Flexible timing of eye movements when catching a ball

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In ball games, one cannot direct ones gaze at the ball all the time because one must also judge other aspects of the game, such as other players' positions. We wanted to know whether there are times at which obtaining information about the ball is particularly beneficial for catching it. We recently found that people could catch successfully if they saw any part of the ball's flight except the very end, when sensory-motor delays make it impossible to use new information. Nevertheless, there may be a preferred time to see the ball. We examined when six catchers would choose to look at the ball if they had to both catch the ball and find out what to do with it while the ball was approaching. A catcher and a thrower continuously threw a ball back and forth. We recorded their hand movements, the catcher's eye movements, and the ball's path. While the ball was approaching the catcher, information was provided on a screen about how the catcher should throw the ball back to the thrower (its peak height). This information disappeared just before the catcher caught the ball. Initially there was a slight tendency to look at the ball before looking at the screen but, later, most catchers tended to look at the screen before looking at the ball. Rather than being particularly eager to see the ball at a certain time, people appear to adjust their eye movements to the combined requirements of the task.

Introduction

Most humans have the impression that they can easily catch a ball that is gently thrown to them. A likely reason for the apparent ease with which they do so is that visual information is constantly available to guide the hand to the ball, starting with seeing the movement of the thrower's arm before the ball is released, and ending with seeing the ball's flight shortly before the ball is caught, at the last moment before sensorimotor delays prevent new visual information from being used (López-Moliner, Brenner, Louw, & Smeets, 2010). Despite the apparent ease, catching a ball cannot be all that simple, considering how long it takes children to learn to do so, and that, for no evident reason, adults do sometimes drop balls that are thrown to them.

There is ample evidence that our brain can make good use of early visual information about a ball's trajectory, indicating that it can make reliable estimates of future states of the world (Diaz, Cooper, Rothkopf, & Hayhoe, 2013; Hayhoe, Mennie, Sullivan, & Gorgos, 2005; Indovina et al., 2005; López-Moliner & Keil, 2012; Zago, McIntyre, Senot, & Lacquaniti, 2009). There is also ample evidence that our brain makes use of continuously updated visual information to guide our actions (Brenner & Smeets, 2011, 2015; Carlton, 1981; Montagne, Laurent, Durey, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994; Zhao & Warren, 2014). Since moving to catch a ball takes time, it is presumably advantageous to both make predictions well before the catch and refine them as the ball approaches (Brenner & Smeets, 2015; López-Moliner et al., 2010). People appear to combine predictive and online information optimally when both sources of information are based on different cues (de la Malla & López-Moliner, 2015). We here examine whether people are particularly inclined to sacrifice obtaining precise visual information about the ball at certain times if they have to look away at some time to perform a secondary task.

Previous studies have manipulated the times at which vision was available. In most cases, these times were determined by the experimenter, and were either evident before the movement started (Brenner & Smeets, 2011; Carlton, 1981; Sharp & Whiting, 1974, 1975; Whiting, Gill & Stephenson, 1970; Whiting & Sharp, 1974) or completely unpredictable (de la Malla

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& López-Moliner, 2015; López-Moliner et al., 2010). In one case, visibility was terminated at movement onset, forcing people to weigh the viewing time against the time left to execute the required movement (Faisal & Wolpert, 2009). The latter study used a very simple display, but it is somewhat similar to a situation that arises in real-life ball catching, during ball games, when players have to allocate the short available time across different tasks. For example, a basketball player receiving a pass may divert his or her gaze from the ball to quickly search for an unmarked teammate before the catch. Examining which part of the ball's flight the player decides to miss (or to track less precisely, with peripheral vision and without the benefit of pursuing it with their eyes) in order to find a suitable teammate could reveal which period the player regards as being the least important for seeing the ball. Also, it could be the most relevant for gathering information about where others are moving given the state of the game. Since we wanted to determine when people consider it least important to see the ball, not when they consider it most important to obtain other information, we used a secondary task for which it was not evidently advantageous to look at a particular time, other than that one had to look at some time while the ball was approaching. Our secondary task was to read information that was only provided on a screen during the ball's flight time. This information was needed during a subsequent stage of the "game" (when throwing the ball back).

We measured the movements of a ball and of two people's hands as they threw the ball back and forth. We measured the eye movements of one of the two people (who we will refer to as the catcher). The ball was thrown gently across a short distance, so the time available to obtain all the required visual information was quite short. Consequently, the catcher only really had two options. Since the ball's trajectory was fully determined once it left the thrower's hand, the catcher could look at the ball until she could predict its trajectory, and then make a saccade to the screen in order to gather the information required for the secondary task while catching the ball on the basis of the prediction. Alternatively, the catcher could look at the screen until she had read the information required for the secondary task, possibly starting to move her hand on the basis of when she anticipates that the ball will be thrown or on the basis of information from peripheral vision, and only then make a saccade to the ball in order to have the last part of the catching movement guided by the best possible visual information. Our previous study showed that either choice would work for this type of gentle underarm throwing in terms of being able to catch the ball (López-Moliner et al., 2010). In that study, subjects performed equally well when the catch relied on predictive information as when it relied on late information. Therefore, there is no evident advantage of using one strategy over the other. With an analysis of the gaze pattern we hope to determine whether people consider it more important to look at the ball at certain moments.

Methods

Participants

Six female subjects, all members of the department of Human Movement Sciences of the Vrije Universiteit Amsterdam, participated in the experiment as catchers. All subjects had normal or corrected-to-normal vision, and none had evident motor abnormalities. Four subjects took part in four 10-min sessions and two subjects took part in three 10-min sessions. The first author was always the thrower. The study was conducted in Amsterdam and was part of a program that was approved by the department of Human Movement Sciences' ethical committee.

Apparatus and stimuli

An Optotrak 3020 3-D motion capture system (with two sensor-bars; Northern Digital, Waterloo, Ontario, Canada) was used to record the positions of a ball and of the thumb and index finger of the right hand of the catcher, the position of a biteboard that was held in the catcher's mouth, the position of the thrower's hand, and a static reference attached to the screen located next to the thrower that was used to display information during the ball's flight (Figure 1A, B). The ball had a diameter of 75 mm and a mass of 150 g, and was fitted with six infrared emitting diodes (IREDs) distributed evenly across its surface. These IREDs were powered by a battery and synchronized by telemetry so there were no wires attached to the ball. The positions of the 13 IREDs (six for the ball, two for the catcher's hand, three for the catcher's biteboard, one for the thrower's hand, and one on the display) were recorded at 100 Hz. The movements of the eyes relative to the head were recorded at 500 Hz using an EyeLink II (SR Research Ltd., Mississauga, Ontario, Canada). The orientations of the two eyes were averaged to estimate a single orientation of gaze relative to the head. Head position and orientation were determined at 100 Hz using the IREDs on the biteboard (IRED measurements were converted into head position and orientation using custom software; for details see Sousa, Brenner, & Smeets, 2010). The screen was located

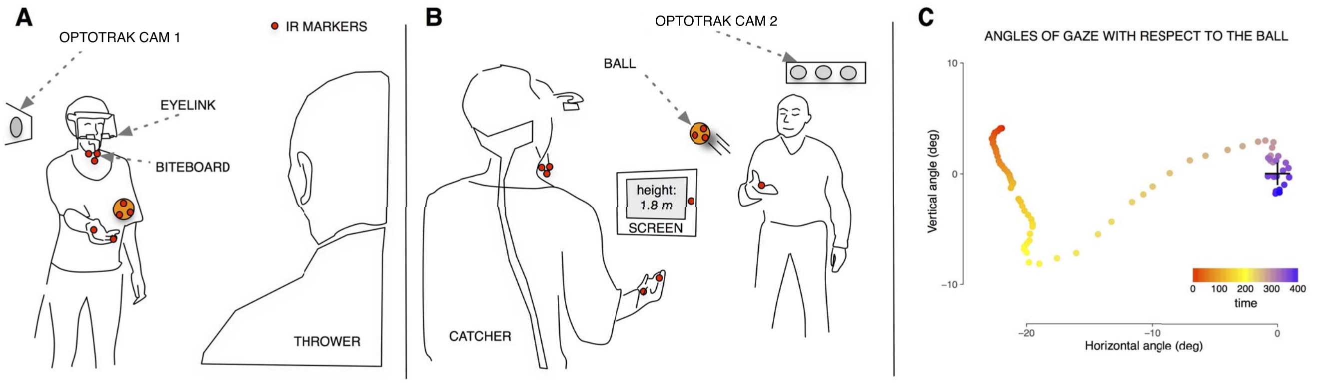

Figure 1. Sketch of the experimental setup. (A) The catcher, wearing the eye tracker, seen from the perspective of the thrower. (B) The thrower seen from the perspective of the catcher. The IRED marker on the screen for displaying the target height was about 90 cm to the right of the thrower. The screen and the thrower were at about the same distance from the catcher. Red dots denote IRED markers. (C) Gaze during one catch. The dots show the direction of gaze with respect to the moving ball (cross at the origin). Dots are drawn for every 2 ms during the ball's flight. The yellow part with the large separation between consecutive dots is the saccade from the screen to the ball.

about 90 cm to the left of the thrower, as seen by the catcher, and was used to display numerical information that the catcher had to read and use when throwing the ball back (see Procedure).

A custom program written in C programming language kept track of the ball's motion and of the positions of the markers attached to the thrower's and catcher's hands throughout the experiment. The program recognized six different phases of the back and forth underarm throwing that were needed to run the experiment:

1. The thrower has the ball. This phase started when any one of the visible IREDs on the ball was within 15 cm of the IRED attached to the thrower's hand. Note that some IREDs on the ball were not visible when the thrower (or catcher) held the ball, or when the hand was very close to the ball. If none of the IREDs were visible, the ball was also assumed to be in the thrower's (or catcher's) hand.
2. The thrower is throwing the ball. This phase starts when the ball moves upward at more than 5 cm/s, while at the same time moving toward the catcher. It is therefore restricted to the part of the movement that could provide information about where the ball can be caught. The information for the secondary task appears on the screen as soon as this phase is recognized.
3. The ball is in the air on its way to the catcher. Since the precise moment of release is not critical during the experiment, this phase was simply recognized by the thrower's hand moving backward. For the analysis, we align the data with respect to the release of the ball, so the moment of release is important. This moment was determined more precisely when analyzing the data.
4. The catcher has the ball. This phase starts when any one of the visible IREDs on the ball was within 15 cm of either of the IREDs attached to the catcher's hand. At that moment, the information for the secondary task disappears from the screen
5. The ball is thrown back. This phase starts when the ball moves upward at more than 5 cm/s, while at the same time moving toward the thrower.
6. The ball is descending toward the thrower's hand. This phase starts when the ball starts moving downward. At that moment, the peak height of the ball's trajectory is known, so feedback about the secondary task can be, and is, provided (for 400 ms).

The program recorded these phases, as well as the positions of the IREDs attached to both participants' hands, the position of the ball and of the IRED attached to the screen, the position and orientation of the head, and the eye movement data for further analysis.

Procedure

Prior to the start of the session, eye movements were calibrated by moving the index finger around while looking at it. The direction from the eye to the finger was related to the pupil position measured by the EyeLink (SR Research), considering the orientation of the head, although subjects were encouraged to keep their head still during calibration. At the start of each session, the catcher and thrower stood so that the distance between them was about 250 cm. They were instructed not to move from those positions. Their compliance with this instruction was monitored by the second experimenter during the experiment and checked later during the analysis by looking for systematic changes in where the ball was caught.

Within each session, the two participants continuously threw the ball back and forth for 10 min. Although both thrower and catcher threw the ball and caught the ball, the participant whose eye movements were recorded (and who had to perform the secondary task) is referred to as the catcher and the other as the thrower because we are interested in performance when the participants had those roles. The secondary task was to try to attain a certain peak height of the trajectory when throwing the ball back to the thrower. The text "goal height: 1.X m" appeared on the screen next to the thrower's right arm (see Figure 1B), where X could be 2, 5, or 8 (so the peak height that the catcher was aiming for when throwing back the ball was 1.2, 1.5 or 1.8 m from the floor, with the height chosen at random for each trial). We refer to this task as the secondary task, but it was only secondary in terms of the purpose of the study. No indication was given to the catcher that either of the tasks was more important than the other. The text was on the screen throughout Phases 2 and 3 described above. On average it was present on the screen for 800 ms. The catcher was told that the information would only be present while the ball was being thrown toward them, and that they could read it at any time they wanted as long as they caught the ball and threw it back in accordance with the indicated height.

Once the ball started descending on its way back (Phase 6), feedback about the attained ball height was shown on the same screen (for 400 ms). If the height was within 20 cm of the goal height, the screen turned green and the text "reached X.Y m, success" was displayed (where X and Y were digits corresponding to the ball's peak height). Otherwise, the screen turned red and the same text was displayed except that "success" was replaced by "too high," or the screen turned blue and "success" was replaced by "too low." We used color as well as text to make it easy for the catcher to access this information. Feedback was provided to encourage the catcher to be precise in the secondary task. The catchers were not instructed as to how to catch the ball, except that they should do so with one hand, and that they were to remain at the same position when doing so.

Data analysis

For the analysis, we determined the moment that the ball was released and the moment that it was caught again after filtering the positions of the relevant IREDs with a second order digital Butterworth filter (cut-off frequency of 6 Hz). The moment of release was the moment at which the mean position of all visible IREDs on the ball was further than 15 cm from the IRED on the thrower's hand. The moment of the catch was the moment at which all visible IREDs on the ball were within 15 cm of either of the IREDs on the catcher's hand. The times that were determined in this manner were similar to the times that were determined during the experiment (the mean difference was less than 15 ms for all subjects).

The eye-in-head orientation data from the EyeLink (SR Research) were converted into gaze angles with respect to a coordinate system that was fixed to the head. What participants were looking at was determined by calculating the angle between this direction of gaze and the direction toward the positions of the landmarks of interest (the mean position of the IREDs of the ball and the position of the IRED at the edge of the screen) expressed in the same coordinate system fixed to the head. It was evident from looking at how these angles changed during the session that people almost exclusively fixated either the screen or the ball during the ball's flight to the catcher. The example in Figure 1C shows the horizontal and vertical gaze angles with respect to the ball throughout one such flight of the ball. On this trial, the subject was initially looking at the screen. The ball initially moves upward, so the gaze angle with respect to the ball was initially about –20° horizontally and decreasing vertically. After about 200 ms the subject made a saccade to fixate the ball. After that moment the horizontal and vertical angles are close to zero.

The horizontal angle between the ball and the edge of the screen closest to the ball was about 20° throughout the ball's flight. The catcher was considered to be looking at the ball whenever the horizontal angle between the direction of gaze and the direction towards the mean position of the visible IREDs of the ball was smaller than the horizontal angle between the direction of gaze and the edge of the screen. She was considered to be looking at the screen if the horizontal angle between the direction of gaze and the direction toward the edge of the screen was smaller. This method made it very easy to separate the fixations between the two regions, but it will assign fixations to one of these regions even if the catcher is looking elsewhere altogether. We therefore also required gaze to be within 15° of the ball or of the IRED attached to the edge of the screen (here it is the overall distance, not the horizontal distance). If it was not within this range we considered the catcher to be looking elsewhere. This occurred on a very small number of trials (3, 5, 5, 9, 6, and 3 times for the different catchers).

We choose the lenient value of 15° because this value ensured that gaze would be assigned to the screen when the catcher was looking at any position on the screen, and that we would not classify the central part of the saccade between the ball and the screen as looking

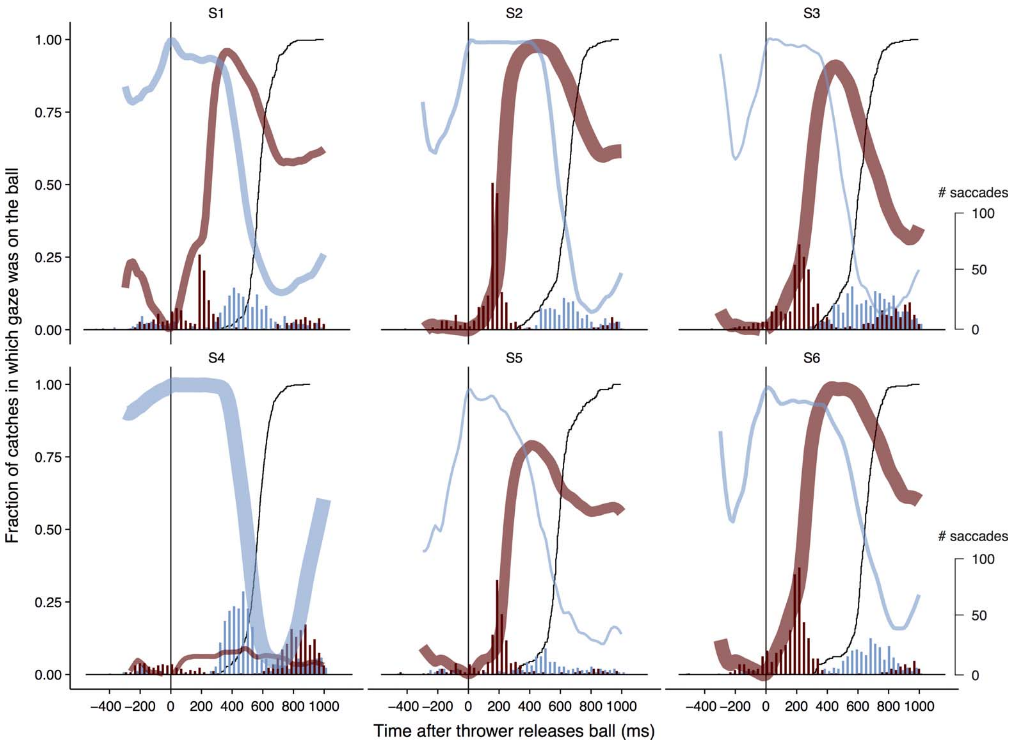

Figure 2. Gaze pattern as a function of time relative to release of the ball. Each panel shows the data of an individual subject. The ordinate shows the proportion of trials in which subjects are looking at the ball at each moment in time (dark reddish and light bluish curves). The color separates trials by where subjects were looking when the ball was released. Dark red denotes trials in which subjects were looking at the screen at the time of release. Light blue shows trials in which subjects were looking at the ball. The thin black curve shows the fraction of balls that had been caught by that time. The histograms denote the number of saccades from the screen to the ball (dark red) and from the ball to the screen (light blue) that started at that moment.

elsewhere. A potential drawback of this choice is that if the catcher is, for example, looking at the thrower's hand after the ball is released, gaze would still be assigned to the ball. During the times that we considered the catcher to be looking at the ball, the median horizontal angle between the estimated direction of gaze and the estimated direction to the center of the ball was less than 2°. This angle combines errors in determining the direction of gaze with errors in determining the position of the center of the ball and actual variability in where the catcher was looking with respect to the center of the ball. Although we may be slightly overestimating how long gaze was on the ball and the screen, there is no reason to believe that the catchers were regularly looking elsewhere.

For each attempt to catch the ball, we determined where catchers were looking at each moment before and after the thrower released the ball. We then separated the attempts to catch the ball into ones in which the catcher was looking at the ball when the ball left the thrower's hand, and ones in which the catcher was looking at the screen at that time. For each of these cases, we then determined the fraction of attempts to catch the ball while gaze was directed at the ball for each moment with respect to ball release.

The velocity of changes in gaze was computed by two-point differentiation, after filtering gaze position with a second-order digital Butterworth filter (cut-off frequency of 20 Hz; Koken & Erkelens, 1992). We used a velocity threshold of 35°/s to identify saccades. To complement the changes in the above-mentioned fractions of attempts while gaze was either oriented at the ball or the screen, we made histograms of the times of saccade initiation relative to the moment the thrower released the ball, both for leftward and rightward saccades (from the ball to the screen and from the screen to the ball, respectively; see histograms in Figure 2).

Finally, we identified failures to catch the ball and checked whether the catchers managed to read the information on the screen. Failing to catch the ball resulted in it being dropped, which was easily recognized because the ball moved well below the height of the hand, rather than the distance between the hand and the ball reaching an approximately constant minimal value, as is characteristic of a catch. Moreover, the next throw was clearly delayed. To evaluate whether the catchers had not just looked at the screen but also obtained the relevant information, we examined whether the peak heights of the balls when they threw them back to the thrower were different for the three different instructions. We compared the fraction of drops and the peak heights across different gaze strategies: first looking at the ball and then at the screen, first looking at the screen and then at the ball, only looking at the screen, and only looking at the ball.

Results

In three sessions, the IREDs on the ball ceased to function properly after the ball had been dropped or caught with a high impact between the hand and the ball, so the session was terminated and the ball was repaired for the next session. Except for this, 17 trials were removed because critical measures were missing. The average number of times that each catcher caught the ball was 535. The standard deviation across catchers was 90. They dropped 5, 9, 15, 16, 25, and 26 balls, respectively. The mean flight time of the ball was 713 ms (standard deviation across sessions of 71 ms, with no significant difference between catchers, $F(5, 16) = 0.5$; $p = 0.8$). During that time the ball covered an average horizontal distance of 2.1 m (standard deviation across sessions of 0.24 m, again with no significant difference between catchers, $F(5, 16) = 1.4$; $p = 0.28$). The variability in flight time and distance is presumably due to differences in how (and therefore also where) the catchers tried to catch the ball, and maybe also to the thrower having thrown slightly differently on different occasions. An indication of the spatial variability in how the ball was thrown to the catcher within a session is given by the variability of the lateral position of the catcher's hand at the moment of the catch. The lateral position was approximately normally distributed with a standard deviation of 23 cm, with no significant difference between catchers, Bartlett's test: $k^2(5) = 5.3$, $p = 0.4$.

Strategies revealed by gaze behavior

Figure 2 summarizes the gaze behavior of each of the subjects. The dark reddish and light bluish curves show the fractions of catches during which gaze was directed towards the ball, as a function of the time relative to when the thrower released the ball. This is shown from about 400 ms before release to about 200 ms after the ball was caught. Time zero (indicated by a gray vertical line) indicates when the ball left the thrower's hand. The catches are divided into two types, depending on where the catcher was looking at the moment of release (dark reddish if the catcher was looking at the screen at that moment; light bluish if she was looking at the ball). The thickness of the line is proportional to the number of catches of that type.

When catchers were looking at the screen at the moment of release (dark reddish curves), they made saccades to the ball about 200 ms after the ball was released (dark reddish histograms in Figure 2). Consequently, the fraction of trials in which they were looking at the ball increased almost to 1 before the catch (the fraction of attempts in which the ball had been caught at the indicated times is shown by the thin, rising black curves). The complementary strategy (light bluish curves and histograms in Figure 2) was to look at the ball at the moment of release in order to predict its trajectory, and then make a saccade to the screen before catching the ball (at which time the information on the screen disappeared).

Gaze evolution across trials

Figure 3 shows the evolution of the gaze strategy across sessions and trials. The curves are moving averages in which the weights given to the trials fall off with the difference in trial number from the trial in question within that session (weights given by a normal distribution with a standard deviation of 50 trials). There was initially a lot of variability, both between catchers and across time, but by the end of the last session, five of the six catchers were usually first reading the information that was needed for the secondary task from the screen, and then using late information to catch the ball. They sometimes looked at the ball at the moment of release, but the overall trend is evident. Only one catcher (S4) did not show this preference. She also tried both strategies, but after the first session she almost always looked at the ball near the time that it was released, and only looked at the information on the screen after having acquired enough information to be able to catch the ball. Note that this subject did not drop more balls than the others, so this strategy appears to be just as good in terms of catching the ball. In about 5% of the trials, the catchers started making a second saccade before catching the ball, usually just before they caught the ball.

Performance on the secondary task

Figure 4 shows the peak height of the ball on its way back from the catcher to the thrower, as a function of the catch number. Colors indicate the three different target heights that were presented on the screen. There is clearly a lot of variability in the peak heights. Part of this variability is undoubtedly the result of failures to read the text that was presented on the screen, but even when one does know the requested peak height it is difficult to throw a ball so that its peak height will correspond to that value while at the same time

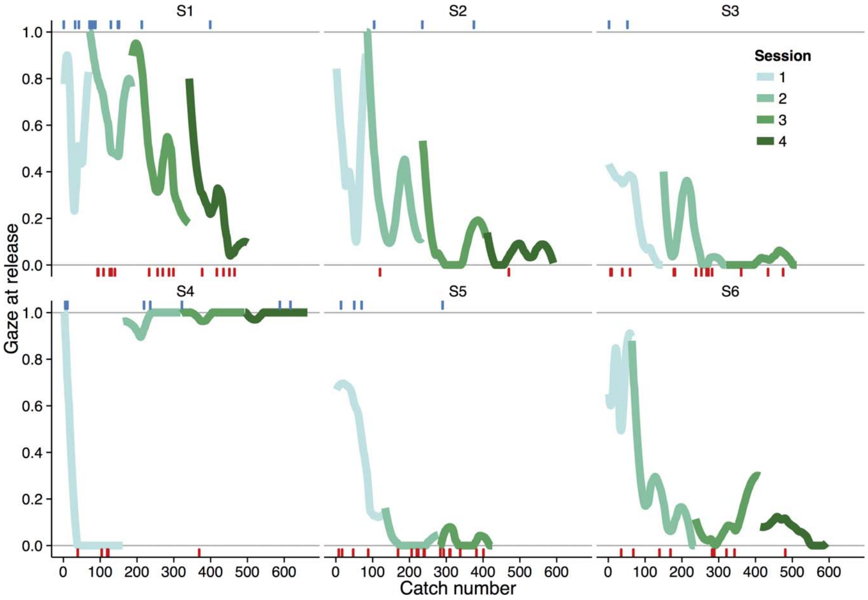

Figure 3. Evolution of gaze behavior. Each panel shows how the gaze at the moment of release changes across subsequent catches for one catcher (S1–S6), with different sessions coded in different shades of green. A value of zero indicates that the catcher was looking at the screen when the ball was released, and a value of one indicates that she was looking at the ball in the thrower's hand. The curves show averages, weighted by a Gaussian distribution with a standard deviation of 50 catches within each session. The small red and blue lines above and below the curves indicate when balls were dropped. They are drawn in red below the curves if the catcher was looking at the screen when that ball was released, and in blue above the curves if she was looking at the ball when it was released.

ensuring that the ball will reach someone else (the thrower). In general, the catchers threw the ball higher when they were asked to throw it higher, so they must have usually managed to read the text. The average height was also quite reasonable. The one catcher who ended up looking at the ball before looking at the screen (S4) was not particularly poor at matching the ball's peak height to that indicated on the screen. Thus, it is evident both from the catcher's eye movements, and from the peak height of the ball on its way back to

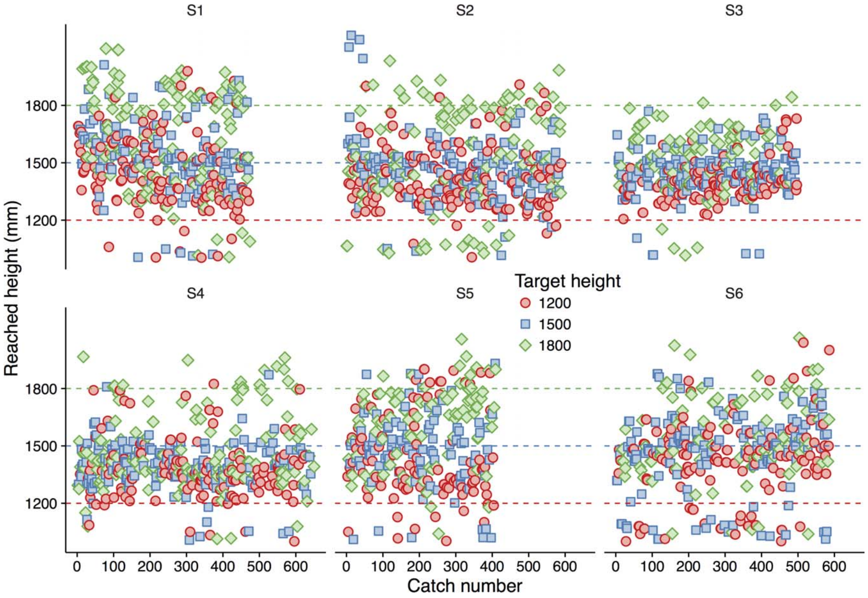

Figure 4. Performance on the secondary task. The peak height of the ball on its way back to the thrower after every catch is shown. Each panel shows the values for one of the catchers. The colors indicate the heights mentioned on the screen while the ball was approaching (these target values are also indicated by horizontal lines).

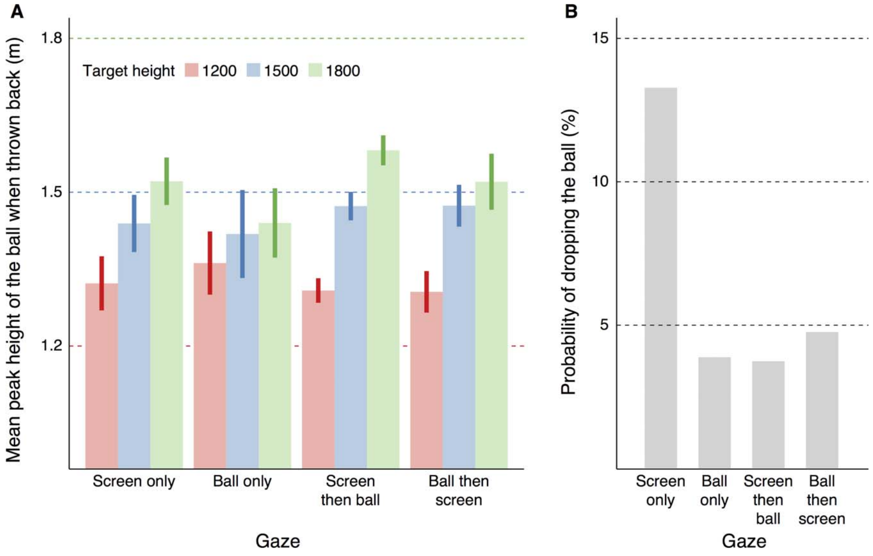

Figure 5. (A) Average peak height of the ball's trajectory when thrown back to the thrower for the different target heights presented on the screen and gaze patterns while catching that ball. Error bars show standard errors across the catchers' mean values. (B) Probability of dropping the ball for each gaze pattern.

the thrower, that subjects did at least try to perform the secondary task.

Further evidence that the catchers were indeed trying to perform the secondary task can be found by looking at the average height for trials in which the catchers shifted their gaze differently. We categorized the trials into four types depending on where the catcher was looking during the ball's flight toward her: screen only, ball only, screen then ball, and ball then screen. The occasional trials in which the catcher looked elsewhere during the ball's flight were excluded from this analysis. Figure 5A shows the average peak height of the ball on its way back to the thrower for each height mentioned on the screen, for each of the four gaze categories mentioned above. We might expect no difference between the three heights on the screen (indicated by the differently colored bars) if the catcher only looked at the ball. In accordance with this expectation, the difference between the heights of the differently colored bars was smallest when subjects were looking at the ball only. This is supported by a significant interaction between the within-catchers effects of height mentioned on the screen and gaze category in a linear mixed-model ANOVA using the lme4 R package (v.1.0–6; Bates, Maechler, Bolker, & Walker, 2014), $F = 2.7$, $p = 0.013$. A main effect of height mentioned on the screen, $F = 27$, $p < 0.001$, provides evidence that subjects were using the information shown on the screen.

Figure 5B shows that the number of dropped balls is clearly related to having looked at the ball. The figure shows the percentage of balls that were dropped for each of the four above-mentioned gaze categories. Participants dropped significantly more balls when they only looked at the screen during the ball's flight, $\chi^2(3) = 13.8$, $p = 0.003$. However, even then they caught most balls, so apparently they could catch the balls without directing their gaze at them.

Discussion

We examined whether people would consistently choose to look at an approaching ball that they were required to catch during a certain time interval if the need to also perform a second task prevented them from looking at the approaching ball all of the time. We found that all subjects tried out different options before converging on a single strategy. Five of the six subjects ended up looking at the screen that provided information for the secondary task before shifting their gaze to the ball in order to catch it. The sixth subject ended up looking at the ball as it was being thrown before shifting her gaze to the screen. Unlike in previous studies, in which subjects were constrained to use information provided at a certain time (Brenner & Smeets, 2011; de la Malla & López-Moliner, 2015; López-Moliner et al., 2010; Sharp & Whiting, 1975), here subjects could choose when to look at the ball. This ability to choose, together with the fact that gaze had to be directed elsewhere at other times, is characteristic of normal eye movements.

Diverting one's gaze from the ball to look elsewhere might be less disruptive than removing information altogether, because one can follow what the ball is doing to some extent with peripheral vision. The fact that our subjects could catch the ball on most trials in which they only looked at the screen demonstrates this. On the other hand, looking and attending to information provided elsewhere might disrupt planned movements in a way that removing vision altogether does not, for instance as a result of automatically directing visual information processing to where one is looking or intends to look (Deubel & Schneider, 1996). That might explain why most catchers ultimately chose to look at the ball later during its path. However, it is evident from those catchers' earlier performance, and from the remaining catcher's performance, that the ball can be caught despite diverting one's gaze.

The peak height of the ball in the secondary task is often quite far from the height indicated on the screen (Figure 4). Presumably, the rather inaccurate performance on the secondary task is partly due to the fact that throwing the ball with a certain peak height is difficult, and partly the result of having failed to read the value off the screen. Even in the ball-only trials, the mean performance seems to follow the required height to some extent (Figure 5A). This could be chance, but it could mean that the letters on the screen were large enough to be read to some extent without directing one's gaze at the screen. Importantly, the mean performance followed the required height better, though still far from perfectly, in the other conditions, so looking at the screen was useful for performing the secondary task. The mean performance on this task was not exceptionally good in the screen-only trials, so it is unlikely that the poor performance was often due to having seen the message on the screen too briefly to read it despite having looked at it.

One subject (S2) commented about the feedback occasionally appearing to be wrong in one of the sessions. In the session in question, we encountered some technical problems, so it is possible that it really was incorrect. We removed catches with technical problems, but if the subject adjusted her throwing to the incorrect feedback on the previous trials her performance on the secondary task might have suffered. The fact that she noticed that the feedback was incorrect indicates that she certainly read the text on the screen.

The tendency to throw closer to the average indicated value than one should, and perhaps also to throw lower than one should, suggests that catchers were sometimes guessing. Whenever the catcher is uncertain about the target height it would make sense for her to aim for the mean of the heights that she was certain about on previous trials. Ensuring that the ball reaches the thrower without him having to move, as well as ensuring that the ball reaches a given peak height, undoubtedly also contributes to the poor performance. Knowing the precise reason for the poor performance on the secondary task is not critical for our interpretation, because we wanted to know when catchers would look at the screen while catching the ball, so it was critical that they diverted their gaze, but not to what extent they managed to use the information on the screen.

The fact that not all balls were dropped when the catcher did not look at the ball at all (screen-only condition in Figure 5B) shows that the ball can be caught with peripheral vision alone. However, it is evident that looking at the ball does help catch it. Thus, the strategy of looking both at the screen and at the ball, at different times, does appear to be the best strategy for completing both tasks.

It would appear that for most people there is some benefit in looking at the ball later during the flight, after having acquired the information about the throwing height. In a previous study (López-Moliner et al., 2010), we did not find poorer performance when the ball was seen during the early part of its flight compared to when the ball was seen during the last part of its flight. However, the mean flight time in that study was about 480 ms, which is about 230 ms shorter than the flight time that was used in the present study. The longer flight time means that subjects would have to be able to predict further in advance, and to perform reliably on the basis of such information after a longer time interval, if they were to first look at the ball. In addition, subjects had to collect other visual information by looking elsewhere during this time period. This could all be avoided by first looking at the screen and then at the ball. However, one subject chose the opposite strategy, and she did not drop the ball excessively. Neither did the other subjects drop the ball particularly often when they chose the opposite strategy. Thus, we confirm that it is not essential to see any particular part of the ball's path, even for slightly longer flight times.

This study is only a first step in trying to understand how people distribute their gaze across competing aspects of a task, or across different tasks. Since we found that individual catchers varied their gaze strategies, and that they ultimately converged on different choices, we suspect that we could have influenced the results by manipulating the difficulty of the two aspects of the task, or by placing more emphasis on one or the other aspect. Our main finding is, therefore, not that people pick these particular times to look at the ball, but that they try out different timings and end up with different preferences. This confirms our previous finding that people do not need visual information at a specific time, as long as they receive enough visual information to be able to predict the ball's trajectory well enough (López-Moliner et al., 2010). It extends that finding in showing that people can gather visual information that they need for performing a different task during the intervening time.

Conclusion

Subjects showed high flexibility in timing their eye movements to extract the information that they needed to perform both a catching and a secondary task. This flexibility allowed them to explore different gaze strategies and assess which was most adequate to meet the requirements of the task. All subjects ended up exploiting a preferred strategy. For most subjects, the preferred strategy involved optimizing the acquisition of visual information about the ball by looking at it late during the catch.

Keywords: interception, eye movements, strategy, gaze, selection, prediction

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References

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*, 1–48.

Brenner, E., & Smeets, J. B. J. (2011). Continuous visual control of interception. *Human Movement Science*, *30*, 475–494.

Brenner, E., & Smeets, J. B. J. (2015). How people achieve their amazing temporal precision in interception. *Journal of Vision*, *15*(3):8, 1–21, doi:10.1167/15.3.8. [PubMed] [Article]

Carlton, L. G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 1019–1030.

de la Malla, C., & López-Moliner, J. (2015). Predictive plus online visual information optimizes temporal precision in interception. *Journal of Experimental Psychology: Human Perception and Performance*, *41*, 1271–1280.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research*, *36*, 1827–1837.

Diaz, G., Cooper, J., Rothkopf, C., & Hayhoe, M. (2013). Saccades to future ball location reveal memory-based prediction in a virtual-reality interception task. *Journal of Vision*, *13*(1):20, 1–14, doi: 10.1167/13.1.20. [PubMed] [Article]

Faisal, A. A., & Wolpert, D. M. (2009). Near optimal combination of sensory and motor uncertainty in time during a naturalistic perception-action task. *Journal of Neurophysiology*, *101*, 1901–1912.

Hayhoe, M., Mennie, N., Sullivan, B., & Gorgos, K. (2005). The role of internal models and prediction in catching balls. In *Proceedings of the American Association for Artificial Intelligence* (pp. 1–5). Palo Alto, CA: AAAI.

Indovina, I., Maffei, V., Bosco, G., Zago, M., Macaluso, E., & Lacquaniti, F. (2005). Representation of visual gravitational motion in the human vestibular cortex. *Science*, *308*, 416–419.

Koken, P. W., & Erkelens, C. J. (1992). Influences of hand movements on eye movements in tracking tasks in man. *Experimental Brain Research*, *88*, 657–664.

López-Moliner, J., Brenner, E., Louw, S., & Smeets, J. B. J. (2010). Catching a gently thrown ball. *Experimental Brain Research*, *206*, 409–417.

López-Moliner, J., & Keil, M. (2012). People favour imperfect catching by assuming a stable world. *PLoS One*, *7*(4), 1–8.

Montagne, G., Laurent, M., Durey, A., & Bootsma, R. (1999). Movement reversals in ball catching. *Experimental Brain Research*, *129*, 87–92.

Peper, L., Bootsma, R., Mestre, D. R., & Bakker, F. C. (1994). Catching balls: How to get the hand to the right place at the right time. *Journal of Experimental Psychology: Human Perception and Performance*, *20*, 591–612.

Sharp, R., & Whiting, H. (1974). Exposure and occluded duration effects in a ball-catching skill. *Journal of Motor Behavior*, *6*, 139–147.

Sharp, R., & Whiting, H. (1975). Information-processing and eye-movement behaviour in a ball catching skill. *Journal of Human Movement Studies*, *1*, 124–131.

Sousa, R., Brenner, E., & Smeets, J. B. J. (2010). A new binocular cue for absolute distance: Disparity relative to the most distant structure. *Vision Research*, *50*, 1786–1792.

Whiting, H., Gill, E. B., & Stephenson, J. M. (1970). Critical time intervals for taking in flight information in a ball-catching task. *Ergonomics*, *12*, 265–272.

Whiting, H., & Sharp, R. (1974). Visual occlusion factors in a discrete ball-catching task. *Journal of Motor Behavior*, *6*, 11–16.

Zago, M., McIntyre, J., Senot, P., & Lacquaniti, F. (2009). Visuo-motor coordination and internal models for object interception. *Experimental Brain Research*, *192*, 571–604, doi:10.1007/s00221-008-1691-3.

Zhao, H., & Warren, W. H. (2014). On-line and model-based approaches to the visual control of action. *Vision Research*, *89*, 1–59.