Behavioral/Cognitive

Managing Gaze Competition during Simultaneous Manual Action Control and Environment Monitoring

Jolande Fooken,[1,2] Roland S. Johansson,[3*] and J. Randall Flanagan[2*]

[1]Department of Psychology and Centre for Cognitive Science, Technical University of Darmstadt, Darmstadt 64283, Germany, [2]Department of Psychology and Centre for Neuroscience Studies, Queen's University, Kingston, Ontario K7L 3J7, Canada, and [3]Department of Medical and Translational Biology, Umeå University, Umeå 901 87, Sweden

Research on visually guided object manipulation has shown that participants fixate goal locations—including objects to be grasped and locations where they are placed—prior to hand arrival, with gaze serving two primary functions: directing the hand (or object in hand) to the vicinity of the goal using peripheral vision and gaze-related signals and guiding the hand using central vision as it approaches the goal. However, real-world manipulation tasks are often performed while concurrent monitoring of the environment, resulting in competition for gaze. We examined gaze–hand coordination under such conditions. Human participants of either sex performed a manipulation task that involved grasping balls and placing them at target locations, while concurrently monitoring a display to detect probabilistically occurring visual events, which required central vision. Participants managed gaze competition in two main ways. First, fixations allocated to the action task were brief and prioritized directing the hand toward the goal (object or target location); participants then relied on tactile feedback to complete the action (grasping or placing the object). When tactile feedback was reduced—by using a tool instead of the fingertips to perform the task—gaze additionally served the guiding function. Second, participants reduced gaze competition by exploiting temporal regularities of events in the monitoring task. Specifically, they adjusted both gaze allocation and hand movement timing to reduce the likelihood that action task fixations would coincide with visual events. These findings demonstrate how individuals flexibly integrate sensorimotor control with analysis of environmental statistics to manage competing visual demands.

Key words: **decision-making; eye–hand coordination; human; motor control**

Significance Statement

In everyday behavior, we often perform manual tasks while simultaneously monitoring the environment, creating competition for gaze. How the brain resolves this competition remains poorly understood. Using a novel paradigm combining an object manipulation task with visual event monitoring, we show that participants integrate knowledge of sensorimotor demands and temporal regularities in the monitoring task to manage gaze. Specifically, we found that participants preferentially allocated gaze to the action task when it is most critical for sensorimotor control and when the likelihood of a visual event was low. Additionally, participants adjusted their hand movement timing based on event statistics to reduce gaze competition. These findings reveal how the brain dynamically allocates gaze resources across competing sensorimotor and visual task demands.

Introduction

In everyday life, we often perform manual tasks while also monitoring the environment for events of interest, leading to competition for gaze between action and observation (Land and Furneaux, 1997; Kowler, 2011; Hayhoe, 2017; Fooken et al., 2023; Keshava et al., 2024). For example, while cooking, one may use gaze both to slice vegetables and to detect the moment when water begins to boil or a pan starts to smoke. In principle, we can consider three complementary strategies—which can operate in parallel—by which individuals might manage this

Received Nov. 24, 2025; revised April 14, 2026; accepted May 6, 2026.

Author contributions: J.F., R.S.J., and J.R.F. designed research; J.F., R.S.J., and J.R.F. performed research; J.F., R.S.J., and J.R.F. analyzed data; J.F., R.S.J., and J.R.F. wrote the paper.

This work was supported by a Deutsche Forschungsgemeinschaft (DFG) Research Fellowship to J.F. (FO 1347/1-1), the Swedish Research Council Project (grant 22209 to R.S.J.), the Canadian Institutes for Health Research (grant RGPIN/05944-2019 to J.R.F.), and the Natural Sciences and Engineering Research Council of Canada (grant 156173 to J.R.F.).

*R.S.J. and J.R.F contributed equally to this work.

The authors declare no competing financial interests.

Correspondence should be addressed to Jolande Fooken at jolande.fooken@tu-darmstadt.de.

https://doi.org/10.1523/JNEUROSCI.2157-25.2026

competition. First, individuals may selectively allocate gaze to the action task only when gaze is most critical for sensorimotor control. Second, they may exploit temporal regularities of events in the visual environment, preferentially directing gaze to the action task when the likelihood of an event is low. Third, they may further leverage these regularities by modifying the timing of their manual actions so that gaze-critical phases of the task coincide with periods of reduced event probability.

To investigate how people manage competing demands on gaze, we designed a novel paradigm in which participants performed a continuous object manipulation task while monitoring a display to detect visual events [letter changes (LCs) from M to W; Fig. 1*A*]. The manipulation task involved grasping a small ball, moving it to a slot, and inserting it and thus captured the key components of many manual actions: grasping, transporting, and placing objects (Johansson et al., 2001; Flanagan et al., 2006; Fig. 1*B*). Visual events in the monitoring task occurred probabilistically, with the likelihood of events varying predictably over time.

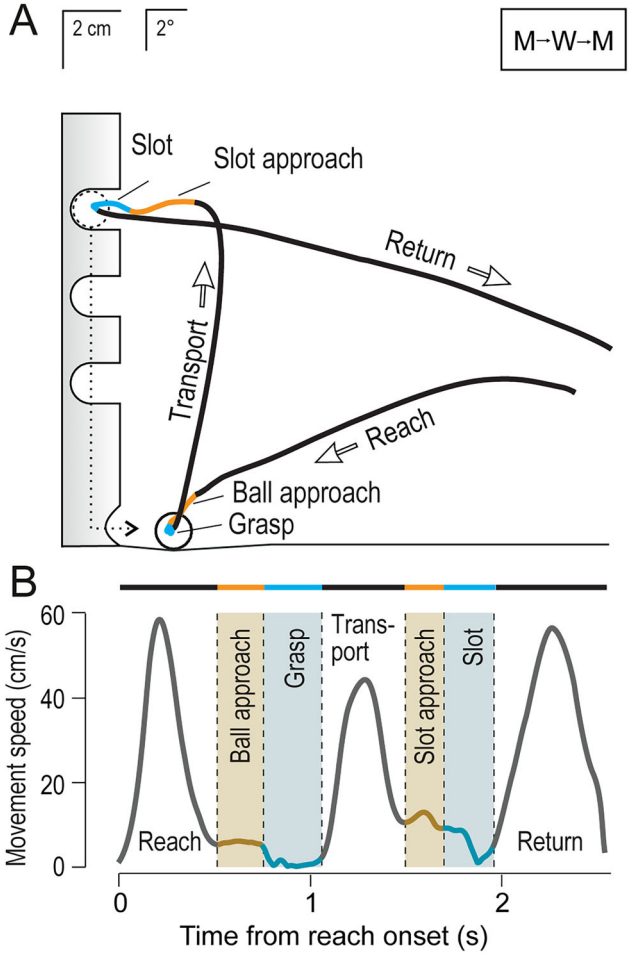

Figure 1. Apparatus and action phases in the ball-drop task. ***A***, Participant's view of the task setup, showing the ball-drop platform and text display (top right), and the hand movement path in a single trial. Movements were executed in a frontal plane positioned ~40 cm in front of the participant's eyes. The vertical tube contained three slots. ***B***, Representative end-effector velocity profile from a single trial, illustrating the segmentation of the trial into seven action phases based on kinematic and contact events (see Materials and Methods for details). These phases include the following: (1) Reach—movement initiation from the home position; (2) Ball approach—deceleration toward the ball; (3) Grasp—ball contact to lift-off; (4) Transport— movement toward the slot; (5) Slot approach—final deceleration before insertion; (6) Slot—entry into the slot and ball release; and (7) Return—movement back to the starting position.

When manual tasks are performed without competing visual demands, gaze typically shifts between action targets and can serve three primary functions: directing the hand movement toward the vicinity of the current target using peripheral vision and gaze-related signals (Goodale et al., 1986; Saunders and Knill, 2003, 2004), guiding the hand with central vision as it nears the target (Ballard et al., 1992; Johansson et al., 2001; Land, 2006), and checking goal completion (e.g., confirming an object has been successfully grasped) also using central vision (Säfström et al., 2014). We hypothesized that in the face of gaze competition, participants would prioritize the directing function, relying primarily on tactile feedback from the fingertips to complete the action goal (e.g., grasp the object). In a condition in which participants used a tool (tweezers) to perform the manipulation task, we further predicted that both the directing and guiding functions would be prioritized due to reduced tactile feedback, which impairs dexterity (Boada et al., 2016; Moog et al., 2020), and increased precision demands.

Previous research has shown that people can learn and exploit temporal regularities of events to optimize gaze allocation when monitoring multiple locations (Hoppe and Rothkopf, 2016). We predicted that participants would similarly leverage the temporal structure of events to reduce gaze competition while concurrently manipulating objects and monitoring the environment. Specifically, we hypothesized that participants would be more likely to fixate action targets (i.e., the ball and slot) during periods of low event probability. Additionally, we hypothesized that participants would adjust the timing of their hand movements to lower the likelihood of an event occurring at moments when gaze is most critical for the action.

Confirmation of these hypotheses would provide evidence that people can flexibly integrate sensorimotor control with temporal prediction based on environmental statistics to adaptively allocate gaze when simultaneously manipulating and monitoring the world.

Materials and Methods

Participants. Eleven right-handed participants (8 male; age 22–33 years) with normal or corrected-to-normal vision took part in the study. All were naive to the study purpose. Written informed consent was obtained prior to participation. The study was approved by the ethics committee at Umeå University.

Apparatus and general procedure. Participants were seated at a table with the ball-drop apparatus positioned in front of them (Fig. 1*A*). It consisted of a 15 cm high vertically oriented Perspex tube (inner diameter, 14 mm; wall thickness, 3 mm) mounted on a wooden platform. The tube was positioned ~2.5 cm to the left of the participant's mid-sagittal plane, with its top aligned at eye level. Three vertical slots were cut into the front of the tube, with their centers located at 5, 8, and 11 cm above the platform surface.

Participants continuously performed the ball-drop task, which required them to reach for and grasp a small ball (12-mm-diameter polished brass sphere) at a designated start position on the platform, transport it to the target slot, insert it into the tube, and release it. After it was released, the ball dropped through the tube and rolled back to its starting position on the platform via a slightly sloped surface. One second after the ball returned to the start position (or was already present at the start location in the first trial), a pre-recorded auditory instruction ("bottom," "middle," or "top") indicated the slot to be used (i.e., the target slot) in the upcoming trial.

All movements were performed in a vertical plane aligned with the participant's coronal plane and located 40 cm from the eyes. The start position for the ball was located 3 cm to the right of the tube's vertical midline. After releasing the ball, the participant returned their hand to

a support plate—the hand start position in each trial—positioned 20 cm to the right of the platform. In separate trial blocks, the ball was grasped either directly with the fingertips or with a handheld tool (plastic tweezers, 14-cm-long, with 4-mm-diameter tips coated with thin plastic tubing to enhance friction). Note that we included trial blocks with this tool to increase the visuomotor demands of the action task. This increase can be attributed to three factors. First, the contact surfaces of the tool tips are small compared with the fingertips and thus require greater spatial precision, particularly during ball grasping. Second, unlike the more malleable fingertips, the rigid tool tips do not conform to the ball's surface, reducing grasp stability. Indeed, in robotic manipulation, soft contact surfaces are used to enhance stability and reduce spatial precision demands (Bicchi, 2000; Billard and Kragic, 2019). Third, the tool provides limited tactile feedback about the contact state, and impaired tactile sensibility is known to increase reliance on vision during object manipulation (Brink and Mackel, 1987; Jerosch-Herold, 1993; Jenmalm and Johansson, 1997; Chemnitz et al., 2013).

In the single-task conditions, participants performed the ball-drop task only. In the dual-task conditions, participants concurrently performed a visual monitoring task that involved detecting brief LCs on an LED text display, which required central vision. The text display was positioned in the upper right quadrant of the scene (Fig. 1*A*), 7 cm behind the frontal plane in which the tube was located. The visual angle between the center of the letter area and the center of the top slot and ball were 24 and 28°, respectively.

At the start of the task, the letter M was displayed on the text display. The letter height and width corresponded to 0.5° × 0.7° visual angle. The LC from the letter M to the letter W occurred at randomly distributed intervals (1.5–6.5 s, uniform distribution) and lasted for 300 ms before reverting to M. Note that even though the time at which the next LC occurred was drawn from a random distribution, there was a regular 1.5 s "silent period" during which the probability of another letter change occurring was 0. Following this silent period, the probability of the next LC was time dependent and increased linearly from 0 to 1 over the next 5 s (hazard rate). The participants were instructed to press a button held in their left hand as soon as they detected an LC. If they failed to respond within 1 s after a change, the LC was considered missed. Missed detections were signaled by a brief beep and flashing hash marks on the display for 600 ms. To ensure that the participants relied on central vision to detect LCs rather than peripheral visual cues, the letter M randomly shifted its horizontal position by 0.6° visual angle at intervals between 1 and 3 s (uniform distribution). Pilot tests confirmed that participants had to foveate the display to detect LCs.

To ensure that participants remained engaged with both the object manipulation task and the monitoring task, a performance-based incentive system was implemented. Participants earned 1 Swedish krona (SEK) for each successful ball-drop and incurred a penalty of 3 SEK for each missed LC.

Each participant completed four conditions in a fixed order: single task with fingertips, single task with the tool, dual task with fingertips, and dual task with the tool. Each condition included 30 trials (10 per slot) with the order of target slot varying unpredictably across trials. Note that each participant completed three versions of the experiment that differed in how the correct slot was specified. In the version reported here, the slot was cued auditorily; in the visual cue version, LEDs on the tube indicated the slot; and in the "memory" version, participants were instructed to follow a predefined slot sequence from memory. The order in which these three versions were completed was counterbalanced across participants. As no clear differences in manual or gaze behavior were observed across versions, we decided to focus our analysis on the auditory cue version.

Data collection and analysis. Gaze position was recorded at 120 Hz (RK-726PCI pupil/corneal tracking system, ISCAN). The head was stabilized with chin and forehead support. The standard deviations of gaze position measurement errors were 0.50° (horizontal) and 0.52° (vertical) of visual angle, corresponding to 0.35 and 0.36 cm in the vertical plane in which the ball was moved during the task.

The positions of the right index finger and the tool tips were tracked at 60 Hz using 6 DOF position-angle sensors (RX1-D miniature receiver; FASTRAK, Polhemus). The fingertip sensor, attached to the nail, recorded the preferred contact point with the ball. The mapping between the position and orientation of the sensor and the preferred contact points was established during calibration trials in which the participants grasped the stationary ball at a known position. The position of the tool sensor, attached to the proximal end of the tool, was offset to the midpoint between the tool tips.

A six-axis force-torque transducer (Nano F/T transducer, ATI Industrial Automation; sampling rate 400 Hz), mounted under the platform plate, detected when the ball contacted the platform after being dropped, was first contacted by the fingertips or the tool and was lifted off the platform. Optical sensors (SG-2BC, Kodenshi) indicated when the ball was inserted into the tube and when it was at its start position. Gaze and sensor signals were synchronized and sampled at 200 Hz using SC/ZOOM software (Umeå University).

To characterize the movement sequence in the ball-drop task, we defined seven action phases based on the speed of the fingertip or the tool (Fig. 1*B*). Speed was computed as the vector magnitude of the first time derivatives of filtered horizontal and vertical position signals (second-order Butterworth low-pass filter, 10 Hz cutoff frequency). The reach phase began when end-effector speed exceeded 2 cm/s as the hand left its starting position, typically showing a bell-shaped velocity profile. The ball approach phase began at the first local minimum or inflection point in the velocity profile following the reach. The grasp phase started upon contact with the ball and ended at lift-off. The transport phase spanned from lift-off to the next local minimum in speed (typically preceding final slot approach), also bell-shaped. The slot approach phase started at the inflection point following transport and was characterized by reduced speed as the end-effector neared the slot. The slot phase started when the end-effector tip crossed into the tube (1 cm right of release point) and ended at ball release, detected by optical sensors. Finally, the return phase began after release and concluded when the hand returned to the start position, again showing a bell-shaped velocity profile.

Gaze fixations were identified based on previously established criteria (Johansson et al., 2001). Fixations were classified into three categories according to their location, each defined as a centroid with a 2.5 cm radius: the ball at its start position, the target slot, and the text display. Note that fixation data were pooled across all slot positions (bottom, middle, and top). To qualify as a fixation, gaze had to remain within a designated zone for at least 100 ms. Notably, practically all fixations occurred within these zones (~95%). Consistent with previous findings on object manipulation, participants almost never fixated their hand or the tool in hand, during hand movement.

To assess whether the timing of ball and slot fixations—relative to first ball contact and slot entry, respectively—changed across trials within a condition, we split the data into two phases, with the early phase defined as the first 15 trials and the late phase defined as the last 15 trials. For the single-task fingertip, single-task tool, and dual-task tool conditions, we carried out a repeated-measures ANOVA with landmark (ball, slot), fixation type (onset, offset), and phase (early, late) as within-subject factors and participants as a random effect. Critically, there was no main effect of phase in any of these conditions (Single-Task Fingertips: $F_{(1,68)} = 0.001$, $p = 0.977$; single-task tool: $F_{(1,70)} = 0.047$, $p = 0.829$; dual-task tool: $F_{(1,70)} = 0.036$, $p = 0.851$), nor were there any reliable interactions involving phase ($p > 0.13$ in all cases). In the dual-task fingertips condition, participants rarely fixated the ball. Accordingly, we restricted the analyses for this condition to slot fixations. Again, there was no effect of phase ($F_{(1,25)} = 0.54$, $p = 0.47$) and no fixation type by phase interaction ($F_{(1,25)} = 0.07$, $p = 0.80$). In summary, across all tasks and effector conditions, fixation timing relative to manual actions showed no systematic change from early to late trials. Thus, we can be confident that differences between the single- and dual-task conditions are not due to learning effects or fatigue.

All statistical analyses were conducted in R (R Core Team, 2021; www.r-project.org). Trials in which participants dropped the ball after initiating the transport phase were excluded. A total of 64 trials (4.7%) were removed, with no participant losing more than seven trials.

Results

Gaze–hand coordination in single-task conditions

To establish a baseline for interpreting gaze behavior under dual-task demands, we first examine gaze behavior in the single-task conditions. The top panels in Figure 2*A*,*B* show representative gaze and end-effector paths during trials performed with the fingertips and the tool, respectively. The bottom panels show the average speed of the tip of the end-effector (top row) and the instantaneous probabilities of gaze fixating the ball (at its start position) and the target slot as a function of time (bottom row). These averages are based on aggregate data from all trials and participants. To preserve phase-specific information while aligning trials temporally, we normalized the duration of each phase in each trial to the median phase duration within each condition.

Across all fingertip and tool trials, 96% of all fixations were directed to an action landmark (ball or slot). Participants typically fixated the ball during the reach phase, shifted gaze to the slot around the time ball contact, and maintained the fixation of the slot until around the time the ball was dropped. Gaze then returned to the ball's start position at the tube's base. However, in fingertip trials, gaze was occasionally located at the slot during the reach phase. As expected, participants completed the ball-drop trials more rapidly ($t_{(10)} = 4.94$, $p < 0.001$; $d = 1.49$) when using fingertips (2.04 ± 0.33 s) compared with the tool (2.53 ± 0.31 s). The timing of the gaze shift from the ball to the slot, relative to ball contact, differed between fingertip and tool trials ($t_{(10)} = 13.24$; $p < 0.001$; $d = 3.99$). In fingertip trials, the shift occurred just before contact (-0.06 ± 0.05 s; mean ± SE) whereas, in tool trials, the shift occurred well after ball contact (0.29 ± 0.11 s). These findings are consistent with the idea that tool use increases reliance on central vision to establish stable grasp on the ball.

Gaze–hand coordination when there is competition for gaze

The remainder of the results focuses on the dual-task conditions. As shown in Figure 2*C* and *D*, participants divided their gaze fixations between the text display and the action-related landmarks. As a result, the probability of fixating the ball or slot during the ball-drop task was reduced compared with the single-task conditions, regardless of end-effector. Additionally, the durations of action-related fixations were consistently shorter. Similar to the single-task condition, 94.6% of all fixations in the dual-task condition were directed to one of the landmarks (ball, slot, or text display).

In fingertip trials, participants primarily fixated the display during the reach, ball approach, and grasp phases (88% of trials), indicating that grasping the ball generally did not require central vision. When the ball was fixated, the fixations occurred during the reach phase, with gaze typically shifting away before the ball approach phase, and almost never remaining on the ball after contact. Transporting the ball and inserting it into the slot were also frequently performed with gaze remaining on the display. However, brief fixations of the slot occurred in about half the trials (51%; see example in Fig. 2*C*, top panel). The probability of fixating the slot peaked midway through the transport phase and then declined steadily, approaching zero by the end of the slot phase (Fig. 2*C*, bottom panel). These findings indicate that in fingertip trials, inserting the ball into the slot often did not require central vision.

Consistent with the fixation probabilities described above, we observed two predominant gaze patterns in fingertip trials: "display-only," where gaze remained on the display throughout the trial, and "slot," where gaze shifted from the display to the slot and then back to the display (Fig. 3). To examine the relationship between gaze pattern and manual performance, we compared the action phase durations in display-only and slot trials. Only participants ($N = 9$) who demonstrated both fixation patterns were included. The duration of the slot phase was shorter ($t_{(8)} = 3.76$, Holms–Bonferroni adjusted $p = 0.03$) when participants fixated the slot (0.30 ± 0.054 s) compared with when they did not (0.378 ± 0.056 s). No other phase durations were affected by gaze pattern (adjusted $p > 0.51$ in all cases).

In tool trials, participants were much more likely to fixate both the ball and the slot compared with fingertip trials (Fig. 2*D*). Participants fixated the ball before contact in 88% of trials, and the slot before slot entry in 89% of trials. The probability of fixating the ball peaked toward the end of the reach phase and remained relatively high during the ball approach and most of the grasp phase. Similarly, the probability of fixating the slot peaked toward the end of the transport phase and remained elevated during the slot approach and slot phases. These findings suggest that, in general in tool trials, central vision was crucial for both grasping the ball and inserting it into the slot.

The predominant gaze pattern in tool trials was "ball-display-slot," where gaze shifted from the display to the ball, back to the display, then to the slot, and finally back to the display (Fig. 2*D*). The second most common pattern was "ball-slot," where gaze shifted from the display to the ball and then directly to the slot before returning to the display (Fig. 3). To examine the relationship between gaze pattern and manual performance, we compared the action phase durations between the ball-display-slot and ball-slot trials. Only participants who exhibited both gaze patterns ($N = 8$) were included in this analysis. We found that the transport phase was shorter ($t_{(7)} = 4.71$, Holms–Bonferroni adjusted $p = 0.01$) when gaze shifted directly from the ball to the slot (0.32 ± 0.051 s) compared with when gaze fixated the display between the ball and slot fixations (0.55 ± 0.17 s; $t_{(7)} = 4.71$). No other phase durations differed significantly (adjusted $p > 0.22$ in all cases). As in the single-task conditions, in the dual-task conditions the ball-drop task was performed more slowly with the tool (2.77 ± 0.4 s) than with the fingertips (2.11 ± 0.23 s; $t_{(10)} = 5.61$, $p < 0.001$; $d = 1.69$).

Temporal coupling between fixations and contact events

To examine the trial-by-trial coordination between the timing of action fixations and specific kinematic or contact events, we conducted a multiple linear regression analysis to assess how well the onset and offset times of ball and slot fixations could be predicted by the timing of the following six events marking action phases boundaries: (1) start of the reach phase, (2) start of the ball approach phase, (3) time of first ball contact (start of the ball grasp phase), (4) time of ball lift-off (start of the ball transport phase), (5) start of the slot approach phase, and (6) time for slot entry (start of the slot phase). Predictors were centered for each participant (by subtracting their mean) to mitigate structural multicollinearity, and participant identity was included as a categorical nuisance factor to account for variance due to differences in task performance speed. Separate regression analyses were conducted for fixation onsets and offsets, as well as for each action landmark (ball and slot) and end-effector (fingertips and the tool).

In both fingertip and tool trials, ball fixation timing was best predicted by ball contact and slot fixation timing by slot entry. In fingertip trials, ball fixation onset was predicted solely by the time of ball contact ($t_{(32)} = 2.84$; $p = 0.008$), and slot fixation onset was predicted solely by slot entry ($t_{(158)} = 9.28$; $p < 0.001$). Similarly, in

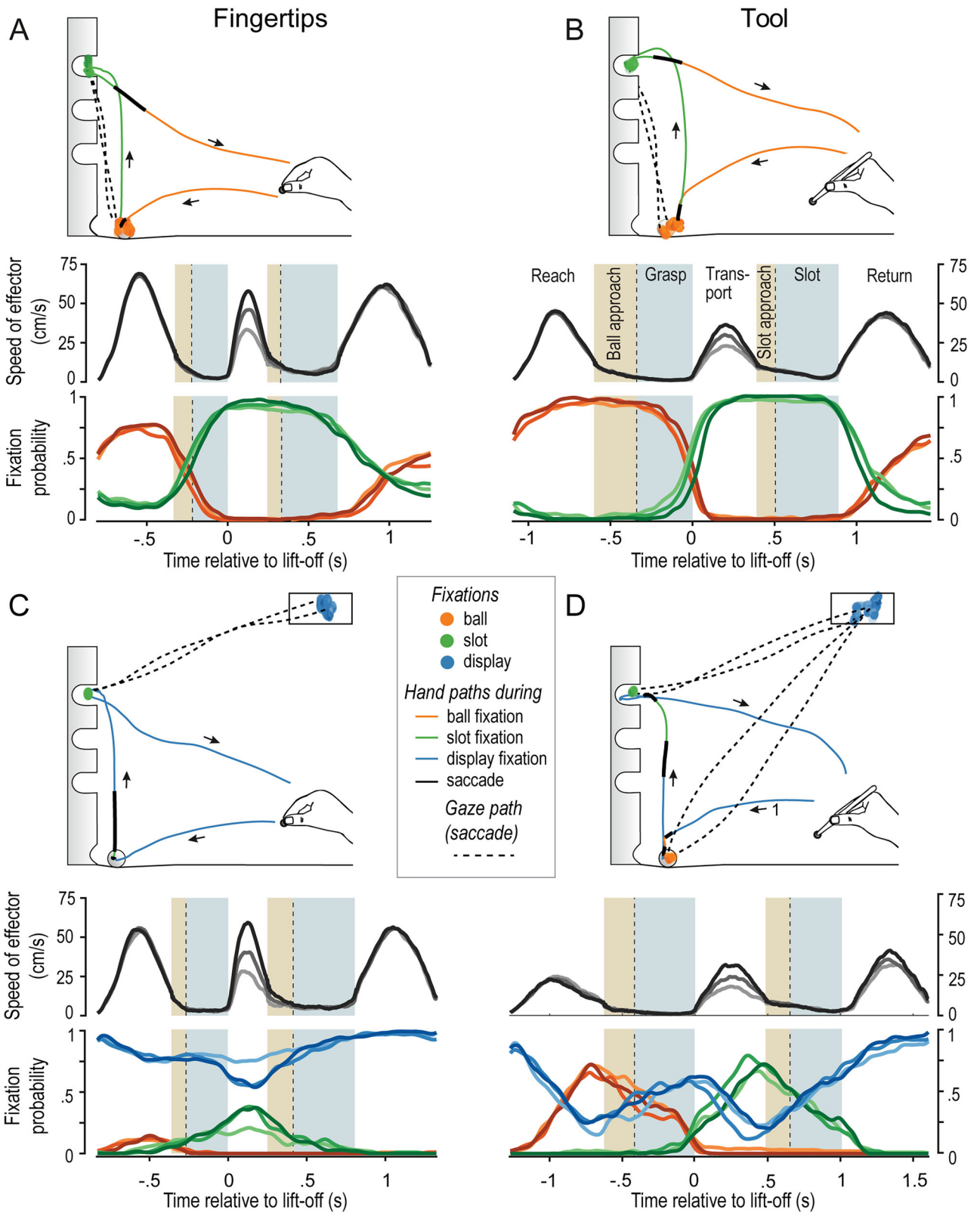

Figure 2. Gaze–hand coordination. ***A–D***, Top panels show gaze and end-effector paths in single fingertip and tool trials in the single- (***A***, ***B***) and dual-task (***C***, ***D***) conditions. Fixations are color coded according to landmark, and end-effector paths are color coded based on the concurrent gaze state. Bottom panels show average end-effector speed and the probabilities of fixating the ball (orange), slot (green), and display (blue) as a function of time relative to lift-off. Separate traces are shown for each slot (top to bottom coded dark to light). Alternating white, brown, and gray-blue regions indicate movement phases labeled in ***B***. Vertical dashed lines mark first ball contact (end of ball approach) and slot entry (end of the slot approach). Data aggregated across all participants, with phase durations in each trial normalized to the median duration of each phase.

tool trials, ball fixation onset was best predicted by first ball contact ($t_{(243)} = 6.26$; $p < 0.001$), and slot fixation onset was solely predicted by slot entry ($t_{(244)} = 11.2$; $p < 0.001$). Comparable results were found for ball and slot fixation offset times in both fingertip and tool trials ($p < 0.004$ in all four cases). These findings demonstrate a robust temporal coupling between the initiation and termination of action-related fixations (ball and slot) and their associated contact events (first ball contact and slot entry), consistent across both end-effectors.

The timing of action fixation onsets, relative to contact events, showed remarkable consistency across action landmarks and end-effectors. Both ball and slot fixations typically began ~0.4 s before ball contact and slot entry, respectively (Fig. 4*A*, solid line curves). The timing of fixation offsets was also consistent across action landmarks but varied with the end-effector used (Fig. 4*A*, dashed line curves). In fingertip trials, gaze generally shifted away from both the ball and the slot before the contact event, with an average lead time of ~0.15 s. In contrast, in tool trials, gaze typically shifted shortly after the contact event, with an average lag of ~0.05 s.

The left column of Figure 4*B* shows, for each end-effector, the relationship between the ball fixation onset time and ball contact time, where time is relative reach onset. The right column of Figure 4*B* shows the relationship between slot fixation onset time and slot entry time, where time is relative to slot entry. These plots show trials involving the main gaze patterns (i.e., ball-slot, ball-display-slot, and slot trials), which are color coded. In all four cases (i.e., plots), we observed strong temporal coupling fixation onsets and contact times ($r = 0.58$–0.85, all p values <0.001), with similar coupling seen across the different gaze patterns. Regression slopes were close to unity (0.89–1.02, mean = 0.98), and intercepts were consistently negative (−0.24 to −0.47, mean = −0.37). These values confirm that both ball and slot fixations typically began ~0.4 s before the corresponding contact event, regardless of gaze pattern or end-effector.

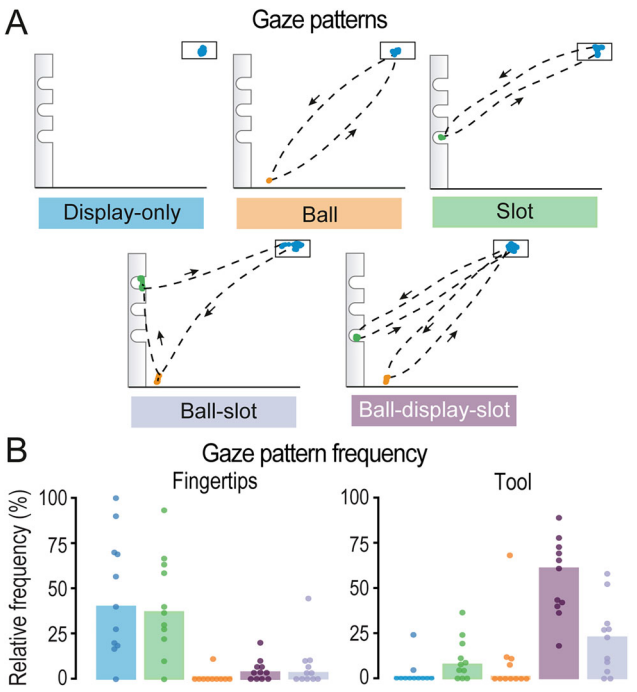

Figure 3. ***A***, The five distinct gaze patterns observed during dual-task trials are illustrated with data from single trials. ***B***, Average percentage of each gaze pattern (color coded as in ***A***) observed across participants in fingertip and tool trials. Individual participants are represented by dots.

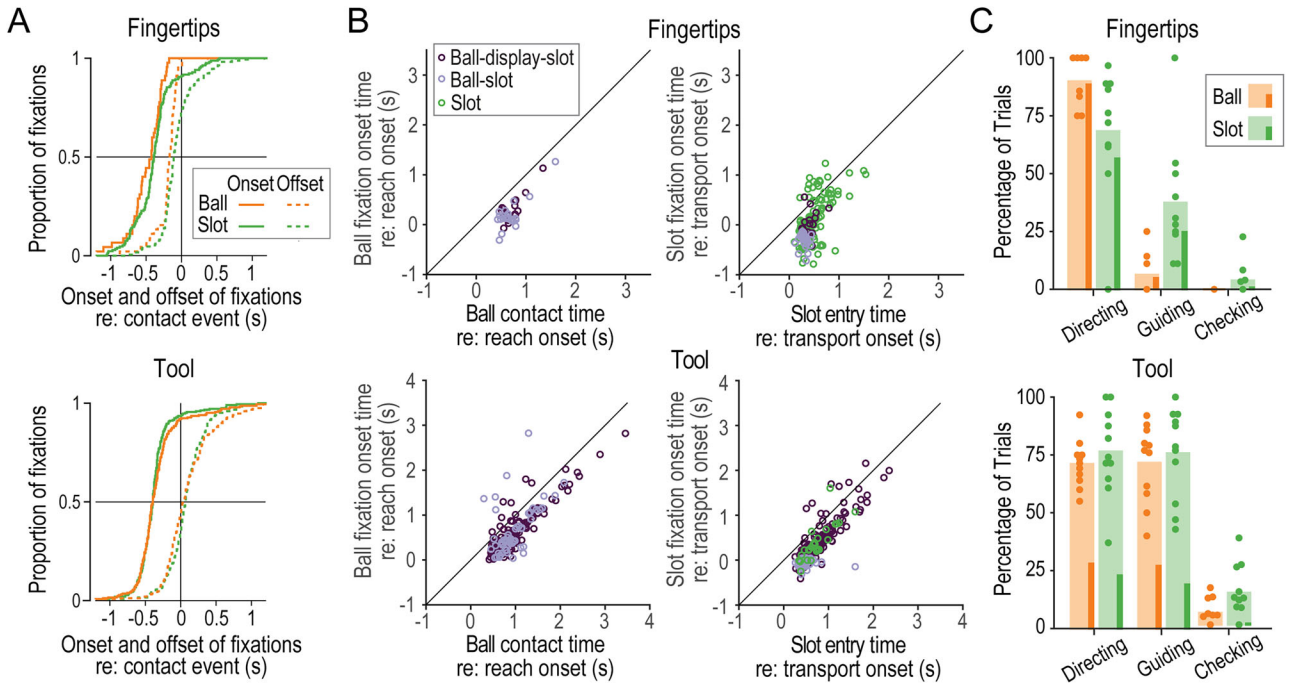

Figure 4. Coordination and classification of action fixations. ***A***, Cumulative distributions of ball and slot fixation onsets and offsets, aligned to the initial ball contact and slot entry, respectively, in fingertip (top) and tool (bottom) trials. ***B***, The top row shows, for fingertip and trials, the relationship between ball fixation onset and ball contact times, both relative to reach onset (left), and the relationship between slot fixation onset and slot entry times, both relative to transport onset (right). Dots represent trials from all participants and are color coded by gaze pattern. The bottom row shows corresponding data for tool trials. ***C***, Wide bars show the mean percentage of ball and slot fixations engaged in directing, guiding, and checking across participants in fingertip (top) and tool (bottom) trials. Note that a given fixation could be engaged in more than one function. Circles represent individual participants, except for the circles at zero which represent all participants with zero. The thin bars represent percentages of single-function fixations.

Functional roles of action-related fixations

Although the timing of ball and slot fixations, relative to ball contact and slot entry, was quite consistent, the function(s) served by these fixations (i.e., directing, guiding, and checking) could vary due to intertrial variability in the durations of their corresponding action phases (i.e., reach and ball approach for ball fixations and transport and slot approach for slot fixations). To assess the function, or functions, served by action task fixations, we determined the function of each individual ball and slot fixation. A fixation was classified as directing if the ball or slot was fixated for at least 100 ms during the reach or transport phase, respectively. A fixation was classified as guiding if the ball or slot was fixated for at least 100 ms between the start of the ball or slot approach phase and the end of the grasp or slot phase, respectively (i.e., the combination of the approach and manipulation phases). Finally a fixation was classified as checking if the ball or slot was fixated for any period of time after the end of the grasp or slot phase, respectively, allowing visual confirmation of the action's completion (Säfström et al., 2014). Note that a given fixation could serve multiple functions depending on its timing and duration.

In fingertip trials, ball fixations primarily served a directing function, whereas slot fixations often served both a guiding and a directing function (Fig. 4C, top panel). In contrast, in tool trials, both ball and slot fixations frequently served both directing and guiding functions (Fig. 4D, bottom panel). Across end-effectors, checking fixations were infrequent. Finally, in fingertip trials, most of the ball and slot fixations served only one function (80% overall), whereas in tool trials, this proportion was lower (48% overall; Fig. 5C,D, thin solid bars within each wide bar).

Adaptation to temporal structure of monitoring task

We next examined whether participants could learn and exploit the statistical properties of LCs to mitigate competition for gaze

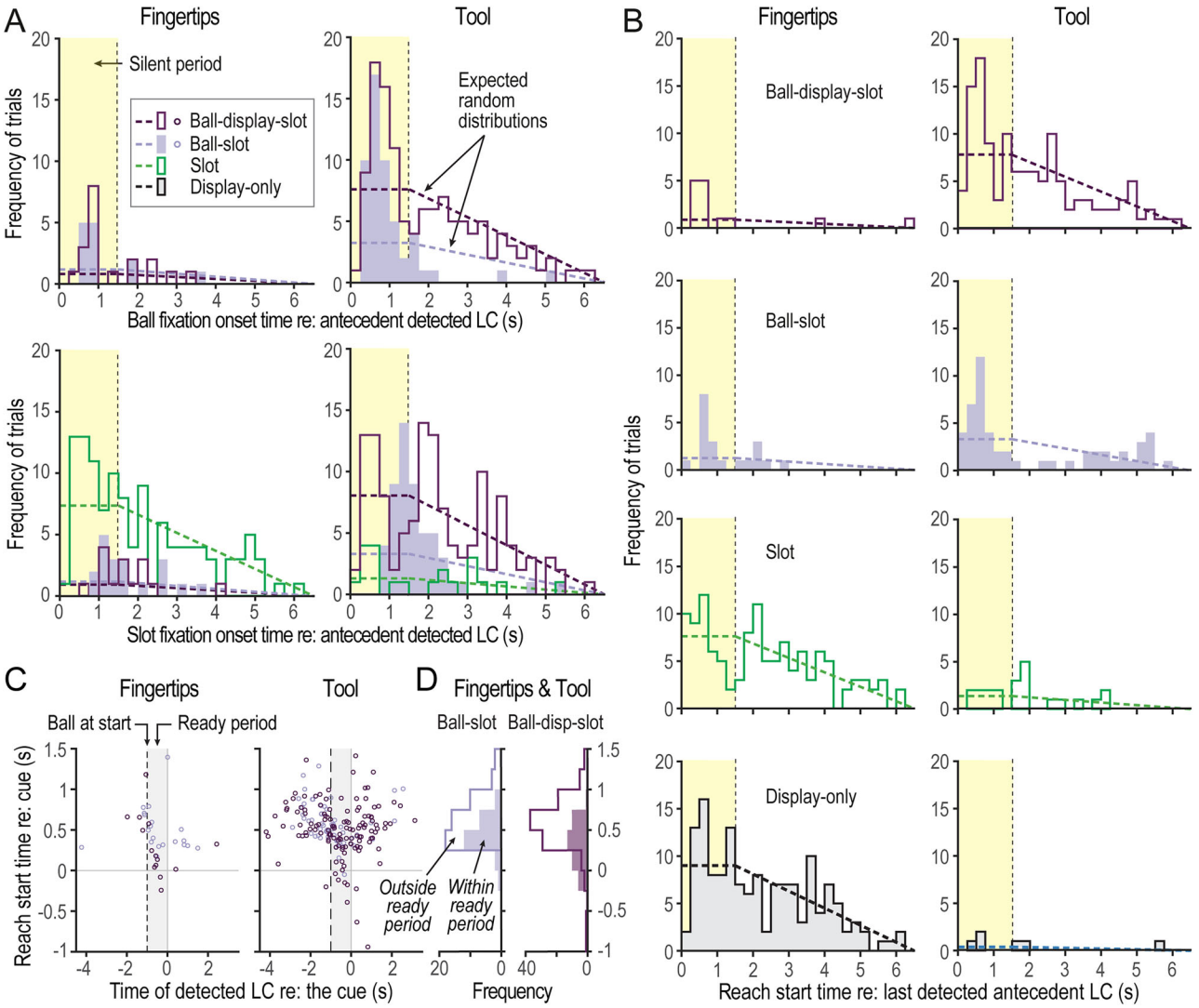

Figure 5. Impact of timing of letter changes (LCs) on gaze fixations and hand movements. ***A***, The top row shows frequency distributions, combining trials from all participants, of ball fixation onsets—relative to the time of the last detected LC before the fixation onset—in fingertip (left) and tool (right) trials. Yellow regions indicate the silent period. Separate distributions are shown for trials with the main gaze patterns. Dashed lines show expected distributions. The bottom row shows corresponding plots for slot fixation onsets relative to the time of the last detected LC before the fixation onset. ***B***, Frequency distributions, combining trials from all participants, of reach start times relative to the last detected antecedent LC in fingertip and tool trials. Yellow regions indicate the silent period. Separate plots are shown for the four main gaze patterns. ***C***, Relationship between reach start time and time of nearest detected LC, both relative to cue onset, in fingertip and tool trials with ball-slot and ball-display-slot gaze patterns. ***D***, Frequency distributions, combining fingertip and tool trials, of the reach start times in trials with ball-slot and ball-display-slot gaze patterns, aligned with the data shown in ***C***. Separate distributions are shown for trials in which the LC was within or outside the "ready period" (1 s period prior to the cue).

between the visual monitoring and manipulation tasks. Our findings reveal that participants adapt their gaze behavior both directly, by selecting different gaze patterns, and indirectly, by adjusting the timing of their manual actions in response to LC statistics.

In the dual-task condition, the interval between LCs was drawn from a uniform distribution spanning 1.5–6 s. As a consequence, there was a 1.5 s "silent period" following each LC, during which no new LC could occur. After this silent period, the likelihood of the next LC occurring (i.e., the hazard rate) increased linearly over the subsequent 5 s. On average, participants encountered 1.08 LCs per trial in fingertip trials and 1.41 LC per trial in tool trials. Importantly, LC detection accuracy was high: 88.8 ± 11.8% in fingertip trials and 87.1 ± 9.1% in tool trials (mean ± SD across participants).

Gaze allocation relative to letter change timing

To analyze whether LCs influenced gaze allocation to action landmarks, we compared the observed frequency distributions of ball and slot fixation onset times—aligned to the most recently detected LC preceding each fixation—with the distributions expected under a random model (Fig. 5*A*). For each fixation, time zero was defined as the last LC detected before that fixation. Importantly, fixations were included regardless of when the next LC occurred (i.e., trials were not truncated or excluded based on the timing of the next LC). Thus, each fixation contributed a single observation to the distributions shown in Figure 5*A*.

In the random model, fixation onset probability was constant during the silent period (hazard rate = 0) and then decreased linearly over the next 5 s as the hazard rate of LC occurrence increased from 0 to 1. Accordingly, the decline in the expected distributions (dashed lines) after the silent period reflects the increasing probability of LC occurrence over time. For each end-effector, we conducted separate analyses for trials exhibiting each of the primary gaze patterns: ball-display-slot, ball-slot, and slot trials.

In both fingertip and tool trials in which participants fixated both the ball and slot (i.e., ball-slot and ball-display-slot trials), the distribution of ball fixation onsets deviated significantly from the expected random distribution (Kolmogorov–Smirnov test, $p \leq 0.01$ in all four cases). Specifically, ball fixation onsets during the silent period occurred more frequently than predicted by the random model (Fig. 5*A*, top row).

In tool trials, the choice of gaze pattern was strongly influenced by the timing of the ball fixation relative to the preceding LC. When the onset of the ball fixation occurred during the silent period, participants were equally likely to adopt either the ball-slot or ball-display-slot pattern. However, when the onset of the ball fixation occurred after the silent period, the ball-display-slot pattern was predominantly chosen. That is, participants rarely shifted their gaze directly from the ball to the slot (ball-slot pattern) unless the ball was fixated within the silent period. Conversely, when ball fixation took place after the silent period, participants almost always fixated the display before shifting their gaze to the slot (ball-display-slot pattern).

As expected, in trials with the ball-slot gaze pattern, a peak in the distribution of slot fixation onsets followed the peak in the distribution of ball fixation onsets during the silent period (Fig. 5*A*, bottom row). This reflects the fact that in 96.4% of these trials, the last LC detected before the ball fixation was also the last LC before the slot fixation. For both fingertip and tool trials, the distribution of slot fixation onsets differed significantly from the expected random distributions (K-S test, $p < 0.02$ in both cases).

Similarly, in trials with the ball-display-slot gaze pattern, a peak in the distribution of slot fixation onsets occurred later than the peak in the distribution of ball fixation onsets, again reflecting trials where the same LC preceded both fixations. In fingertip trials, this slot fixation distribution differed significantly from the expected random distribution (K-S test, $p < 0.01$). In tool trials with the ball-display-slot pattern, an additional earlier peak in the distribution of slot fixation onsets was observed during the silent period, representing trials where an LC was detected while gaze was still on the display prior to shifting to the slot. As a result, the overall distribution of slot fixation onsets did not differ significantly from the expected random distribution (K-S test, $p = 0.4$). In trials where only the slot was fixated (slot pattern), the distribution of slot fixation onsets did not differ significantly from the expected random distribution (K-S test, $p > 0.06$ for both fingertip and tool trials; Fig. 5*A*, bottom panels).

Together, these results demonstrate that participants adapted their gaze behavior to exploit the statistical properties of LCs, preferentially fixating action targets during low-probability periods to mitigate gaze competition between monitoring and manipulation demands.

Timing of manual actions

We found that participants also adapted the timing of their manual actions—specifically, reach initiation—in response to LC statistics. In both fingertip and tool trials in which participants fixated the ball (i.e., the ball-slot and ball-display-slot gaze patterns), the distribution of reach onset times relative to the preceding (or antecedent) detected LC differed from the expected random distribution (K-S test, $p < 0.05$ in all four cases). Reach onsets were biased toward the silent period (Fig. 5*B*, top two rows), mirroring the bias observed in ball fixation onsets (Fig. 5*A*). In contrast, in fingertip trials where the ball was not fixated (i.e., the slot and display-only gaze patterns), the distribution of reach onset times did not differ from the random distribution (K-S test, $p \geq 0.4$; Fig. 5*B*, bottom two rows). Because of the limited number tool trials with the slot and display-only gaze patterns, we did not test whether the distributions of reach onsets in these trials differed from the random distribution. These findings suggest that initiating the reach during the silent period was a strategy to reduce the risk of missing LCs.

In the ball-drop task, participants typically initiated their reach movement toward the ball in response to the auditory cue signaling the active slot for that trial. These "reactive reaches" generally began ∼0.5 s after the cue. However, in a notable proportion of trials, participants initiated their reach in anticipation of the cue, starting either before or shortly after the cue (within 0.5 s). If these "anticipatory reaches" were triggered by an LC occurring shortly before the cue, and accompanied by ball fixation, they could contribute to the greater-than-expected frequency of both reach onsets and ball fixation onsets during the silent period in trials with the ball-slot and ball-display-slot gaze patterns.

To investigate this possibility, we focused on fingertip and tool trials involving ball fixation and examined the relationship between the timing of reach onset relative to the cue and the timing of the detected LC relative to the cue. For each trial, we identified the detected LC closest in time to the midpoint of the "ready period," defined as the 1 s interval between the ball returning to its start position and the auditory cue. This LC could occur either before or after the midpoint of the ready period. We observed that most anticipatory reaches—characterized by reach onset

times near or preceding the cue—occurred when the detected LC fell within the ready period. This relationship is illustrated in Figure 5*C*, which plots reach onset times relative to the cue against the timing of the detected LC relative to the cue. These findings suggest that the decision to initiate an anticipatory reach is closely linked to the detection of an LC during the ready period.

Further support for this idea comes from the frequency distributions of reach onset times relative to the cue, shown in Figure 5*D* for trials with the ball-slot and ball-display-slot patterns. Reach onset times occurred earlier when the LC was detected within the ready period compared with when it occurred outside of it. Due to the relatively small number of fingertip trials, fingertip and tool trials were combined for these analyses. Importantly, for both gaze patterns, the distributions within and outside the ready period differed significantly (K-S test, $p < 0.02$ in both cases), indicating that the timing of LCs had a distinct influence on reach initiation during the ball-drop task.

Overall, these results demonstrate a second strategy by which participants exploited LC statistics to manage gaze competition. That is, in addition to selecting gaze patterns—on a trial-by-trial basis—to increase the likelihood that gaze could be allocated to the action task with minimal disruption of LC monitoring, participants also adjusted the timing of their reaching movements so that the ball could be preferentially fixated during the silent period.

Discussion

This study investigated how individuals manage competition for gaze resources when performing an object manipulation task while simultaneously monitoring the environment for visual events. Participants employed two complementary strategies: they selectively allocated gaze to the action task and exploited temporal regularities in the monitoring task by adjusting gaze allocation and manual action timing to minimize interference between monitoring and manipulation demands.

Timing, frequency, and function of gaze fixations in the ball-drop task

As expected, when the ball-drop task was performed in isolation, gaze was directed to the ball and slot in nearly all trials. Gaze typically arrived at the target (ball or slot) well ahead of the end-effector and departed around the time the end-effected arrived at the target. This behavior aligns with prior research on eye–hand coordination in visually guided tasks (Land et al., 1999; Johansson et al., 2001; Flanagan and Johansson, 2003; Sailer et al., 2005; Foerster et al., 2011; Hayhoe, 2017; Fooken et al., 2021; Illamperuma and Fooken, 2024).

When participants performed the ball-drop task concurrently with the monitoring task, gaze was intermittently directed to the action task. When the task was performed with the fingertips, the ball was fixated infrequently and the slot was fixated in approximately half of the trials. These fixations were relatively brief (~0.25 s on average) and primarily served a directing function, whereby peripheral vision and gaze-related signals support fast, automatic adjustments to the ongoing hand movement (Goodale et al., 1986; Neggers and Bekkering, 2000, 2001; Saunders and Knill, 2003, 2004; Dimitriou et al., 2013; de Brouwer et al., 2018). These results indicate that participants capitalized on the tactile capacity of the fingertips to complete the movement goal without relying on central vision to guide the hand. Tactile information not only supports force adjustments once the ball is grasped but can also drive kinematic corrections during grasping and placement via fast automatic feedback control processes (Johansson and Flanagan, 2009; Pruszynski et al., 2016, 2018).

Tool use and increased visual demands

Using the tool increased the visuomotor demands of the task due to reduced tactile feedback and increased precision requirements. We included tool trials to alter the balance of gaze demands between the manipulation and monitoring tasks, thereby providing a broader understanding of how individuals manage gaze competition. When using the tool, participants almost always fixated both the ball and the slot, and these fixations were longer in duration (~0.4 s on average). Moreover, these fixations served both directing and guiding functions, with the latter involving the use of central vision for deliberate closed-loop control during the final approach to the target (Ballard et al., 1992; Johansson et al., 2001; Land, 2006).

Temporal anchoring of fixations

Despite differences in fixation function across conditions, the onset and offset times of action-related fixations were most closely linked to contact events (ball contact and slot entry) rather than other movement events (e.g., reach or transport onset). This finding supports the idea that contact events—representing sub-goals within the task—serve as anchor points for sensorimotor control (Johansson and Flanagan, 2009), even when gaze must be shared between competing demands.

Gaze patterns and task performance

When the ball-drop task was performed in isolation, participants exhibited highly stereotyped gaze patterns, as commonly observed in sequential hand movement tasks (Epelboim et al., 1995; Wilmut et al., 2006; Bowman et al., 2009; Säfström et al., 2014). However, when the ball-drop task was performed concurrently with the monitoring task, participants used different gaze patterns across trials. Importantly, the choice of gaze patterns was linked to task performance. In fingertip trials, the duration of the slot phase was shorter when participants chose to fixate the slot, and in tool trials, the duration of the transport phase was shorter when participants shifted their gaze directly from the ball to the slot, bypassing the display. These results suggest a risk-reward trade-off between the visual monitoring and action tasks; allocating gaze to the action task improves performance but increases the risk of missing an LC.

Integration of environmental statistics

Participants mitigated the trade-off between risks and rewards by exploiting the temporal statistics of LCs. Rather than simply shifting the timing of fixations, participants selectively engaged or omitted action-related fixations depending on whether they could occur during the silent period following an LC, when no new event could occur. For example, in fingertip trials, fixations to the ball were almost exclusively observed when they could be completed within the silent period and were otherwise largely absent. Similarly, decisions about whether to fixate the display or maintain gaze on the action task were influenced by the likelihood of an upcoming LC. These findings indicate that gaze allocation was not only temporally biased but conditionally structured based on the statistical properties of the environment.

In addition, participants adjusted the timing of their reach movements to reduce competition for gaze resources. Specifically, participants modulated reach onset timing so that ball fixations preferentially occurred during the silent period

more often than expected under a random model. This suggests that participants not only learned the statistical properties of the monitoring task but also used this knowledge to coordinate both gaze allocation and action timing. These findings align with previous research demonstrating that gaze behavior is sensitive to probabilistic regularities in the environment (Jovancevic-Misic and Hayhoe, 2009; Hoppe and Rothkopf, 2016). For example, in visual search tasks, gaze is allocated strategically based on spatial statistics to optimize exploration (Najemnik and Geisler, 2005; Renninger et al., 2007; Eckstein, 2017; Hoppe and Rothkopf, 2019). Our study adds a novel perspective by demonstrating that humans can learn and exploit the temporal patterns of externally determined events in the visual environment while concurrently performing an action task that relies on visual guidance.

Task priority and attentional competition

Task priority is expected to play a central role in shaping how gaze is allocated between these competing demands. In our task, participants maintained high monitoring performance by modifying the motor task in both "inexpensive" ways (e.g., reducing visual sampling when using the fingertip) and more "costly" ways (e.g., slowing movements). Importantly, the two tasks differ in their flexibility: whereas the timing of the motor task can be adjusted by the performer, the timing of events in the monitoring task is externally determined. This asymmetry likely contributes to prioritization of monitoring behavior, as the monitoring task affords fewer opportunities for strategic adjustment.

Although the present study employed a fixed reward structure, we speculate that increasing the priority of the motor task —for example, by increasing the reward for successful actions —would shift gaze allocation toward the action task, potentially reducing reliance on nonvisual control and increasing visual sampling of action-relevant locations. In contrast, the exploitation of temporal regularities (see below) may be relatively robust to changes in task priority, as it likely reflects an implicit strategy for minimizing the probability of missing monitoring events. More generally, our findings align with frameworks of multitasking that emphasize flexible allocation of limited processing resources under competing task demands (Goschke, 2013; Koch et al., 2018; Musslick and Cohen, 2021).

From an attentional perspective, gaze allocation can be viewed as a manifestation of biased competition between action-relevant and perceptual targets (Desimone and Duncan, 1995). While gaze provides a direct index of overt selection, covert attention is likely also dynamically allocated between the motor and monitoring tasks. Visual attention is thought to support the selection of behaviorally relevant information under conditions of limited processing capacity (Zelinsky and Bisley, 2015; Hopfinger, 2025). Previous work has shown that both eye and hand movements are preceded by attentional shifts to their respective targets (Deubel and Schneider, 1996; Schiegg et al., 2003) and that attentional resources can be distributed across eye and hand movement targets (Jonikaitis and Deubel, 2011; Kreyenmeier et al., 2020; Hanning et al., 2022). An interesting question for future work is whether participants can covertly allocate attention to the action task while maintaining gaze on the display and whether this incurs a cost for monitoring performance.

Temporal expectations and coordination

Temporal expectations are known to guide both perception and action (Nobre and van Ede, 2018) and can facilitate performance in multitask settings (Gresch et al., 2022) while shaping gaze allocation (Hoppe and Rothkopf, 2016; Boettcher et al., 2022). In the present study, temporal structure arose from the probabilistic timing of LCs, which included a brief silent period (1.5 s) during which no change could occur, followed by an interval in which a change became increasingly likely. This pattern resembles familiar real-world situations in which event likelihood increases with elapsed time. Participants appeared to readily exploit this structure, preferentially allocating gaze to the action task during periods of low monitoring event probability. This strategy emerged without explicit instruction or external temporal cues and was stable across the session, consistent with rapid formation of temporal expectations (Nobre et al., 2007; Nobre and van Ede, 2018). Unlike previous studies that manipulated temporal expectations through explicit cues or rhythmic structure, our findings demonstrate that internally derived expectations based on hazard-like temporal statistics can be used to reduce competition between ongoing action and environmental monitoring. Future work should examine how different forms of temporal regularity interact with task priority and action control mechanisms.

Conclusions

This study provides novel insights into eye–hand coordination under competing visual demands. When gaze competition arises, participants prioritize key control points—specifically, contact events between the hand (or tool) and target object—when allocating gaze to the action task. Participants also exploit temporal regularities in the environment, flexibly adapting gaze allocation and movement timing to minimize interference between monitoring and manipulation demands. Together, these findings highlight how humans integrate perceptual and sensorimotor mechanisms to manage visual competition in complex tasks.

References

Ballard DH, Hayhoe MM, Li F, Whitehead SD (1992) Hand-eye coordination during sequential tasks. Philos Trans R Soc Lond B Biol Sci 337:331–338; discussion 338–339.

Bicchi A (2000) Hands for dexterous manipulation and robust grasping: a difficult road toward simplicity. IEEE Trans Robot Autom 16:652–662.

Billard A, Kragic D (2019) Trends and challenges in robot manipulation. Science 364:eaat8414.

Boada MD, Eisenach JC, Ririe DG (2016) Mechanical sensibility of nociceptive and non-nociceptive fast-conducting afferents is modulated by skin temperature. J Neurophysiol 115:546–553.

Boettcher SEP, Shalev N, Wolfe JM, Nobre AC (2022) Right place, right time: spatiotemporal predictions guide attention in dynamic visual search. J Exp Psychol Gen 151:348–362.

Bowman MC, Johansson RS, Flanagan JR (2009) Eye-hand coordination in a sequential target contact task. Exp Brain Res 195:273–283.

Brink EE, Mackel R (1987) Sensorimotor performance of the hand during peripheral nerve regeneration. J Neurol Sci 77:249–266.

Chemnitz A, Dahlin LB, Carlsson IK (2013) Consequences and adaptation in daily life - patients' experiences three decades after a nerve injury sustained in adolescence. BMC Musculoskelet Disord 14:252.

de Brouwer AJ, Gallivan JP, Flanagan JR (2018) Visuomotor feedback gains are modulated by gaze position. J Neurophysiol 120:2522–2531.

Desimone R, Duncan J (1995) Neural mechanisms of selective visual attention. Annu Rev Neurosci 18:193–222.

Deubel H, Schneider WX (1996) Saccade target selection and object recognition: evidence for a common attentional mechanism. Vision Res 36:1827–1837.

Dimitriou M, Wolpert DM, Franklin DW (2013) The temporal evolution of feedback gains rapidly update to task demands. J Neurosci 33:10898–10909.

Eckstein MP (2017) Probabilistic computations for attention, eye movements, and search. Annu Rev Vis Sci 3:319–342.

Epelboim JL, Steinman RM, Kowler E, Edwards M, Pizlo Z, Erkelens CJ, Collewijn H (1995) The function of visual search and memory in sequential looking tasks. Vision Res 35:3401–3422.

Flanagan JR, Johansson RS (2003) Action plans used in action observation. Nature 424:769–771.
Flanagan JR, Bowman MC, Johansson RS (2006) Control strategies in object manipulation tasks. Curr Opin Neurobiol 16:650–659.
Foerster RM, Carbone E, Koesling H, Schneider WX (2011) Saccadic eye movements in a high-speed bimanual stacking task: changes of attentional control during learning and automatization. J Vis 11:1–16.
Fooken J, Kreyenmeier P, Spering M (2021) The role of eye movements in manual interception: a mini-review. Vision Res 183:81–90.
Fooken J, Baltaretu BR, Barany DA, Diaz G, Semrau JA, Singh T, Crawford JD (2023) Perceptual-cognitive integration for goal-directed action in naturalistic environments. J Neurosci 43:7511–7522.
Goodale MA, Pelisson D, Prablanc C (1986) Large adjustments in visually guided reaching do not depend on vision of the hand or perception of target displacement. Nature 320:748–750.
Goschke T (2013) Volition in action: intentions, control dilemmas, and the dynamic regulation of cognitive control. In: *Action science: foundations of an emerging discipline* (Prinz W, Beisert M, Herwig A, eds), pp 409–434. Cambridge, Massachusetts, USA: MIT Press.
Gresch D, Boettcher SEP, Nobre AC, van Ede F (2022) Consequences of predictable temporal structure in multi-task situations. Cognition 225:105156.
Hanning NM, Wollenberg L, Jonikaitis D, Deubel H (2022) Eye and hand movements disrupt attentional control. PLoS One 17:e0262567.
Hayhoe MM (2017) Vision and action. Annu Rev Vis Sci 3:389–413.
Hopfinger J (2025) *The neuroscience of attention*. Cambridge: Cambridge University Press.
Hoppe D, Rothkopf CA (2016) Learning rational temporal eye movement strategies. Proc Natl Acad Sci U S A 113:8332–8337.
Hoppe D, Rothkopf CA (2019) Multi-step planning of eye movements in visual search. Sci Rep 9:144.
Illamperuma NH, Fooken J (2024) Towards a functional understanding of gaze in goal-directed action. J Neurophysiol 132:767–769.
Jenmalm P, Johansson RS (1997) Visual and somatosensory information about object shape control manipulative fingertip forces. J Neurosci 17:4486–4499.
Jerosch-Herold C (1993) Measuring outcome in median nerve injuries. J Hand Surg Br 18:624–628.
Johansson RS, Flanagan JR (2009) Coding and use of tactile signals from the fingertips in object manipulation tasks. Nat Rev Neurosci 10:345–359.
Johansson RS, Westling G, Backstrom A, Flanagan JR (2001) Eye-hand coordination in object manipulation. J Neurosci 21:6917–6932.
Jonikaitis D, Deubel H (2011) Independent allocation of attention to eye and hand targets in coordinated eye-hand movements. Psychol Sci 22:339–347.
Jovancevic-Misic J, Hayhoe M (2009) Adaptive gaze control in natural environments. J Neurosci 29:6234–6238.
Keshava A, Nezami FN, Neumann H, Izdebski K, Schuler T, Konig P (2024) Just-in-time: gaze guidance in natural behavior. PLoS Comput Biol 20:e1012529.
Koch I, Poljac E, Müller H, Kiesel A (2018) Cognitive structure, flexibility, and plasticity in human multitasking—An integrative review of dual-task and task-switching research. Psychol Bull 144:557–583.
Kowler E (2011) Eye movements: the past 25 years. Vision Res 51:1457–1483.
Kreyenmeier P, Deubel H, Hanning NM (2020) Theory of visual attention (TVA) in action: assessing premotor attention in simultaneous eye-hand movements. Cortex 133:133–148.
Land MF (2006) Eye movements and the control of actions in everyday life. Prog Retin Eye Res 25:296–324.
Land MF, Furneaux S (1997) The knowledge base of the oculomotor system. Philos Trans R Soc Lond B Biol Sci 352:1231–1239.
Land MF, Mennie N, Rusted J (1999) The roles of vision and eye movements in the control of activities of daily living. Perception 28:1311–1328.
Moog P, Schulz M, Betzl J, Schmauss D, Lohmeyer JA, Machens HG, Megerle K, Erne HC (2020) Do your surgical glove characteristics and wearing habits affect your tactile sensibility? Ann Med Surg (Lond) 57:281–286.
Musslick S, Cohen JD (2021) Rationalizing constraints on the capacity for cognitive control. Trends Cogn Sci 25:757–775.
Najemnik J, Geisler WS (2005) Optimal eye movement strategies in visual search. Nature 434:387–391.
Neggers SF, Bekkering H (2000) Ocular gaze is anchored to the target of an ongoing pointing movement. J Neurophysiol 83:639–651.
Neggers SF, Bekkering H (2001) Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. J Neurophysiol 86:961–970.
Nobre AC, van Ede F (2018) Anticipated moments: temporal structure in attention. Nat Rev Neurosci 19:34–48.
Nobre AC, Correa A, Coull JT (2007) The hazards of time. Curr Opin Neurobiol 17:465–470.
Pruszynski JA, Johansson RS, Flanagan JR (2016) A rapid tactile-motor reflex automatically guides reaching toward handheld objects. Curr Biol 26:788–792.
Pruszynski JA, Flanagan JR, Johansson RS (2018) Fast and accurate edge orientation processing during object manipulation. Elife 7:1–22.
R Core Team (2021) *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.
Renninger LW, Verghese P, Coughlan J (2007) Where to look next? Eye movements reduce local uncertainty. J Vis 7:6.
Säfström D, Johansson RS, Flanagan JR (2014) Gaze behavior when learning to link sequential action phases in a manual task. J Vis 14:1–15.
Sailer U, Flanagan JR, Johansson RS (2005) Eye–hand coordination during learning of a novel visuomotor task. J Neurosci 25:8833–8842.
Saunders JA, Knill DC (2003) Humans use continuous visual feedback from the hand to control fast reaching movements. Exp Brain Res 152:341–352.
Saunders JA, Knill DC (2004) Visual feedback control of hand movements. J Neurosci 24:3223–3234.
Schiegg A, Deubel H, Schneider W (2003) Attentional selection during preparation of prehension movements. Vis cogn 10:409–431.
Wilmut K, Wann JP, Brown JH (2006) How active gaze informs the hand in sequential pointing movements. Exp Brain Res 175:654–666.
Zelinsky GJ, Bisley JW (2015) The what, where, and why of priority maps and their interactions with visual working memory. Ann N Y Acad Sci 1339:154–164.