line of gaze intersected the ball was progressively earlier relative to the zenith with increasing throwing frequencies for both experts and intermediates. For the intermediates, this meant that they were maintaining a constant mean time between viewing and catching, 315 msec, across frequencies. This time may reflect the temporal requirements of this particular task. Experts, on the other hand, varied the time between viewing and catching, as well as the mean viewing phase, across frequencies by intersecting the ball with their line of gaze later in time relative to the catch as frequency increased.

Participants in this throwing-and-catching task did not just control the mean phase and time of viewing, as they did in Amazeen et al.'s (1999) study. Rather, they controlled when the gaze was initially brought to the region around the ball, when it was closest to the ball, and how long the gaze was maintained near the ball. When this viewing window (i.e., the window during which the line of gaze was closest to the ball) was analyzed, it became apparent that the intermediates varied neither the phase at which this window was initiated, the phase at which it ended, nor the phase at which the line of gaze was closest to the ball. To the extent that the direction of gaze represents the direction of attention, the intermediates appeared to attend to the same range of phases across frequencies. This range of phases was roughly centered about the ball's zenith, with the minimum distance between the line of gaze and the ball occurring just after the zenith.

All of this suggests that the intermediates were selecting information at or around the ball's zenith while, in the meantime, accommodating the increased frequencies by viewing the ball at an earlier phase. Experts, on the other hand, exhibited greater variations in the direction of gaze across conditions. Experts varied the viewing window across frequencies so that the initiation of the window, the point of minimum gaze-to-ball distance, and the mean viewing phase all occurred at earlier phases with increased frequencies. The endpoint of the window, however, did not vary as a function of frequency. These results are also consistent with the conclusion that experts elected to view the ball at its zenith, but they also suggest that experts were using information from earlier phases of the ball's trajectory in order to accommodate the varying demands of increased frequencies.

If the direction of gaze indicates the direction of attention, then the participants in this experiment did appear to attend to the ball at and around its zenith. The fact that participants attend to this physical variable suggests that there is important optical information for catching at and around the ball's zenith (Bootsma et al., 1997). Such a conclusion is consistent with the conclusions of others who have pointed out that the optical transformations associated with the ball passing through its zenith could specify the future trajectory of the ball (Todd, 1981; Van Santvoord & Beek, 1994; Watson et al., 1992). The additional finding that both experts and intermediates initiated the final downward acceleration of the hand toward the catch 89 msec after the ball's zenith suggests that participants would need information about the time of the ball's zenith as well as information about the time and location of the final contact.

Expertise

In addition to the overall greater flexibility in viewing exhibited by the experts, this experiment confirmed a pervasive finding in previous research on expertise in controlled interceptions, namely, that experts tend to use earlier information than do novices and intermediates (Abernethy, 1991; Abernethy & Russell, 1984, 1987; Bard & Fleury, 1981; Jones & Miles, 1978; Shank & Haywood, 1987; Vickers & Adolphe, 1997). Experts in this experiment tended to view the ball earlier than the intermediates. In so doing, the experts were able to expand the time available for using optical information and, conversely, decrease the associated temporal constraints. It is possible, therefore, that the experts are better attuned to information along the entire trajectory in the manner suggested by E. J. Gibson (1969) and J. J. Gibson (1979/1986). Another indication that experts were decreasing the temporal constraints on the catching movements was the overall increase in flight time and associated decrease in time spent holding the ball (also identified in the three-ball cascade juggle by Beek & Van Santvoord, 1992). Decreasing the time window allocated to one component of the task makes more time available for the other components and, thus, further alleviates the temporal constraints.

Using optical information from earlier physical events and acting more expeditiously both would presumably make additional time available for the unfolding act. These characteristics, however, may reflect more than just an improved accommodation of speed-of-processing constraints. Experts may possess greater flexibility in their ability to meet varying task demands. Such an increased flexibility was at least suggested in the results on flight time and viewing time relative to the catch. Expertise in this study, then, can be equated with an earlier and more flexible acquisition and use of optical information.

CONCLUSIONS

During a rhythmic throwing-and-catching task participants controlled the movements of their eyes, hand, and ball to select the requisite optical information for successful catching. Analyses of these movements were used to generate hypotheses regarding the information that was used. Two complementary hypotheses were offered: first, that participants viewed the ball at or around its zenith in order to obtain optical information about its future trajectory, and second, that participants used optical information about the time of the ball's zenith (presumably from attending to the ball rising toward the zenith) to control the timing of the hand's movement toward the catch.

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