Keeping Your Eye, Head, and Hand on the Ball:

Rapidly Orchestrated Visuomotor Behavior in a Continuous Action Task

Anna Schroeger[1, 2], Alexander Goettker[1, 2], Doris I. Braun[1, 2], Karl R. Gegenfurtner[1, 2]

[1]Abteilung Allgemeine Psychologie, Justus Liebig University Giessen, Germany

[2]Center for Mind, Brain and Behavior, Universities of Marburg, Giessen, and Darmstadt, Germany

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Abstract

While many studies on eye movements focus on highly controlled, repetitive conditions, we expanded this approach by measuring eye, head, and hand movements of participants playing an iPad-based version of the classic computer game Pong. This allowed us to capture more natural sequential behavior while maintaining the benefits of experimental control. Participants intercepted a moving ball by sliding a paddle at the bottom of the screen so that the ball bounced back and moved toward the computerized opponent. We tested i) how participants adapted their eye, hand, and head movements to this dynamic, continuous task, ii) whether these adaptations are related to interception performance, and iii) how their behavior changed under different conditions and over time. We found that eye, hand, and head movements are largely shaped towards participant's action (and lesser so towards the opponent's action). Movements that reduce or destabilize visual input, like saccades, blinks and head movements, are reduced during critical periods of interception. Instead, participants increase the frequency of pursuit eye movements, ensuring that they closely track the ball when their action comes closer. This pursuit strategy is associated with better game performance. Our results demonstrate an orchestration of eye, head, and hand movement patterns, which is rapidly established and finely adjusted to meet the evolving demands of impending actions and task demands.

Introduction

Eye movement measurements have become an important and highly informative behavioral tool to gain insights into active vision during action, planning and decision processes (Gold & Shadlen, 2000; Hayhoe & Ballard, 2005; Orquin & Loose, 2013; Schütz et al., 2011; Spering, 2022). Foveated animals like primates and humans have to direct their eyes continuously to relevant locations to benefit from the highest visual acuity of their central small foveae (Osterberg, 1935) and their corresponding enormous processing resources (Stewart et al., 2020; Strasburger et al., 2011). Therefore, the analysis of eye movements can provide an objective and implicit 'window into the mind' (van Gompel et al., 2007). So far, many studies on the fundamentals of oculomotor control often used a repetitive trial-by-trial structure to measure single reactions to the same artificial target stimulus. While this approach offers the highest level of experimental control to directly relate low-level stimulus properties, like position, speed or contrast to changes in behavior (Becker & Fuchs, 1969; Carl & Gellman, 1987; Goettker, Braun, & Gegenfurtner, 2019; Rashbass, 1961; Spering et al., 2005), it lacks important features of natural behavior (see Miller et al., 2022). Instead of single eye movement responses to the same event we aim to investigate the coordination of eye, head, and hand movements in response to dynamic, sequential task demands that mimic the requirements of our natural environment.

Natural behavior differs in several ways from the typical lab setting (e.g., Foulsham et al., 2011). First, at each moment in time, the real world provides us with rich information that forces us to select and direct our attention to the most relevant object or area (Nuthmann et al., 2010; Tatler et al., 2017). In contrast, in a simplified lab experiment participants often just need to attend to a single and simple object. Second, in the real world we can interact with and change our environment over time (Findlay & Gilchrist, 2003), instead of just passively observing and reacting

to sequences of very similar stimuli during large numbers of trials. Third, instead of planning only a single action during a short trial, we usually plan action sequences (Hallett & Lightstone, 1976; Hoppe & Rothkopf, 2019; Najemnik & Geisler, 2005; Renninger et al., 2005; Renninger et al., 2007; Wagner et al., 2023) to achieve a certain goal.

Choosing tasks that impose realistic, less predictable, dynamic demands is essential for investigating naturalistic behavior, because task demands can fundamentally shape how we move (Hayhoe & Ballard, 2005; Rothkopf et al., 2007). For example, in lab paradigms the head is often constrained, while head movements are an integral part of natural behavior. While eye movements enhance the processing of previously peripheral locations, head movements serve exploration of new areas (Solman et al., 2017). Moreover, when a task contains temporal regularities, eye movements are adjusted to sample information (Hoppe & Rothkopf, 2016) and minimize information loss (Hoppe et al., 2018; Shalom et al., 2011) at critical times. Anticipatory eye responses often precede future target movements, indicating that participants strategically time their gaze shifts to align with upcoming events (Diaz et al., 2013; Goettker et al., 2023; Goettker et al., 2021; for review, see Kowler et al., 2019; Land & McLeod, 2000). Not only the point in time when the eyes move, but also where they move can be adapted to new demands, as demonstrated by saccadic adaptation (Deubel et al., 1986; McLaughlin, 1967; Schütz et al., 2014; Souto et al., 2016). These and similar adaptation processes can provide an ideal vehicle for understanding learning processes (Chen-Harris et al., 2008; Herman et al., 2013; Sailer et al., 2005; Wagner & Schütz, 2023). In summary, understanding how we dynamically adapt our behavior to varying task demands provides valuable insights into human behavior in naturalistic settings.

In this study, we use a gamified, continuous interception task (Pong) on an iPad to examine sequences of simultaneously recorded eye, hand, and head movements. By leveraging the technical

developments of mobile eye tracking systems, our setup allowed us to investigate the joint coordination of eye, hand, and head movements without restricting natural behavior through a chin rest. We focus on how these movements are adapted in response to a sequence of actions, across different time scales, and under various experimental manipulations. Our paradigm fulfills several aspects of a naturalistic task while still offering a high level of experimental control. It presents participants with several moving objects they need to attend to: their own paddle on the bottom of the screen, an automated paddle on the top of the screen, and the ball. Instead of passively observing, participants continuously interact with the scene by positioning their own paddle to intercept the ball and thereby shape its future trajectory. The task requires to plan and execute a sequence of actions until one of the paddles misses the ball. We show that behavior is tailored to the intricate dynamic requirements of the task. Across all experimental conditions and over time, pursuit, saccades and blinks, but also head and hand movements are properly timed to keep the ball in foveated vision shortly before intercepting it, while not losing visual information at crucial times. This complex orchestration of behavior is intuitively established and benefits interception performance.

Results

While playing Pong, participants (N = 24) control the horizontal position of a paddle on the bottom of the screen with their index finger and aim to intercept a moving black dot representing a ball. An automated paddle moving horizontally on the top of the screen serves as an opponent. All participants experienced two paddle sizes (1.5 vs. 2.3 cm) and two ball speeds (~16 vs. ~21 cm/s) resulting in four conditions. The order of conditions was counterbalanced across participants. Each condition consisted of at least 60 interception attempts and was preceded by a baseline of at least 15 interceptions (see **Fig. 1F**). We measured participants' finger

movements on the iPad and their eye and head movements with state-of-the-art mobile eye tracking glasses (Tobii Pro Glasses 3) allowing for free movements. By employing image processing tools including edge detection and homography transformation on each frame captured by the eye-tracker, we were able to convert the gaze coordinates to align with the iPad's screen (see **Fig. 1A-C**). Participants moved their eyes to mostly track the ball, the opponent's paddle, or their own paddle (see **Fig. 1E**). Only occasionally, gaze was directed toward the players' scores or off-screen. The duration of one typical action cycle (see **Fig. 1D**) ranged between 1.2 s and 9.3 s (95% of durations, *median* = 3.4 s). Our setup allowed us to investigate how gaze behavior was adapted across multiple time scales and whether these adaptations benefit game performance: First, we tested whether and how eye, head and hand movements changed across the continuous sequence of the ball bouncing from the participant's paddle to the opponent's paddle and back. Second, we examined how differences in behavior were related to task performance. Third, we analyzed how behavior generally adapted through experience over playing time, and across varying demands of ball speed and paddle size.

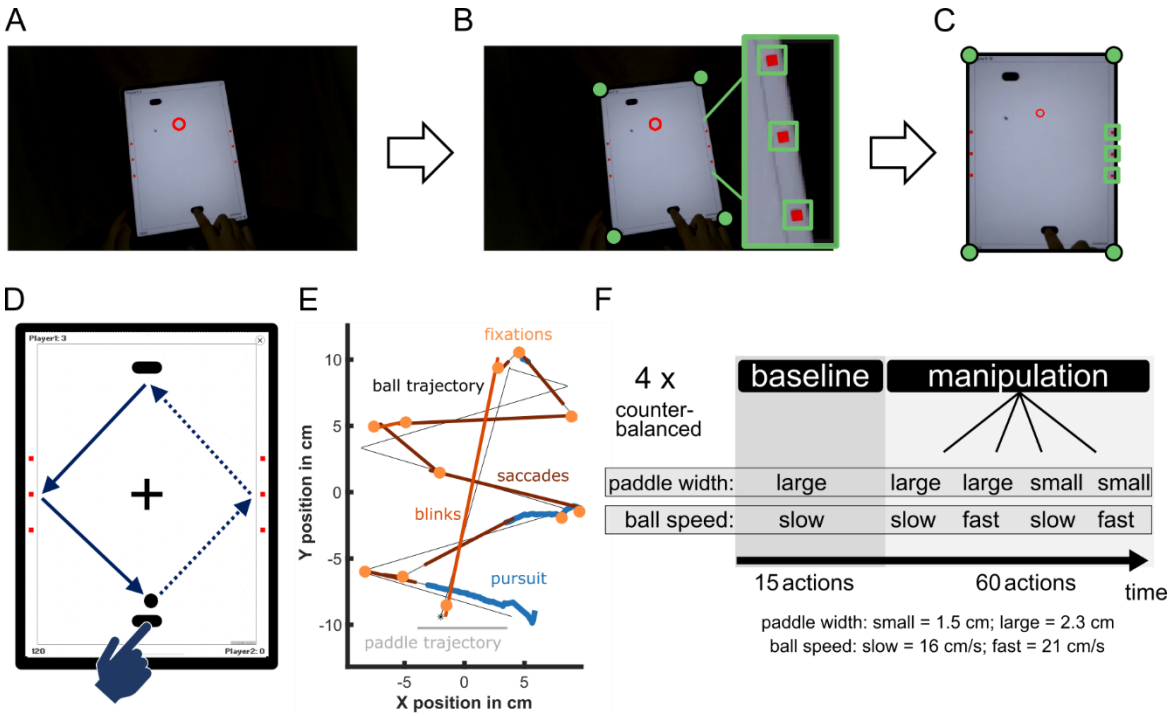

Figure 1. Illustration of the video game Pong and the methods. A) View of the iPad through the front camera of the mobile eye-tracker with the gaze position indicated by a red circle. B) We detected the red reference markers (three red squares on each side) or the corners of the iPad (illustrated by green dots) in a binary version of each frame using a color mask and/or luminance threshold. C) A homography transformation aligns the image and the gaze coordinates to the iPad's dimensions. D) Illustration of an action cycle: starting with the participant's interception, followed by the return of the opponent and concluding with the next interception. The task demands largely differ between the phase in which the ball recedes from the participant's paddle (dotted) compared to the phase in which the ball is approaching (solid). Therefore, we expect differences in gaze behavior across the time of an action cycle. E) The ball trajectory (black line) and gaze positions are shown for a representative action cycle. Participants track the ball using a mixture of saccades (red segments) and pursuit (blue segments) with fixations (yellow circles) primarily near bounce points. Gaze positions also change during blinks (orange segments). In this example, the ball moves directly towards the opponent without wall bounces, is returned, and bounces twice on each side before reaching the paddle of the participant. F) Experimental Procedure: participants completed four manipulation blocks, each preceded by a baseline of 15 interception attempts with the slower ball and larger paddle.

Do we adapt to the dynamic demands of the task?

Fig. 2 illustrates the relative frequency of the investigated behavior across the time of an action cycle: pursuit (**Fig. 2A**), saccades, blinks and fixations (**Fig. 2B**), and hand and head movements (**Fig. 2C**). Do we adapt the type and timing of movements to the dynamic demands of the task?

The most striking effect was on the frequency of pursuit eye movements: the closer the ball approached the participant's paddle the more likely the participant pursued the ball – that is, they

smoothly tracked the ball to keep it foveated (bright blue line in **Fig. 2A**). Fitting a 2-piece linear function to the time course indicated that the increase in pursuit frequency started shortly after the ball was hit by the opponent's paddle (see dashed lines in **Fig. 2A**). When comparing the slopes, the increase in ball pursuit during the approaching phase is significant, $t(23) = 4.22$, $p < .001$, $d = 0.861$. In contrast, participants tracked the paddle of the opponent instead of the ball when the ball was close to it (36% - 52% of the time, dark blue line in **Fig 2A**). While pursuit of the ball increased in the second half, the frequency of fixations diminished (bright orange line in **Fig. 2B**). Participants rarely tracked their own paddle, which was controlled by their own hand movement.

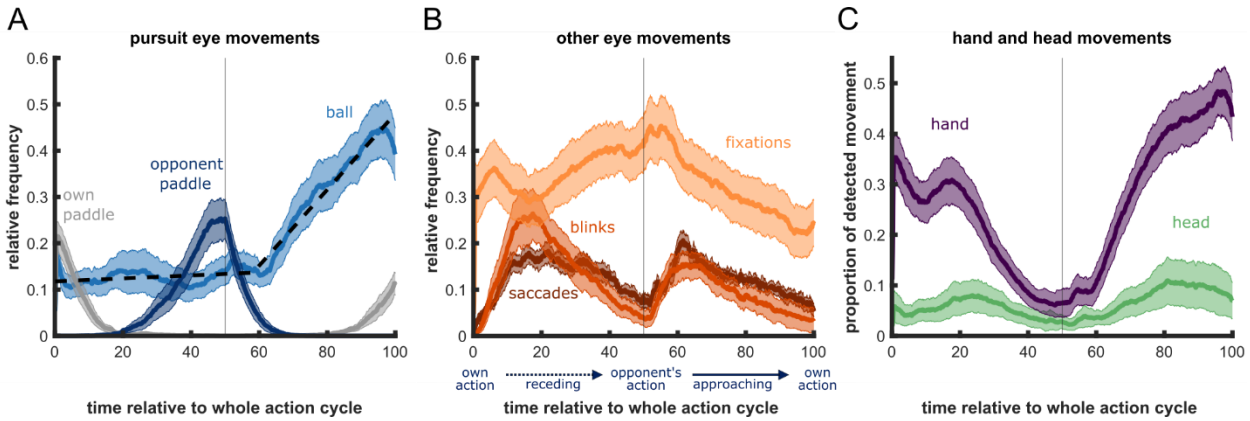

Figure 2. *Frequencies of the different eye movement types, hand, and head movements (mean and 95% between-subject intervals) over time during the action cycles. A) The choice of the pursuit target changed during the action cycle depending on the ball position: participants pursued either paddle movement (own: grey, opponent: dark blue) when the ball was close to one of them. Pursuit of the ball (bright blue) steadily increased during the approaching but not during the receding phase. The dashed line indicates a 2-piece linear fit with the two pieces crossing at 55% of the action cycle. B) Fixations (bright orange) become less frequent with the approach of the next action, blinks (medium orange), and saccades (dark orange) are reduced during the opponent's and participant's actions. C) Hand movements (dark purple) to control the paddle were present during interception and were largely reduced around the opponent's action. Head movements (bright green) were less frequent than eye movements. Participants moved their heads mainly before intercepting the ball and these movements were more closely aligned with the ball trajectory compared to early head movements. Please note, that in ~16% per action cycle gaze behavior did not fulfill any criterion and was therefore not classified as any of these events (see Methods for more details). Consequently, there are non-classified episodes and overall, the curves in Fig. 2A and B do not add up to 1.*

During and shortly before the ball hit one of the paddles (50% and 100% of relative time) participants rarely blinked (medium orange line in **Fig. 2B**). Instead, participants seemed to blink mainly during time periods shortly after the ball bounced back from their own paddle or from the opponent's paddle (vertical line in **Fig. 2B**), so at time periods with the least critical visual

information. In line with this, participants also blinked more frequently in time periods after they had hit the ball with their paddle, and a lot of time was still left until they had to intercept the ball again, compared to when the opponent returned the ball and it was approaching them (mean of 0.15 vs. 0.11 blinks per second), $t(23) = 2.96$, $p = .007$, $d = 0.604$. Additionally, blinks were initiated earlier in receding compared to approaching phases (mean of 0.96 s vs. 1.33 s), $t(23) = 2.41$, $p = .025$, $d = 0.491$. Please note, that *relative* blink initiation time was equal between phases (35% vs. 34 % of relative time, $p = .833$), which is caused by different mean durations of the phases (receding: 1.7 s, approaching: 2.5 s).

Saccades showed a similar time course as blinks (dark orange line in **Fig. 2B**): Most saccades occurred during the middle of the receding and approaching phases. On average saccades were executed ~140 ms later in the approaching phase than in the receding phase (mean of 1.24 s vs. 1.10 s, 1.24 s), $t(23) = 3.31$, $p = .003$, $d = 0.676$. Please note that the *relative* timing was earlier in the approaching phase due to different phase durations (50% vs. 47 % of relative time, $p < .001$). Saccade rates were not significantly different between phases ($p = .757$).

Hand movements mainly occurred towards the end of an action cycle or shortly after an action (purple line in **Fig 2C**). Participants seem to wait for the target when the opponent is interacting with it. Head movements are generally less frequent (green line in **Fig. 2C**) but show small peaks in the middle of receding and approaching phases. Additional analyses showed that head movements were more closely aligned with the ball trajectory, when the ball was approaching the participant compared to the receding phase (mean difference in direction of 27 vs. 57 deg), $t(23) = 7.93$, $p < .001$, $d = 1.69$.

Together, these results demonstrate that participants specifically adapt their behavior to the changing requirements of the different phases of the dynamic task: Participants try to blink, move

their head, and make most of their saccades during times when the ball just started receding from their own or the opponent's paddle. The closer the moment of interception, the more participants focus on pursuing the ball and aligning their head movements with it.

Association between eye movements and performance

The above results raise the question whether this typical pattern of movements benefits performance. To test this, we analyzed behavior, especially pursuit eye movements, with respect to hit vs. miss actions within observers, but also across observers. Within participants, Generalized Additive Mixed Models (GAMMs) fitted to ball pursuit frequencies over time revealed significant differences between hits and misses. Significant intervals are indicated by bars at the bottom of **Figure 3A.** If a participant hit the ball in a given action cycle, it was more likely that the preceding eye movement was pursuit compared to action cycles in which they missed it (**Fig. 3A**). The fact that the general increase in ball pursuit during the approaching phase (see **Fig. 2A**) is even larger before a hit highlights the specific importance of ball pursuit during the final phase before interception. In contrast, early pursuit in each action cycle, especially shortly after the bounce at the opponent's paddle was associated with missing the ball. Additional analyses revealed that more hand and head movements towards the end of the action cycle, as well as pursuit of the own paddle were related to worse performance, as indicated by the significant intervals of the GAMMs (**Fig. 3A and B**).

The beneficial effect of ball pursuit was further supported by analyses across participants. Participants who were more likely to pursue the ball movement immediately before or during interception score higher in the game (**Fig. 3C**), $\tau = 0.37$, $p = 0.01$. In summary, this indicates that the movement patterns shortly before acting are indicative of the interception success. Specifically, pursuit of the ball movement before interception improves interception performance.

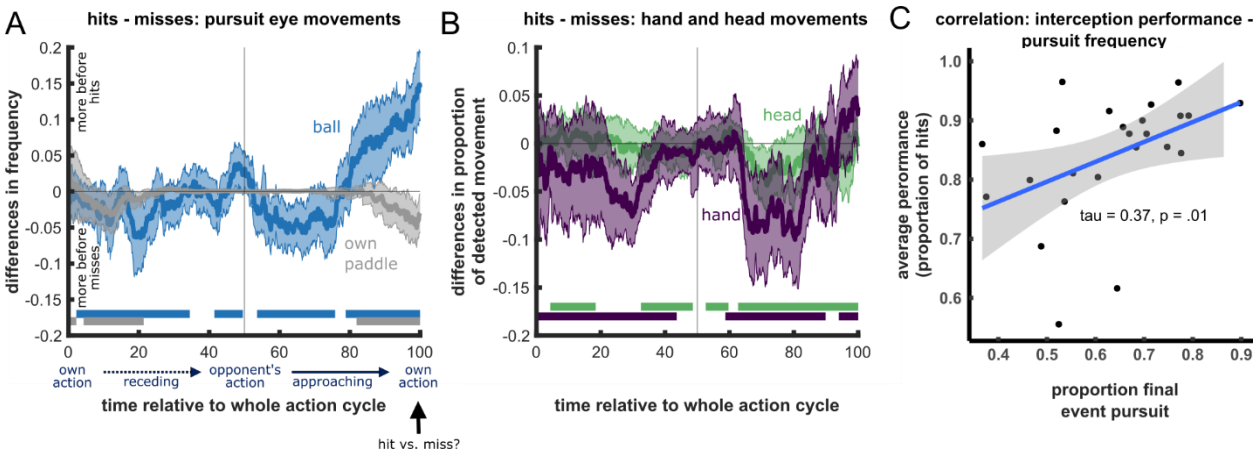

Figure 3. Association between performance and eye, hand, and head movements. A-B) Differences in Eye, Head and Hand Movement Frequencies for hit versus miss actions. Shown are the means and 95% between-subject confidence intervals. Positive values indicate that the respective movement was more frequent prior to hit actions at a specific point in time. Generalized additive mixed models were fitted to the data and time intervals of significant differences between hits and misses are indicated by the bars at the bottom. Pursuit of the ball (bright blue) shortly before interception was associated with hitting the ball, while shortly after the opponent's action it was rather associated with missing it. Shortly before missing the ball participants pursued the movements of their own paddle (bright blue) more frequently compared to the same time when hitting the ball. Hand (dark purple) and head (bright green) movements shortly before interception were indicative of missing the ball. C) Between-subject correlation between pursuit and performance. Participants who show more frequently pursuit as a final eye movement before hitting the ball, perform better in the game.

Practice related changes

Since practice is known to modify movements patterns, we compared these behaviors during the first 15 action cycles of the initial baseline (preceding the first block) with those during the 15 action cycles of the final baseline (preceding the final block). Indeed, interception performance increased from 85% to 94% hit rate in later actions (**Fig. 4F**), $t(21) = 3.26$, $p = .003$, $d = 0.666$. Given the importance of pursuit eye movements for interception (e.g., de la Malla et al., 2017; Spering et al., 2011), we focused on the frequency of ball pursuit (detailed results for other eye movement metrics are provided in the Supplement). Pursuit of the ball did not significantly change over the time of the experiment in the approaching phase, $t(23) = -0.25$, $p = .802$, d = -0.052. There was a trend for more head movements, specifically in the approaching phase, $t(21) = 2.28$, $p = .032$, d = 0.465, but this was not significant after correction for multiple comparisons. Please note that visual inspection of the time course data (see Supplement **Fig. S2** for additional analyses) indicates that these effects might be more restricted to specific time windows and

therefore are underestimated in the current analysis. It additionally suggests that participants increase pursuit of the opponent over the time of the experiment, increasingly blink (especially at times shortly after own or opponent actions) and reduce initial fixations in the receding phase (see Supplement **Fig. S2**). Overall, these analyses show that the movement patterns were intuitively established and relatively stable over the time of the experiment. If behavior was adapted, these adaptations were small and seemed to be limited to specific time windows indicating a fine tuning of the movement timing instead of a general in- or decrease in movement frequency.

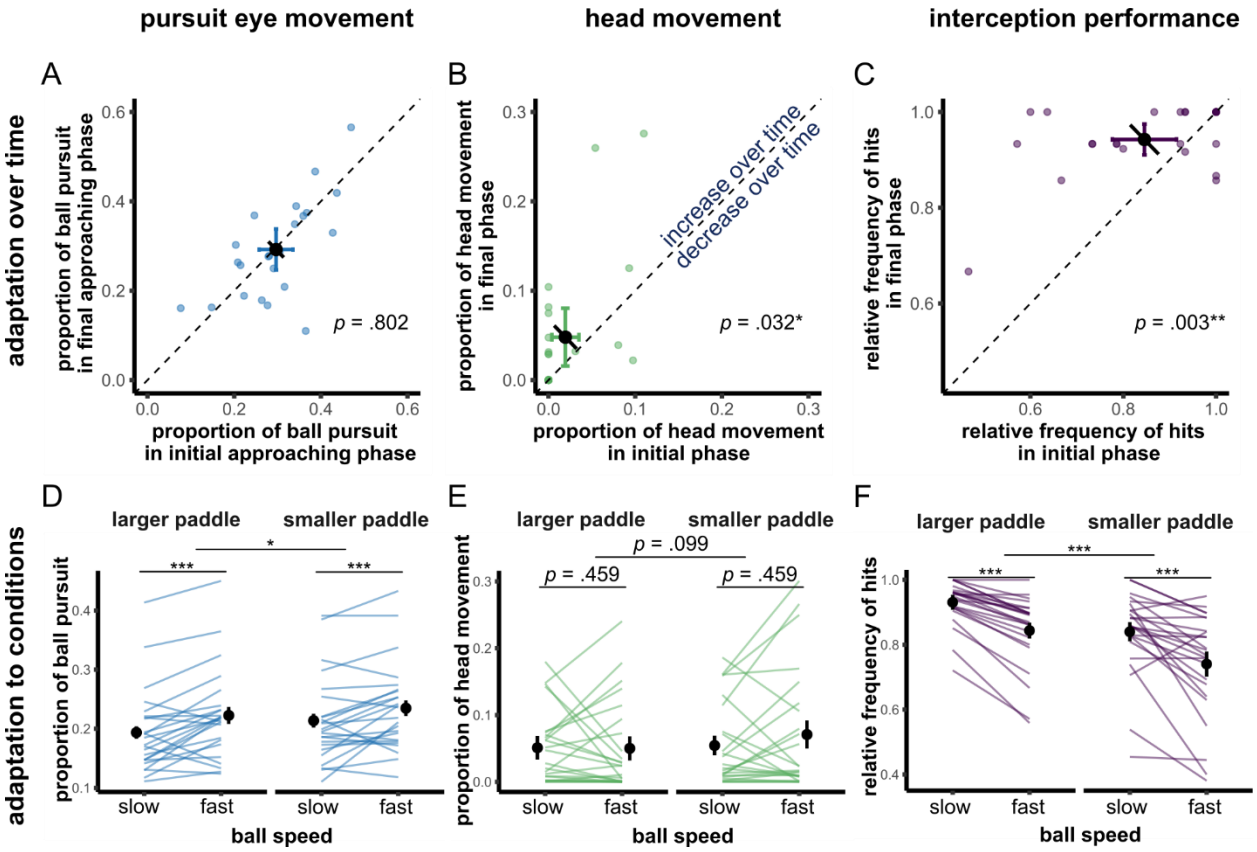

Figure 4. *Overview of adaptation effects.* ***Top row:*** *adaptation effects over time of approaching ball pursuit (A), head movements (B) and interception performance (C).* ***Bottom row:*** *adaptation effects of paddle size and ball speed on ball pursuit (D), head movements (E) and interception performance (F). All plots include individual data (colored dots and connecting lines) and means with 95% within-subject confidence intervals (black). The pairwise comparisons for adaptation over time additionally show the uncorrected confidence intervals (colored).*

Effect of experimental conditions

We tested whether ball speed or paddle size impact performance and oculomotor strategies in repeated measures ANOVAs. The overall pattern of eye movement behavior stayed consistent across conditions (see Supplement **Fig. S3**), but there was again some fine-tuning. There was more pursuit for faster targets (**Fig. 4G**), $F(1, 23) = 20.02$, $p < .001$, $\eta_p^2 = .47$, and for the smaller paddle size, $F(1, 23) = 5.00$, $p = .035$, $\eta_p^2 = .18$. Head movements were unaffected by ball speed or paddle size (ps $\geq .099$, **Fig. 4H**). As expected, interception performance decreased with higher ball speed and smaller paddles (see **Fig. 4I**), as shown by significant main effects of ball speed, $F(1, 23) = 41.61$, $p < .001$, $\eta_p^2 = .64$ and paddle size, $F(1, 23) = 35.31$, $p < .001$, $\eta_p^2 = .61$. This indicates that increased pursuit frequency may compensate partially for performance challenges imposed by increased task demands, though head movements showed no significant adaptation.

Discussion

We investigated how participants used and adapted their eye, head, and hand movements for successful performance in a continuous interception task. Our findings indicate that participants developed a robust and effective strategy for intercepting the ball. They carefully orchestrated their eye, head, and hand movements in anticipation of upcoming actions, and this well-coordinated behavior led to more successful outcomes. Participants relied on a blend of saccades and pursuit to track the ball, and specifically increased pursuit in the moments before interception. By contrast, they seldom pursued their own or the opponent's paddle and minimized potentially distracting movements—such as head shifts, blinks, and saccades—around the critical action moments. Although these patterns remained remarkably stable, participants did make fine adjustments to

their movement patterns with practice and under more demanding conditions, suggesting that they refined their strategies rather than overhauling them.

Adaptation to the action

Participants dynamically adjusted their instrumentation of different motor behaviors to achieve optimal action outcomes. In particular, changes in the proportion of pursuit were a strong indication of the strategic control of eye movements. Firstly, participants increased pursuit frequency as the ball approached their paddle. Secondly, there were significant within-subject differences in the timing of pursuit in relation to successes and failures. Thirdly, there was a significant between-subject correlation between final pursuit frequency and overall game performance. While previous experimental manipulations showed a general advantage of pursuit eye movements compared to fixations for motion perception and interception (de la Malla et al., 2017; for review see Fooken et al., 2021; Spering et al., 2011), we revealed the temporal integration of pursuit within a continuous sequence of actions: Participants intuitively applied but temporally restricted their pursuit to relevant periods in time, maintaining its beneficial outcomes. Shalom et al. (2011) showed that participants kept their eyes closer to the ball before compared to after their interception in a comparable game ('Breakout'). Our results suggest that this is achieved by closely pursuing the ball before interception, a strategy also shown by expert cricket batsman (Land & McLeod, 2000). The positive effect of pursuit for interception might be due to additional information provided by an efference copy (for a review, see Bridgeman, 1995; Sommer & Wurtz, 2008). Thus, the way we track a moving target is predictive of whether we successfully intercept it later. Previous studies have reported that pursuit eye movement behavior within (Arthur et al., 2023; Binaee & Diaz, 2019; Cesqui et al., 2015; Fooken & Spering, 2020; Fooken et al., 2016; Kreyenmeier et al., 2017) and across observers (Brenner & Smeets, 2011; Delle Monache et al.,

2015; Fooken & Spering, 2020; Fooken et al., 2016; Spering et al., 2011) can be directly related to performance in such tasks (for review, see Fooken et al., 2021). Here we expand on these findings by demonstrating that faced with continuously changing task demands, participants can strategically adjust when to pursue a relevant object to aid performance.

We also find that strategic deployment of different types of movements was not limited to pursuit. The impeding action also affected the timing of blinks, saccades and head movements. Participants restricted behavior that reduces the quality of the visual input to periods that were not critical for game performance (Goettker, Brenner, et al., 2019; Hoppe et al., 2018; Shalom et al., 2011). This is interesting due to three reasons: First, saccades during tracking help to correct position mismatches between the eyes and the target (see Goettker & Gegenfurtner, 2021), which should be beneficial. However, visual sensitivity is reduced during saccades (see Binda & Morrone, 2018; Braun et al., 2021). To manage this tradeoff, people restricted saccades to earlier moments and waited at predicted target locations to continue tracking with pursuit eye movements. This strategy aligns with findings from an earlier study, which showed that corrective saccades during tracking are often triggered earlier to avoid that they occur too close to the interception time (Goettker, Brenner, et al., 2019). Second, even though blinks might have a beneficial effect in specific detection tasks (Yang et al., 2024), our results show that blinks are suppressed at critical times in a dynamic task with motor responses to moving objects. Third, the execution of head movements typically supports visual information intake (Bischof et al., 2023). Previous studies on monkeys (Arora et al., 2019) and humans (Bischof et al., 2024; Burlingham et al., 2024; Hooge et al., 2024) showed that head movements often follow eye movements and serve to center the gaze in the visual field. However, head movements also introduce noise due to the transformation of the visual reference frame (Abedi Khoozani et al., 2020). This was reflected in the fact that head

movements toward the end of the trial were related to worse performance. Therefore, during the Pong game, participants might have specifically centered their gaze before the critical moment of interception but avoided further head movements during the action. This again underlines the strategic timing of movements to optimally perform in this task.

In summary, all movement frequencies showed a strong temporal dependency on actions, whether by oneself or the opponent. Movements that potentially cause noise or loss of critical visual information, like blinks, saccades and head movements are largely reduced at these critical points in time. In contrast, pursuit eye movements are increased, as they provide additional motion information of direction and speed by efference copy signals. Thus, we adjust our behavior to receive the critical information at the right time (Fooken et al., 2024; Keshava et al., 2024), and this strategic timing of behavior optimizes game performance. The brain, in the role of a conductor, coordinates the dynamic interplay of the available movement instruments. This culminates in a pursuit solo shortly before the interception, and this was most relevant for successful actions.

Fine tuning behavioral instruments with practice and in relation to task demands

Our results show that the orchestration of behavior is impressively consistent and efficient, with only slight adaptations to changing conditions like target speed and paddle size. This highlights our ability to optimize movements for task success, making subtle or gradual adjustments as situations change. We constantly experience a changing environment in everyday life where we need to interact with dynamic objects, allowing us to quickly tap into effective motor responses with our eyes, head, and hands. Remarkably, we demonstrated that people automatically show

robust movement patterns and sustain these patterns across various conditions, with only a little bit of fine tuning depending on experience and the current task demands.

Our findings suggest that the increased pursuit response is highly trained and automatically applied in interception games. Participants concentrated on the approaching phase from the start (first 15 actions, also in Hoppe et al., 2018), and this pattern was maintained throughout the experiment and across conditions. While pursuit frequency increased slightly for fast balls and small paddles, performance declined under these conditions, suggesting that they pose greater demands on participants. Although participants tried to compensate with closer tracking, higher pursuit rates did not fully offset performance decreases.

Continuous tasks in computer games to study behavior

By combining mobile eye tracking with state-of-the-art computer vision, we establish a methodology that leverages games to study the coordination of eye, head, and hand movements. Our approach extends previous gamified experiments (Avraham et al., 2017; Kirsch & Kunde, 2018; Laitin & Witt, 2020; Mikula et al., 2022; Shalom et al., 2011) by focusing on the investigation of complex, sequential behaviors which points to the outstanding potential of computer games as a tool for exploring human behavior. Gamified tasks keep participants motivated, providing a natural goal that makes the task both engaging and realistic. Therefore, as experimental tool, they allow to study dynamic, less predictable, real-world behaviors while maintaining the precision and control of experimental settings—an exciting step forward from isolated, trial-by-trial approaches.

Conclusion

Using advanced mobile eye-tracking technology, we captured eye, head, and hand movements in a dynamic computer game with continuously changing demands. Our findings

reveal how participants naturally adapt their behavior to the demands of the upcoming task—minimizing information loss by performing some movements (blinks, saccades and head movements) at non-critical times and enhancing pursuit eye movements precisely at moments critical for successful interception. This pattern of behavior was strongly linked to higher interception performance, showcasing the successful orchestration of movements patterns to meet continuously changing demands of our environment.

Methods

Participants

A total of 24 participants (16 females, mean age: 25 (sd = 3.7) years) completed the experiment so that their full data sets are available (2 additional recordings were incomplete and therefore not included in the analysis). For head movements analyses, data of only 22 participants was available due to technical issues during the recording. All participants had self-reported normal or corrected-to-normal vision. Participants gave informed consent prior to participating in the study and received a compensation of 8€ or credits for 1h of participation. This experiment is part of a project approved by the ethics committee of the University of Giessen (approval number: LEK-2021-0028).

Materials

The Pong Game was presented on an iPad 12 Pro (2732 x 2048 px, 264 ppi). The game consists of a black dot representing the ball (radius: 19 mm = 20 px) and two black rectangular paddles with rounded edges, one controlled by the participant and one automated (the opponent) presented on a uniform white background (screen size: 26.3 cm x 19.7 cm). The opponent was

programmed to move in the horizontal direction of the ball whenever the ball approached him, including a small variable temporal delay and variable speed. Every 15 actions, the horizontal position was slightly shifted with respect to the ball, making the opponent miss the ball. We manipulated paddle width (small: 1.5 cm = 160 px and large: 2.3 cm = 240 px), while keeping the height constant (120 px = 1.15 cm). The ball moved linearly with a constant speed over the screen and bounced back from the side walls and paddles. Between blocks, the ball speed (*slow*: 27 px/frame = 15.6 cm/s ≈ 17.3 deg/s, *fast*: 37 px/frame = 21.4 cm/s ≈ 23.2 deg/s; assuming a distance of approximately 50 cm between eyes and iPad) was changed. To achieve variable ball trajectories the bounce angle from the opponent was manipulated (15, 45, or 75 degrees relative to perpendicular) while the emergent angle equaled the incidence angle for all other bounces.

Eye and head movements were recorded with Tobii Glasses Pro 3 and analyzed in Matlab (The MathWorks Inc., 2022) using the GlassesViewer (Niehorster et al., 2020) and self-written code. The sampling rate of gaze data was 100 Hz, scene camera scene 25 Hz, and the IMU ~100 Hz. The iPad displayed the stimuli and saved paddle and ball positions with 60 Hz. For the analysis, all data was interpolated to 100 Hz.

Procedure

The experiment consisted of four experimental blocks (2 ball speeds x 2 paddle sizes) of at least 60 interception attempts, each preceded by a baseline of at least 15 interception attempts with the larger paddle size and slower ball speed. As soon as the minimal number of interceptions for each condition or baseline was reached, the switch to the next condition occurred during the short break following one player scoring a point. The order of the four blocks was counterbalanced across participants After either the participant or the opponent missed the ball, a fixation cross was

presented at the center of the screen and after random time between 2.5-3 s (uniform distribution) the ball started again from the center and moved linearly into the direction of the opponent. Before starting the experiment participants answered a few demographic questions (age, gender, vision) and were familiarized with the mobile eye tracker before a calibration and validation were done (glassesValidator, Niehorster et al., 2023). The validation was repeated after the experiment to ensure sufficiently accurate data quality throughout the time of experiment. Altogether the whole experimental session took about 1h.

Eye and Head Movement Analysis

In a first step the gaze data was manually temporally aligned with the iPad using the scene video and a green rectangle displayed on the screen at the beginning of the game only for this purpose. The data was then transformed to the iPad's reference frame by using computer vision algorithms in Matlab. For each video frame of the scene camera, the position of the iPad was extracted. Using either the position of six red rectangular reference objects positioned at the iPad or the iPad's edges (if the reference objects were not detected using a color mask and object detection with the Matlab function bwboundaries), a homography transformation was performed (see **Fig. 1**) using Matlab functions fitgeotrans (projective) and imwarp.

Using the original eye movements without transformation, saccades and blinks (missing data episodes) were classified as implemented in the glassesViewer (Niehorster et al., 2020) choosing the adaptive velocity algorithm from Hessels et al. (2020). In a second step, we relabeled saccades with durations equal to or longer than 200 ms as blinks (Gandhi & Katnani, 2012; Leigh & Zee, 2015). Third, based on the gaze position relative to the iPad, pursuit events were detected: every episode lasting at least 100 ms with a gaze velocity of at least 7 cm/s (~50% of the slower

ball velocity), and moving in the same direction as of one of the three objects, the ball and the two paddles (+-30 degrees). Each pursuit event was related to exactly one of these targets, namely the target with the most similar movement direction. All episodes of at least 100 ms in which the eyes did not fulfill any of the other criteria (= nearly no motion in gaze position) were labeled as fixations. Episodes shorter than 100 ms which were not attributed to one of the labels or episodes with missing gaze signal were not labeled as eye movements (16 %).

To detect head movements, the gyroscope data of the eye tracker was used, and all three velocity directions were combined to one measure: the velocity of the total movement (square-root of the summed squared velocities). Times in which the overall velocity was at least 10 deg/s for at least 100 ms were labeled as head movement events. Head direction angles were computed from the directional gyroscope data of the head mounted eye-tracker and evaluated relative to the target motion direction

Statistical Analysis

To analyze the adaptation of eye movements over time only complete episodes of an action cycle from one interception (or the start from the center) to the next interception were included. The frame after the ball bounced from the participants' paddle was labeled as the start frame and the frame of the next bounce from the participant's paddle was labeled as end frame. In between the ball bounced once from the opponent. If more than 45% of the gaze data between those frames were missing, the whole episode was excluded.

We summarized frequencies of eye, head and hand movements per participant and point in time (relative to the next action) in steps of 0.1%. Difference-scores were calculated for each participant. For statistical analyses we used R (R Core Team, 2021) and RStudio (RStudio Team,

2016). To test for aggregated differences between phases, after misses or over time, we report means and t-tests. If the data violated the assumption of normal distribution additional non-parametric Wilcoxon signed rank exact tests were executed, but they revealed the same results. To test for overall effects of the two manipulations, repeated measures ANOVAs (package ez, Lawrence, 2016) on the performance or summarized gaze statistics were performed using the within factors paddle size (small or large) and ball speed (slow or fast). To contrast successful interceptions with misses and analyze the exact time windows, we fitted Generalized Additive Models (package itsadug, van Rij et al., 2020; package mgcv, Wood, 2011) including either random intercepts, both random intercepts and random slopes or random intercepts and random smooths to the data streams (see below). Using *plot_diff* we derived the significant intervals for differences between hit and miss actions.

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Supporting Information

Additional analysis and discussion on error correction. We tested for changes in behavior with respect to the interception success. Do we change our behavior after missing the ball? For this purpose, we compared action cycles after missing the ball with action cycles after the opponent missed the ball. In both cases the ball movement restarted in the center of the screen and moved towards the opponent, making these conditions highly comparable. Results indicated that eye movements were relatively resistant to own misses. Descriptively the frequency of ball pursuit was slightly increased during the receding phase after own misses, but this difference was not significant (Fig. S1C), $t(23) = 1.68$, $p = .107$, $d = 0.342$. In contrast, for head movements a more pronounced effect was evident: After misses of the participant head movements were increased in the receding phase (Fig. S1I), $t(21) = 2.88$, $p = .009$, $d = 0.614$. Yet, the direction of head movements relative to the ball direction during this phase did not significantly differ between own an opponent's misses, $t(14) = 0.09$, $p = .930$, $d = -0.023$. Results showed no adaptation of hand movement frequency after misses (Fig. S1I). This shows that after errors, participants only made small changes in their behavior, mostly by moving their head more frequently.

After own misses, compared to opponent's misses, participants were more likely to move their head, whereas eye and hand movements were mostly unaffected. These results suggest that the overall pattern of movements was almost not adjusted at all after own mistakes. We interpret this as another sign, that interacting with moving objects by hitting them is a highly trained behavior making it easy for us to access appropriate motor responses and not change this strategy. We have learned that pursuit is useful to successfully intercept, even if we occasionally miss the target. Potentially, if participants made more errors they would have explored new ways to use their eye, hand and head movements to better perform in this task, but given the current demands,

this behavior has proven to be most successful. Future research in children might evaluate when this behavior is learned and whether different types of movements are learned at different stages.

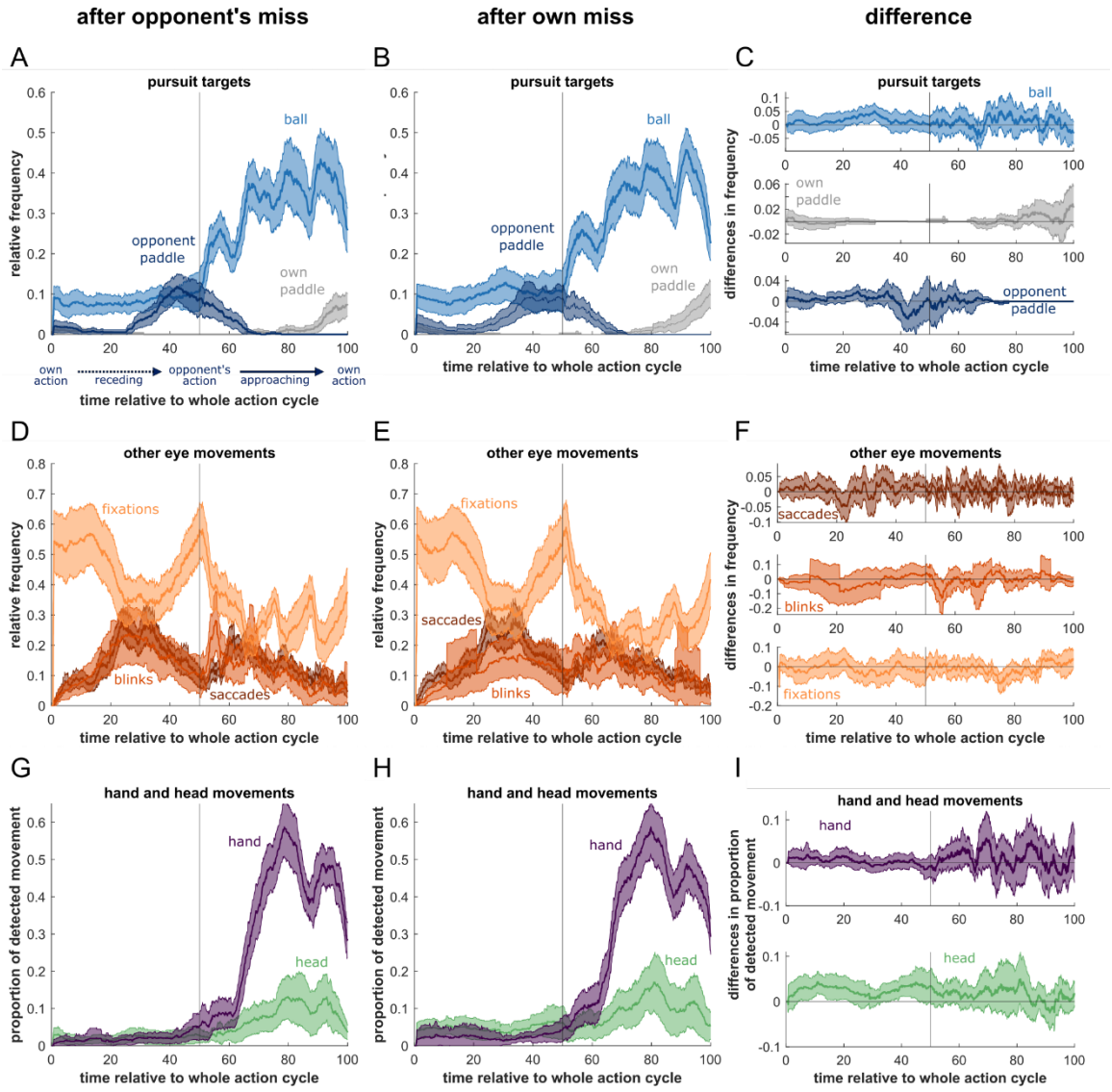

Fig. S1. Adaptation after misses. The first column shows eye, hand and head movements after misses of the opponent and the second column after own misses. The third column shows differences between the two, with positive values indicating higher frequencies for own misses.

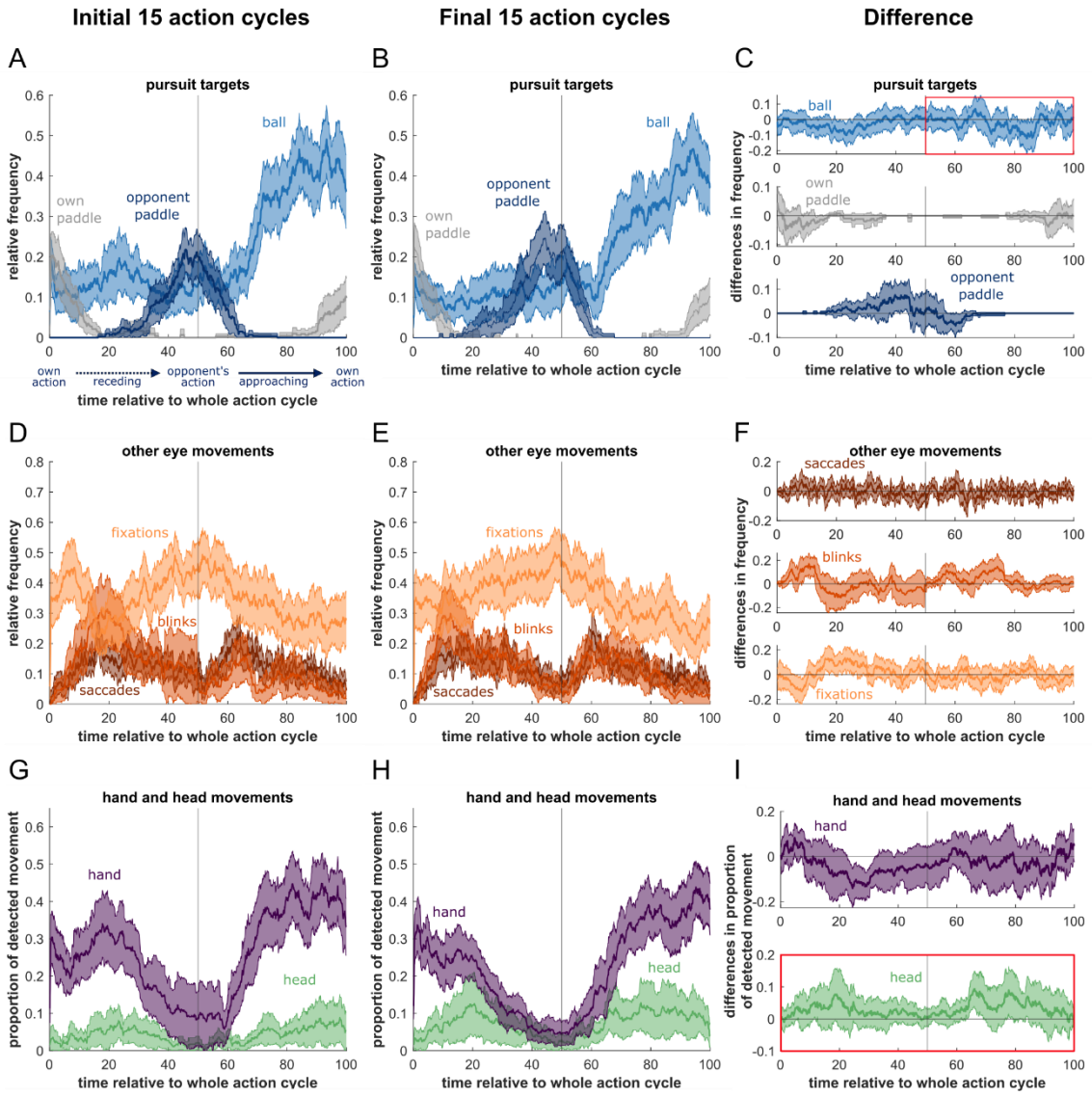

Fig. S2. Adaptation over time. The first column shows eye, head and hand movements for the initial baseline (15 actions) and the second column for the baseline preceding the final block (15 actions). The third column shows differences between early and late trials, with positive values indicating higher frequencies in late trials. Red boxes indicate intervals (approaching vs. receding phase) plotted in the main manuscript and analyzed via t-tests in the main manuscript.

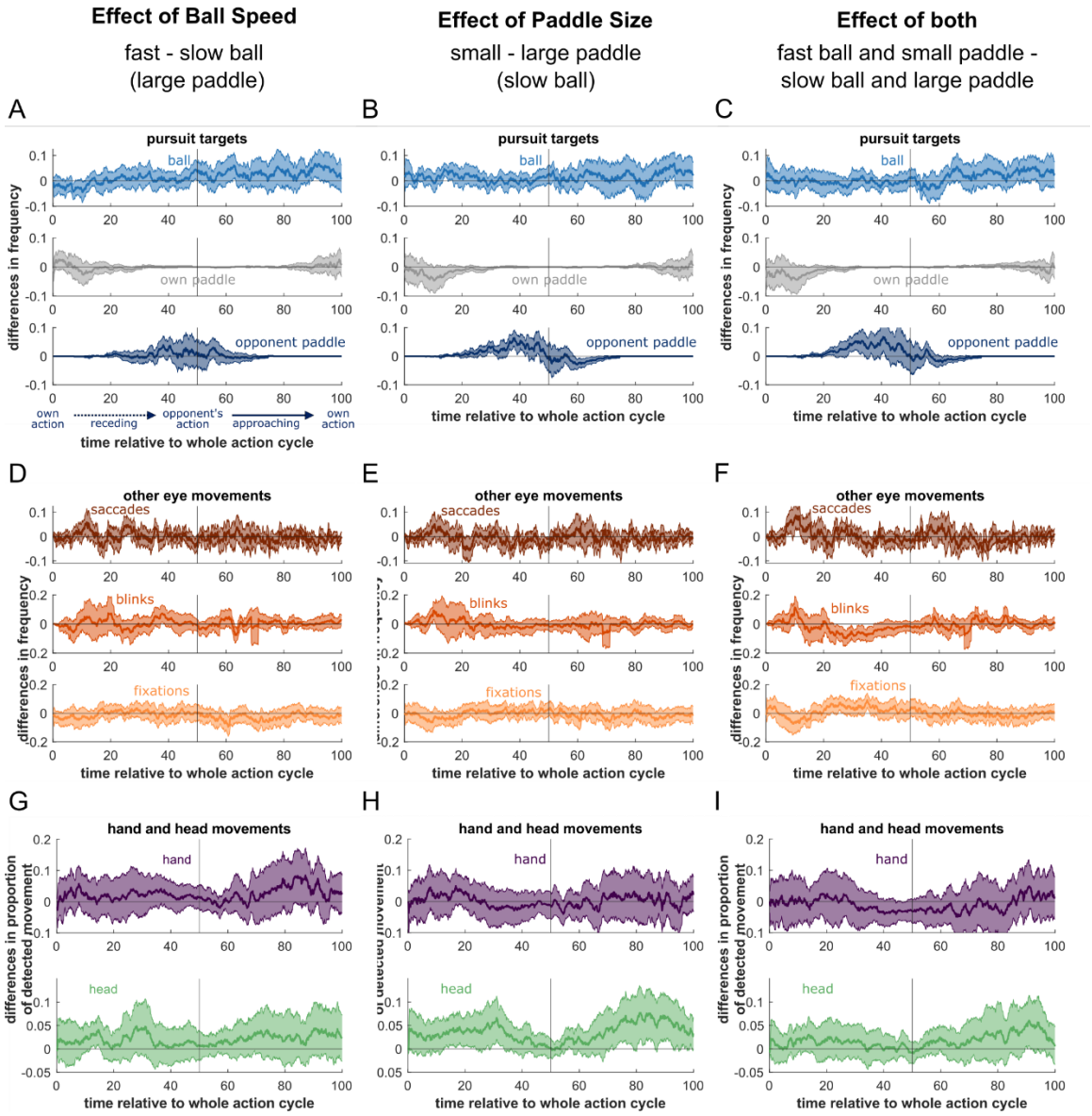

Fig. S3. Adaptation across manipulations time. All conditions are compared to the same reference condition with the small paddle and slow ball (same as baseline).