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RESEARCH ARTICLE

Eye–hand coordination: memory-guided grasping during obstacle avoidance

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Abstract
When reaching to grasp previously seen, now out-of-view objects, we rely on stored perceptual representations to guide our actions, likely encoded by the ventral visual stream. So-called memory-guided actions are numerous in daily life, for instance, as we reach to grasp a coffee cup hidden behind our morning newspaper. Little research has examined obstacle avoidance during memory-guided grasping, though it is possible obstacles with increased perceptual salience will provoke exacerbated avoidance maneuvers, like exaggerated deviations in eye and hand position away from obtrusive obstacles. We examined the obstacle avoidance strategies adopted as subjects reached to grasp a 3D target object under visually-guided (closed loop or open loop with full vision prior to movement onset) and memory-guided (short- or long-delay) conditions. On any given trial, subjects reached between a pair of flanker obstacles to grasp a target object. The positions and widths of the obstacles were manipulated, though their inner edges remained a constant distance apart. While reach and grasp behavior was consistent with the obstacle avoidance literature, in that reach, grasp, and gaze positions were biased away from obstacles most obtrusive to the reaching hand, our results reveal distinctive avoidance approaches undertaken depend on the availability of visual feedback. Contrary to expectation, we found subjects reaching to grasp after a long delay in the absence of visual feedback failed to modify their final fixation and grasp positions to accommodate the different positions of obstacles, demonstrating a more moderate, rather than exaggerative, obstacle avoidance strategy.

Keywords Eye–hand coordination · Obstacle avoidance · Delayed reaching · Grasping

Introduction

Reaching to pick up a cup of coffee from a crowded breakfast table, as with other similar day-to-day tasks, involves the avoidance of task-irrelevant objects. The apparent ease with which we avoid non-target objects when reaching relies upon a complex interplay between incoming visual information about our immediate surroundings and the visuomotor system responsible for executing the reach (Chapman and Goodale 2008, 2010; Marotta and Graham 2016). We often use memory to guide our actions, like when reaching for a coffee cup from behind our morning paper. Yet, little research has examined the strategies used to avoid obstacles under so-called memory-guided conditions. Memory-guided actions are certainly advantageous in that they allow for the simultaneous involvement of the eyes and the hands in different tasks (Hayhoe and Ballard 2005). It is possible that under less-than-ideal visual conditions, salient non-target objects may become perceptually relevant and attentionally captivating (Marotta and Graham 2016; Tipper et al. 1997), thereby influencing reach and grasp performance.

When reaching to grasp a three-dimensional (3D) object, visual information about the object's size, shape, orientation, and relative position in space is translated into motor signals to direct the arm to the spatial location of the target and to appropriately manipulate the object with the hand (Jeannerod 1981, 1984). Key behavioral patterns underlying even the simplest of reach-to-grasp movements have been extensively documented in the literature, in studies involving

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the simultaneous recording of eye and hand (i.e., Neggers and Bekkering, 2000, 2001; Prablanc et al. 1979). When asked to simply look at a symmetrical 3D object, observers tend to fixate the object's center of mass (COM; Brouwer et al. 2009; Desanghere and Marotta 2011; McGowan et al. 1998). When asked to grasp that same object, gaze is rapidly directed toward the eventual contact point of the index finger on the object (Brouwer et al. 2009; Bulloch et al. 2015; Cavina-Pratesi and Hesse 2013; Desanghere and Marotta 2011; Land et al. 1999; Voudouris et al. 2016). Furthermore, grasp point selection is based on a balance between making a stable grasp in consideration of an object's perceived shape and COM (Goodale et al. 1994b; Lederman and Wing 2003) and observer preferences for their natural grasp angle (Kleinholdermann et al. 2013; Paulun et al. 2014).

Goal-directed action becomes even more complicated within cluttered spaces. Though humans are generally adept at obstacle avoidance, task-irrelevant objects can nonetheless influence and interfere with efficient reaching and grasping. The *obstacle avoidance* account is a prominent theory used to explain differences in reach and grasp performance in cluttered environments, namely deviations away from non-target objects and slowed reaches, as related to the perceived risk of collision with positioned "obstacles" (Tresilian 1998). Since the initial proposal of this account, a number of studies have manipulated the influence of obstacle position and size on reach-to-grasp movements. For example, Mon-Williams and colleagues (2001) presented single, or pairs of, obstacles of various heights (short or tall) at any of four possible positions relative to a target object and observed movement speeds and grip apertures differed depending on the degree to which obstacles constrained the reach movement. Chapman and Goodale (2008) extended this work by varying the heights as well as the horizontal and depth configurations of two non-target objects through which participants reached. They similarly found the obstacle avoidance system to be sensitive to the properties of obstacles to the extent that they were obtrusive to the reaching hand. They further noted when reaching between a pair of obstacles, participants bisected the space between obstacles in such a way to avoid collision with either obstacle, by reducing movement speed and maintaining a greater minimum distance around obstacles ipsilateral to the reaching arm. Other studies report similar results, such that obstacles intrusively positioned close to the body or the target object itself, interfere with typical reach, grasp (Chapman and Goodale 2008, 2010; Dean and Brüwer 1994; Garzorz et al. 2018; Mon-Williams et al. 2001; Tresilian 1998), and to a lesser extent, gaze movements (Marotta and Graham 2016).

The dorsal visual stream likely plays a critical role in visually guided obstacle avoidance, as evidenced by studies of brain-lesioned patients (McIntosh et al. 2004a, b; Milner and McIntosh 2004; Rice et al. 2006; Schindler et al. 2004). Such studies have typically required patients either to point to, or reach quickly between, the midpoint of two obstacles at varied horizontal positions. Task demands differ between these types of tasks, with more explicit attention to the properties of obstacles required to make bisection judgements, than reaches in between obstacles. Studies demonstrate preserved avoidance of obstacles in patients with intact dorsal stream function despite impaired ventral stream function (i.e., individuals with neglect (McIntosh et al. 2004a; Milner and McIntosh 2004), extinction (McIntosh et al. 2004b; Milner and McIntosh 2004) and visual form agnosia (Rice et al. 2006)). For example, patients with neglect performed similarly to controls in deviating their reaches to avoid obstacles symmetrically or asymmetrically placed about the midline but were insensitive to the position of obstacles when making midpoint judgements (McIntosh et al. 2004a, b; Milner and McIntosh 2004). On the other hand, impaired avoidance was observed in dorsal stream lesioned patients (optic ataxics; Schindler et al. 2004; Rice et al. 2008).

Memory-guided actions are also common in daily life, as in instances when we reach for our coffee cup from behind our morning paper. It has generally been acknowledged that both the reach and grasp components of a movement can be affected by the availability of visual information during movement planning, execution, and control (Fukui and Inui 2013; Jeannerod 1981, 1984; Milner and Goodale 1995; Woodworth 1899). Indeed, a number of studies report significant kinematic differences in pointing (Elliott and Madalena 1987; Heath and Binsted 2007) and grasping (Berthier et al. 1996; Hesse and Franz 2010; Hu et al. 1999; Hu and Goodale 2000), whereby memory-guided actions tend to be slower, less accurate, and elicit wider grip apertures, relative to visually guided actions. Furthermore, the intimate linkage between eye and hand movements becomes less pronounced under memory guidance (Flanagan et al. 2008; Prime and Marotta 2013).

Memory-guided actions rely on stored perceptual representations of the scene, likely encoded by the ventral visual stream (Goodale and Milner 1992; Milner and Goodale 1995; Prime and Marotta 2013). Studies demonstrate intact grip scaling when ventral stream lesioned patients (i.e., patient D.F.) grasp objects in "real time", but impairments when patients "pantomime" movements toward remembered objects or make natural grasping movements toward target objects no longer visible after a delay as short as two seconds (Goodale et al. 1994a). Patients with lesions to the primary visual cortex (V1) are similarly unable to effectively avoid previously seen obstacles after a brief delay, presumably as this ability would require the support of visual consciousness (Whitwell et al. 2011). In contrast, parietal lobe lesioned patients show good grip scaling when pantomiming a grasp and when reaching to remembered objects after a time delay (Milner et al. 2001, 2003), suggested as evidence for a relay of visuomotor control from the damaged dorsal stream to the unimpaired perceptual memory of the ventral stream (Himmelbach and Karnath 2005).

It is important to acknowledge the limitations of the above-mentioned patient studies in delineating the respective roles of the dorsal and ventral visual streams in visually guided and memory-guided actions (see Humphreys, 2015 for a summary). There is increasing recognition that the interactions between the two visual streams are more complex than initially thought (Milner and Goodale 2008). It is undoubtedly necessary for the two visual streams to take on cooperative roles in goal-directed actions such as obstacle avoidance (Chapman and Goodale 2008; Gentilucci et al. 2001; de Haan et al. 2014; Himmelbach and Karnath 2005; Menger et al. 2013), particularly in situations where the identity of obstacles is inherently related to planning an effective avoidance route (Chapman and Goodale 2008, 2010; Schindler et al. 2004). For instance, the potential for a collision that might result in physical pain to the subject performing the reach (i.e., colliding with a prickly cactus) or a consequence of another sort (i.e., risk of spilling a full glass of water) should accordingly result in modifications to the typical obstacle avoidance maneuver.

It is our impression that obstacles properties might become more relevant in influencing motor behavior under less-than-ideal visual conditions, where the perceptual mechanisms of the ventral stream likely play a larger role in the visuomotor control of action (Milner and Goodale 1995). We explored the extent to which visually- and memory-guided eye–hand coordination is impacted by the perceived interference of obstacles along a reach path, through manipulations of obstacle properties including position and width. We adopted a similar paradigm as the formerly cited studies of obstacle avoidance with patients and controls (Chapman and Goodale 2008, 2010; Mon-Williams et al. 2001; McIntosh et al. 2004a, b; Milner and McIntosh 2004; Rice et al. 2006; Schindler et al. 2004), and a previous investigation in our lab (Marotta and Graham 2016), including a task where participants made reaches in between a pair of tall flanker obstacles, which always remained a constant distance apart, to grasp a centrally located target object. Groups of participants performed this task under visually-guided (entirely closed loop or open loop with full vision prior to movement onset) or memory-guided (short-delay, or long-delay) conditions. We predicted that participants would show sensitivity to the position, but not the widths, of obstacles in the visually-guided conditions, since only the obstacle position with respect to the reaching arm would be relevant for planning and executing an effective obstacle avoidance maneuver. It is possible that without continuous visual feedback, participant obstacle avoidance movements would become less conservative (Chapman and Goodale 2010). Thus, we hypothesized that an exacerbated obstacle avoidance strategy would be observed when reaching after a 2 s delay in the absence of visual feedback (as indexed by increased hand deviations and shifts in final fixation and finger positions). Such an exaggerated avoidance strategy was expected particularly in response to obstacles on the same side as the reaching arm, centered in the grasp space, closer to the body, and wider in dimension, as the perceptual salience of these obstacles would not be overlooked by the calculated accuracy of the dorsal stream guiding the movements. We decided upon a 2-s delay for our long-delay condition, as previous studies have suggested visual information used to program a grasp movement is stored for only a restricted period of time, such that a good portion is lost during the first 2 s of visual occlusion (Elliott and Calvert 1990; Elliott et al. 1990; Elliott and Madalena 1987; Goodale et al. 1994a; Hesse and Franz 2010; Hu and Goodale 2000).

Methods

Participants

Forty-eight undergraduate students (23 males; mean age = 21.6 years) were recruited from the University of Manitoba's Psychology participant research pool and received course credit for their participation. Subjects were evenly divided into four groups ($n = 12$ each group) to perform one of visually-guided [entirely closed loop (CL) or open loop with full vision prior to movement onset (OL-Onset)] or memory-guided [short-delay (OL-SD), or long-delay (OL-LD)] tasks. Informed consent was obtained prior to testing. All participants had normal or corrected-to-normal vision and were right-hand dominant, as determined by a modified version of the Edinburgh Handedness Inventory (Oldfield 1971). Procedures were approved by the Psychology/Sociology Research Ethics Board (P/SREB) at the University of Manitoba.

Apparatus

Reaching and grasping movements were recorded using an Optotrak Certus 3D motion tracking system (Northern Digital Inc., Waterloo, ON, Canada), sampling at 100 Hz. Six infrared light emitting diodes (IREDs) were fastened to each participant's right hand (2 IREDs each placed on the left side of the proximal edge of the cuticle of the index finger, the right side of the proximal edge of the cuticle of the thumb, and on the distal radial portion of the wrist). Only one IRED at each position was used for analysis. In situations where the first IRED sensor for a given participant did not capture data adequately (i.e., when a sensor was blocked due to its position on the hand), the second of the two IREDs was used. An Eyelink II head-mounted eye tracking system

(SR Research Ltd., Mississauga, ON, Canada) sampling at 250 Hz recorded binocular eye movements. Three additional IREDs were placed on the Eyelink II headset to account for any incidental head movement. Eye, head, and hand data were integrated into a common spatial and temporal frame of reference using MotionMonitor software (Innovative Sports Training Inc., Chicago, IL, USA). User defined formulas within MotionMonitor controlled any auditory tones and triggered a "switchable glass" window.

The availability and timing of visual feedback was controlled by a 28 × 26.5 cm switchable glass window (Polytronix Inc, Dallas, Texas, USA; Prime and Marotta 2013). Switchable glass, a polymer-dispersed liquid crystal film embedded within glass, has the capacity to change between opaque and transparent states with the application of a 36 V alternating current (VAC). The window was suspended from above, so that it did not interfere with natural hand and arm movements. The window was hung ~ 10 cm directly in front of subjects' faces, so when opaque, it completely obstructed view of the grasp space. Subjects sat in a height-adjustable chair that allowed their heads to be comfortably stabilized in a chin rest at its set height (30.5 cm above the table). Thus, all subjects had the same clearance under the window for making unimpeded arm movements. The experiment was conducted in a fully lit room by fluorescent lighting from the ceiling directly above the workspace.

Prior to data collection, both eyes were calibrated using a nine-point calibration/validation procedure presented on a Dell U2414H 24-in computer monitor. To ensure accurate calibration, an accuracy check was conducted by the experimenter immediately following the calibration/validation process, and prior to each block of experimental trials. Accuracy checks involved participants fixating on a centrally located dot for approximately 8 s and comparing the position of their fixation to the position of the dot. The presence of an overall gaze displacement error exceeding 1 cm in either the horizontal or vertical dimension resulted in the recalibration/validation of the Eyelink II system.

Stimuli

Participants grasped a lightweight 3D target object on each trial—a white foam-core Efron shape (Efron 1969) measuring 10 cm in width, 6.4 cm in height and 0.5 cm in depth. Three distractor targets (9 cm wide, 7.1 cm tall; 11 cm wide, 5.8 cm tall; 12 cm wide, 5.3 cm tall, all 0.5 cm deep), were included to prevent subjects from relying on a predetermined size of the target object to be grasped. Shapes were mounted on a black, 54.2 × 45.8 cm vertical presentation board with a center 31 cm above the table and 55 cm from the subject in the chinrest (Fig. 1A). The board was attached to the computer monitor that was used to calibrate the eyes. Prior to the beginning of every block of trials, a cluster of IREDs attached to a stylus 20 cm in length were held to the center of a target object positioned on the presentation board to capture the precise coordinates of the target object's geometric center (since the target object is a simple symmetrical rectangle, we will refer to its geometric center as its center of mass; COM). The presentation board was removed between each block of trials to allow for an accuracy check of the eyes.

Participants reached between a pair of tall flanker obstacles, which were white foam-core rectangles measuring 50.8 cm in height and 0.5 cm in depth. The widths of the obstacles were manipulated so that a wide (10 cm) obstacle could be situated on one side of the grasp space while a narrower (5 cm) obstacle would be on the other side of the grasp space, or so neither obstacle would be wide (both 5 cm; Fig. 1B). At all times, the inner edges of the obstacles remained a constant distance apart (20 cm) so to keep the potential for collision with obstacles constant. On any given trial, the pair of obstacles was situated in the grasp space between the start position of the hand and the presentation board either closer or farther from the subject, centered around the target object or slightly deviated to the right (by 5 cm). Four possible positions of obstacles were manipulated [Close Centered (CC): obstacles 12 cm from the start position and 10 cm to the left and right of the midline; Far Centered (FC): obstacles 19 cm from the start position and 10 cm to the left and right of the midline of the grasp space; Close Deviated (CD): obstacles 12 cm from the start position, 5 cm to the left, and 15 cm to the right of the midline; Far Deviated (FD): obstacles 19 cm from the start position, 5 cm to the left, and 15 cm to the right of the midline; Fig. 1C].

Procedure

A trial began with subjects holding their index finger and thumb at a central start position aligned with subjects' midsagittal plane (25 cm from the edge of the table, 30 cm from the target object), with the glass window and participants' eyes closed. The experimenter mounted a target block on the display board and positioned the pair of obstacles. Subjects opened their eyes just before initiation of the trial when the experimenter said "open". In the CL condition, the window opened (becoming transparent) upon initiating the trial. After 1 s, participants were prompted to grasp the target object on the command of an auditory go-tone (350 Hz, 250 ms). In the OL-Onset condition, participants viewed the grasp space for 1 s after which an auditory go-tone indicated the movement should be initiated. The window would close (becoming opaque) at movement onset (the first frame in which either of the IREDs on the wrist exceeded a velocity threshold of 5 cm/s). In the OL-SD condition, participants viewed the grasp space for 1 s after which an

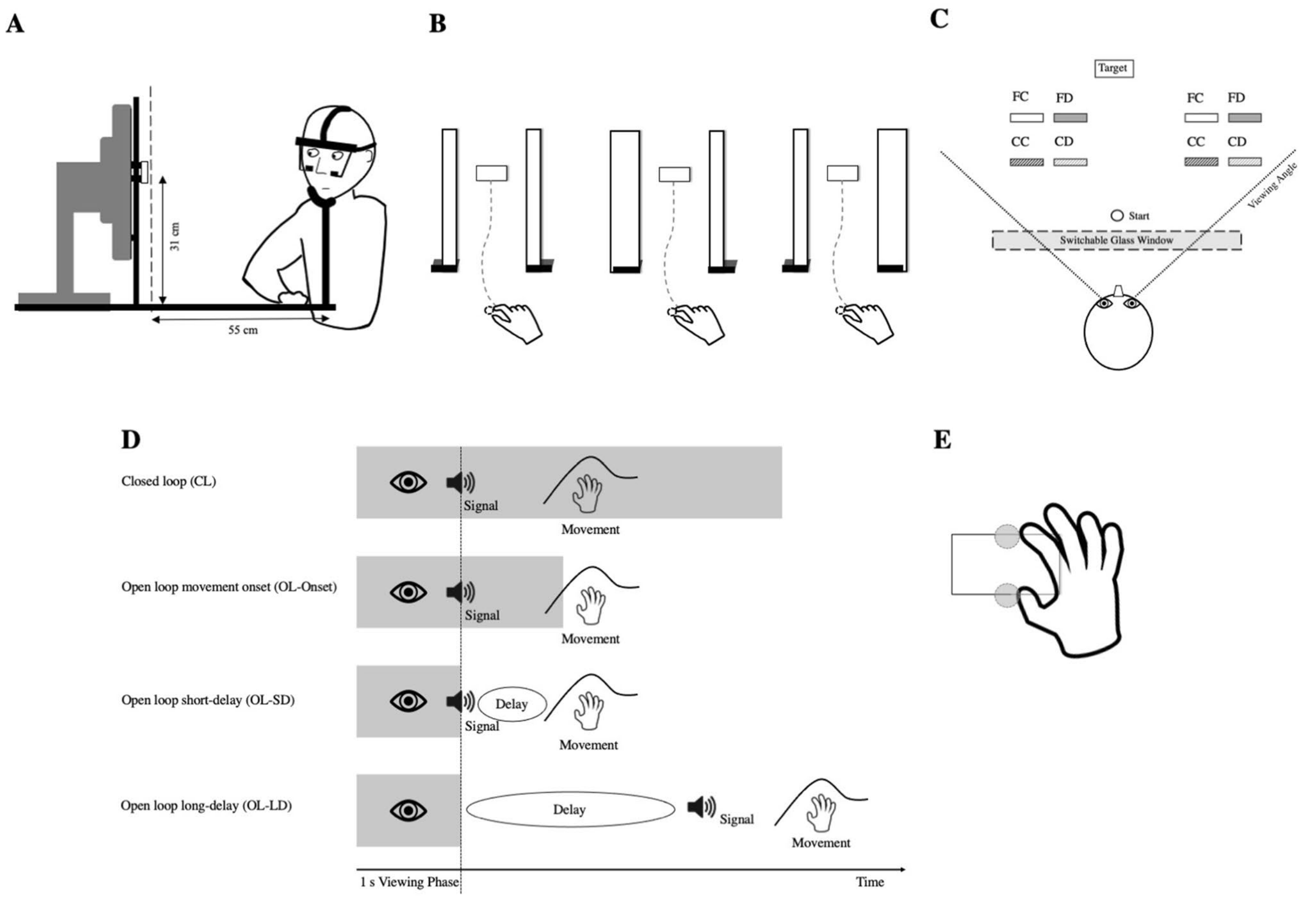


Fig. 1 Schematic of experimental setup with the target object mounted to the computer screen (**A**). Participants reached between a pair of obstacles to grasp a target object (**B**). The widths of the obstacles were manipulated so that a wide obstacle could be situated on one side of the grasp space while a narrower obstacle would be on the other side of the grasp space, or so neither obstacle would be wide. Although the inner edges of the obstacles remained a constant distance apart, the pair of obstacles were situated in between the start position and the presentation board at any of four possible positions in the grasp space [**C**; Close Centered (CC), Far Centered (FC), Close Deviated (CD), and Far Deviated (FD) positions, represented by the *black hashed*, the *solid white*, the *gray hashed*, and the *solid gray rectangles*, respectively]. Viewing conditions used in our experiment (**D**). In all conditions, participants viewed the stimulus for 1 s before an auditory go-tone indicated when the movement should be initiated. Subjects were instructed to grasp using a vertically oriented precision grip such that the index finger would contact the top edge and the thumb would contact the bottom edge of the target object (**E**). Dimensions of the target object and obstacles are not shown to scale

auditory go-tone indicated the movement should be initiated. The window would close immediately after the initial viewing period and the auditory signal. In this condition, visual occlusion occurs immediately after the 1 s viewing phase, creating an embedded, albeit short, delay from the time of the auditory go-tone to the initiation of movement. In the OL-LD condition, participants viewed the grasp space for 1 s, after which the window would close. Participants in this condition were presented with the go-tone after a 2 s delay from when the window closed (Fig. 1D).

Subjects were instructed to reach towards and grasp the target object in a quick but natural manner upon hearing an auditory cue and place it on the table in front of them. Further, subjects were instructed to grasp using a vertically oriented precision grip such that the index finger would contact the top edge and the thumb would contact the bottom edge of the target object (Fig. 1E). The horizontal, vertical, and depth positions of the index, thumb, and wrist sensors were recorded simultaneously from the time when the trial was initiated until the time of grasp (when a subject's index finger came within a threshold of 1 cm from depth position of the target object) and were analyzed at 100 Hz. Horizontal and vertical gaze positions were recorded for the duration of the trial and raw gaze coordinates were characterized into fixations based on a dispersion-threshold identification (I-DT) algorithm (see Salvucci and Goldberg 2000), with a minimum duration threshold of 100 ms and a maximum dispersion threshold of 1 cm.

Participants completed four practice trials before experimentation. Four obstacle positions and 3 obstacle width arrangements resulted in 12 experimental conditions, each presented six times for a total of 72 experimental trials. The three distractor target types were presented four times each, pseudorandomly interleaved among the experimental trials for a total of 84 trials. Trials were divided evenly among 3 blocks. Each session took no longer than 1.5 h to complete.

Data analyses

The goal of this study was to examine obstacle avoidance under memory guidance. Analyses were concerned with subjects' hand kinematic data, gaze, and fixation positions. The number of collisions with obstacles was also recorded to improve understandings of memory-guided collision mitigation. Fixation positions and positions of the index finger, thumb, and wrist were extracted at meaningful timepoints to investigate our dependent variables. Dependent variables analyzed included (1) the horizontal position of the index finger at the point when the index finger just passed between the pair of obstacles (index finger bisection of the grasp space), (2) the horizontal position of the index finger in relation to the target object's horizontal COM at the time of grasp (final index finger position), (3) the horizontal position of the final fixation in relation to the target object's horizontal COM at the time of grasp (final fixation), (4) the difference between the final fixation and the final index finger positions along the horizontal plane, (5) the number of collisions with obstacles**,** and (6) participants' overall gaze patterns. The kinematic variables maximum grip aperture (MGA), reach duration, and maximum wrist velocity data were additionally analyzed to provide context, but are not discussed at length.

Since our manipulation of obstacle width largely revealed non-significant effects in our preliminary analyses, we decided to pool the effects of this data going forward. Thus, for each dependent variable, a 4 (Viewing Condition; between-subjects) × 4 (obstacle Position; within-subjects) mixed ANOVA was performed on the mean condition values for each participant. Any violations of sphericity were tested for using Mauchly's test and were addressed using a Greenhouse–Geisser correction. Analyses were conducted using alpha = 0.05. A Bonferroni correction was applied to post hoc comparisons to analyze significant interactions.

Results

Excluded data

Experimental trials were excluded from analysis on the basis of improper execution of the reach-to-grasp task (i.e., initiating the reach prior to tone presentation) or errors in trial presentation. Trials were also removed in cases where the data was unusable (i.e., crucial missing data points or physiologically implausible data). Trials where participants collided with an obstacle were included in analysis, as collisions tended to only involve grazing of the forearm against obstacles, nonetheless resulting in an appropriate grasp. In total, 11.0% of all experimental trials were excluded from analysis.

Kinematic variables

MGA, reach duration, and maximum wrist velocity data are provided in the Appendix for additional information about the way participants reached in the different viewing conditions. As these data do not present a direct relevance to our present hypotheses, formal analyses will not be discussed at length and are, thus, provided mainly for context.

A significant main effect of Position was found for MGA, $F(2.43, 106.83) = 6.39$, $p < 0.01$, $\eta_p^2 = 0.13$. Subjects had larger grip apertures when reaching between obstacles at Centered positions compared to the Close Deviated position (all $p < 0.01$), reflecting increased carefulness when reaching around the most obtrusive of obstacles.

A significant Position × Viewing Condition interaction was found for reach duration, $F(9, 132) = 2.09$, $p < 0.05$, $\eta_p^2 = 0.13$. When reaching between obstacles at the Close Deviated position, subjects in the CL condition had significantly shorter reach durations than subjects in the OL-SD condition ($p < 0.05$). Subjects in the OL-Onset condition had significantly shorter reach durations when reaching between obstacles at Far Centered position compared to the Close Centered ($p < 0.05$) and Far Deviated positions ($p < 0.01$). Subjects in the OL-SD condition had significantly shorter reach durations when reaching between obstacles at the Far Centered position compared to the Close positions (all $p < 0.05$).

A significant Position × Viewing Condition interaction was found for maximum wrist velocity, $F(9, 132) = 2.04$, $p < 0.05$, $\eta_p^2 = 0.12$. Subjects in the OL-SD condition reached significantly faster between obstacles at the Far Centered position compared to the Close Deviated position ($p < 0.01$). Subjects in the OL-LD condition reached significantly faster between obstacles the Close Deviated position compared to the Centered positions (all $p < 0.01$).

Index finger bisection of the grasp space

The horizontal position of the index finger relative to the inner edge of the right obstacle was extracted at the point at which the index finger passed the depth coordinate of a given pair of obstacles, to inform about deviations around obstacles (Fig. 2). A significant main effect of Position was found, $F(1.93, 84.82) = 145.26$, $p < 0.001$, $\eta_p^2 = 0.77$.

Subjects tended to bisect the grasp space farther away from the right-sided obstacle when reaching between obstacles at Deviated compared to Centered positions (all $p < 0.001$). Nevertheless, subjects tended to bisect the space between Centered obstacles to the left of the target's COM, while they tended to bisect the space between Deviated obstacles to the right of the target's COM. Reaches passing in close proximity to the left-sided obstacle of the pair might reflect this obstacle's close distance to the target object in Deviated conditions (i.e., obstacles are shifted rightward within the grasp space, bringing the left-sided obstacle closer to the target object itself). It is perhaps more likely that the shifted position of the obstacles in the Deviated conditions reduced the salience of the right-sided obstacle, allowing subject reaches to come within a closer distance to the left-sided obstacle, which is disregarded as being a relevant threat for collision. Nonetheless, index finger bisections were never observed to the right of the midpoint between obstacles, suggesting a predominant bias in reach away from obstacles situated on same side as the reaching arm, particularly with obstacles most obtrusive to the reach (Close and Far Centered positions).

Final index finger position in horizontal plane

The contact position of the index finger with the target object relative to its horizontal COM was calculated as an indicator of grasp performance. Final index finger positions were removed from analysis if they fell 2 cm beyond the left or right edges of the target object's contour. On average, participants tended to grasp the target object 0.9 cm to the left of its COM ($SE = 0.2$ cm). A significant Position × Viewing Condition interaction was found, $F(5.41, 79.27) = 2.35$, $p < 0.05$, $\eta_p^2 = 0.14$ (Fig. 3A). Participants in CL, OL-Onset, and OL-SD conditions showed index finger placements that were deviated further to the left of the target object's COM with obstacles at Centered compared to Deviated positions (CL: all $p < 0.001$; OL-Onset: FC vs. FD, CC vs. FD $p < 0.01$; FC vs. CD, CC vs. CD $p < 0.05$; OL-SD: FC vs. FD, $p < 0.001$; FC vs. CD, CC vs. FD, $p < 0.01$; CC vs. CD, $p < 0.05$). Further, participants in the OL-SD condition showed index finger placements that were deviated further to the left of the target object's COM with obstacles at the Close Deviated compared to the Far Deviated position ($p < 0.05$). No significant differences in the horizontal positions of the index finger were apparent in the OL-LD condition. This result suggests a repulsion of the index finger away from obstacles on the same side as the reaching arm, particularly with obstacles located close to the body (Close and Centered positions), but only in conditions where sufficient visual information was available for programming and controlling the reach (all conditions but OL-LD).

Gaze accuracy

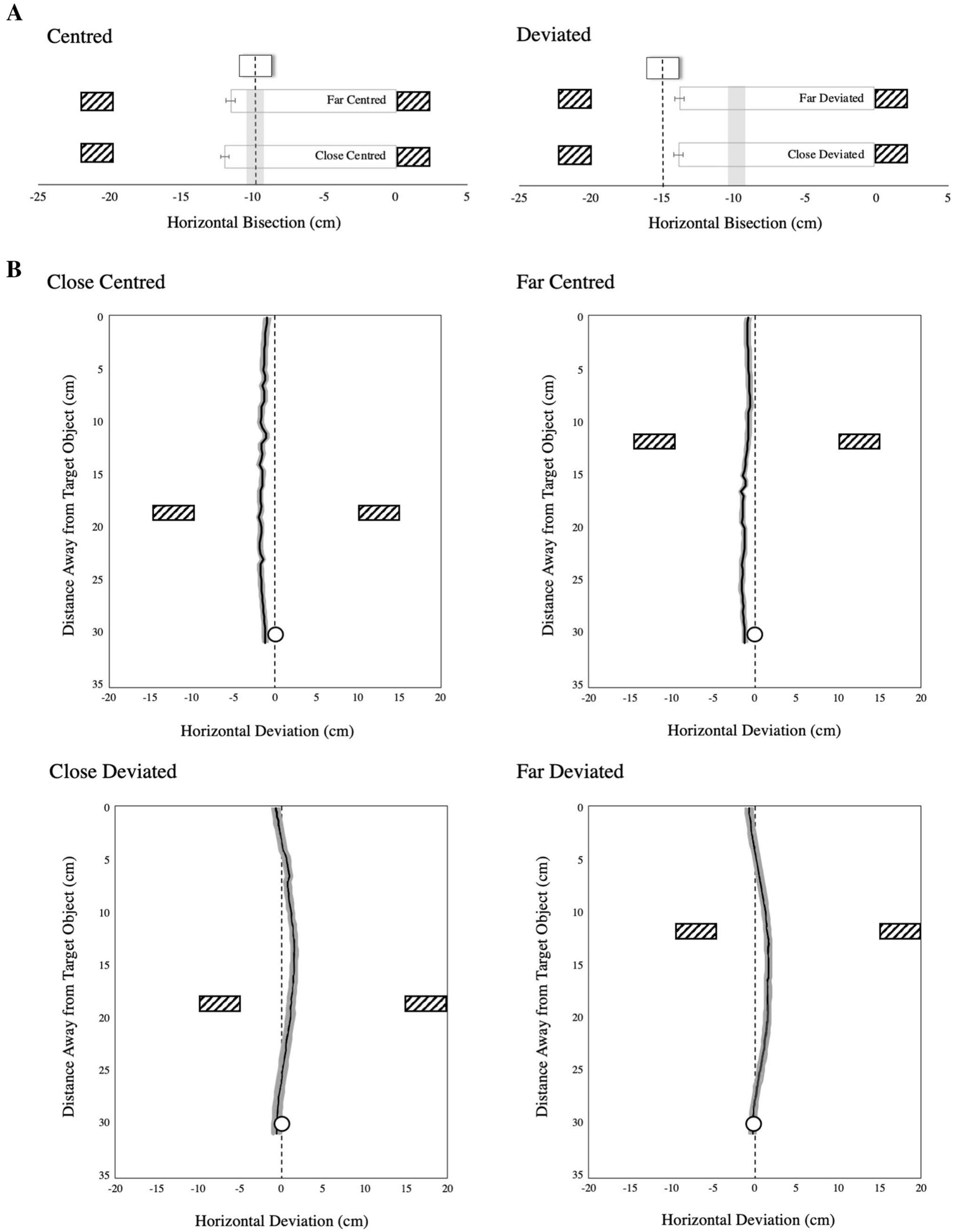
An accuracy check was conducted prior to the beginning of each experimental block, and gaze displacement error was calculated as the distance of a participant's fixation away from a central dot. The average absolute gaze displacement error collapsed across blocks and participants was 0.66 cm ($SE = 0.067$ cm) in the horizontal axis and 0.81 cm ($SE = 0.042$ cm) in the vertical axis.

Final fixation in horizontal plane

The final fixation position at the time of grasp was analyzed in relation to the target object's horizontal COM. As vision was occluded prior to the time of grasp, final fixations for the open loop conditions were directed to locations on the target object that were no longer visible. Final fixations were removed from analysis if they fell 2 cm beyond the left or right edges of the target object's contour. On average, participants' final fixations tended to land 0.13 cm to the right of the target object's COM ($SE = 0.1$ cm). A significant Position × Viewing Condition interaction was found, $F(9, 132) = 5.63$, $p < 0.001$, $\eta_p^2 = 0.28$ (Fig. 3B). Participants in the CL and OL-Onset conditions showed final fixations that were deviated further to the left of the target object's COM with obstacles at Centered compared to Deviated positions (CL: all $p < 0.001$; OL-Onset: FC vs. FD, CC vs. FD and CC vs. CD, $p < 0.01$; FC vs. CD, $p < 0.05$). No significant differences in the horizontal positions of the final fixation were apparent in SD and LD conditions. In line with the results of the final index finger positions, final fixations were effectively repulsed by obstacles most obtrusive to the grasp space (i.e., Close and Far Centered positions). This pattern of fixation behavior is only apparent when visual feedback was available throughout, or up until the point of movement onset (CL and OL-Onset conditions).

Distance between final fixation and final index finger positions on the target in horizontal plane

The distance between the index finger grasp point and the final fixation along the horizontal plane is useful in understanding the relationship between grasp and gaze under different viewing conditions. On average, the final fixation and final index finger positions on the target object were separated by a distance of 1.0 cm ($SE = 0.2$ cm) in the horizontal plane, with the index finger landing to the left of the target object's COM and the final fixation. A significant main effect of Position was found, $F(2.49, 109.68) = 6.05$, $p < 0.01$, $\eta_p^2 = 0.12$. The relationship between final fixation


A
Centred
Far Centred
Close Centred
-25
-20
-15
-10
-5
0
5
Horizontal Bisection (cm)
Deviated
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Close Deviated
Horizontal Bisection (cm)
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Close Centred
Distance Away from Target Object (cm)
Horizontal Deviation (cm)
Far Centred
Distance Away from Target Object (cm)
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Distance Away from Target Object (cm)
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Distance Away from Target Object (cm)
Horizontal Deviation (cm)

◂**Fig. 2** Mean horizontal bisections of the index finger between Centered and Deviated obstacle positions, averaged across the four viewing conditions (**A**). *Dashed rectangles* depict the inner edges of positioned obstacles, consistently separated by a distance of 20 cm. Index finger bisections were analyzed in relation to the inner edge of the right flanker obstacle, such that a bisection at -10 cm indicates the index finger passed between the midpoint of the two obstacles (represented by the *faded grey bar*). The *dashed line* represents the position of the target object's center of mass, which varies in relation to the obstacles at Centered and Deviated positions. *Error bars* represent standard error of the mean. Trajectories of the index finger are plotted in relation to the target object's center of mass (represented by the *black dashed line*) for each obstacle position, averaged across the four viewing conditions (**B**). Index trajectories are displayed in terms of their distance away from the target object in the depth dimension. *Solid white circles* represent the starting position of the index finger (30 cm away from the target object). *Dashed rectangles* depict the inner edges of positioned obstacles, consistently separated by a distance of 20 cm. The shaded area around the averaged trajectories represents standard error of the mean. The presented trajectory plots have been smoothed for illustrative purposes by removing exaggerate data points and dimensions of the target objects and obstacles are not shown to scale

and final index finger position on the target object overall remained fairly consistent across obstacle positions during visually guided and memory-guided grasp conditions, the exception being that all participants displayed increased separation between index finger and fixation placements when reaching between obstacles at the Far Centered ($M = 1.2$ cm, $SE = 0.2$ cm) compared to the Far Deviated positions, ($M = 0.8$ cm, $SE = 0.2$ cm; $p < 0.01$).

Number of collisions

The number of collisions with obstacles of different positions and widths was noted. Overall, participants rarely collided with obstacles (0.01% of trials for the CL condition; 0.04% of trials for the OL-Onset condition; 0.04% of trials for the OL-SD condition; and 0.05% of trials for the OL-LD condition), and so this variable was not further analyzed. When collisions did occur, subjects predominantly collided with the right-sided obstacle of the pair, particularly when situated at the Close Centered position. This position is the most mechanically constraining, as it is closest to the body, and there is a need to orient the elbow in order for the forearm to clear the obstacles. It is not surprising that collisions predominantly occurred with the right obstacle, since participants were reaching with their right hands.

Overall gaze

Participants' gaze patterns were visually examined to assess whether obstacles were capturing gaze at any point during the trial for participants in the closed loop condition, and during the 1 s viewing phase for participants in the open loop conditions. Participants' gazes were almost exclusively directed toward the target object, with only 115 out of 3,011 total trials (3.82% of total trials) across all participants involving gaze directed at some point towards one of the obstacles.

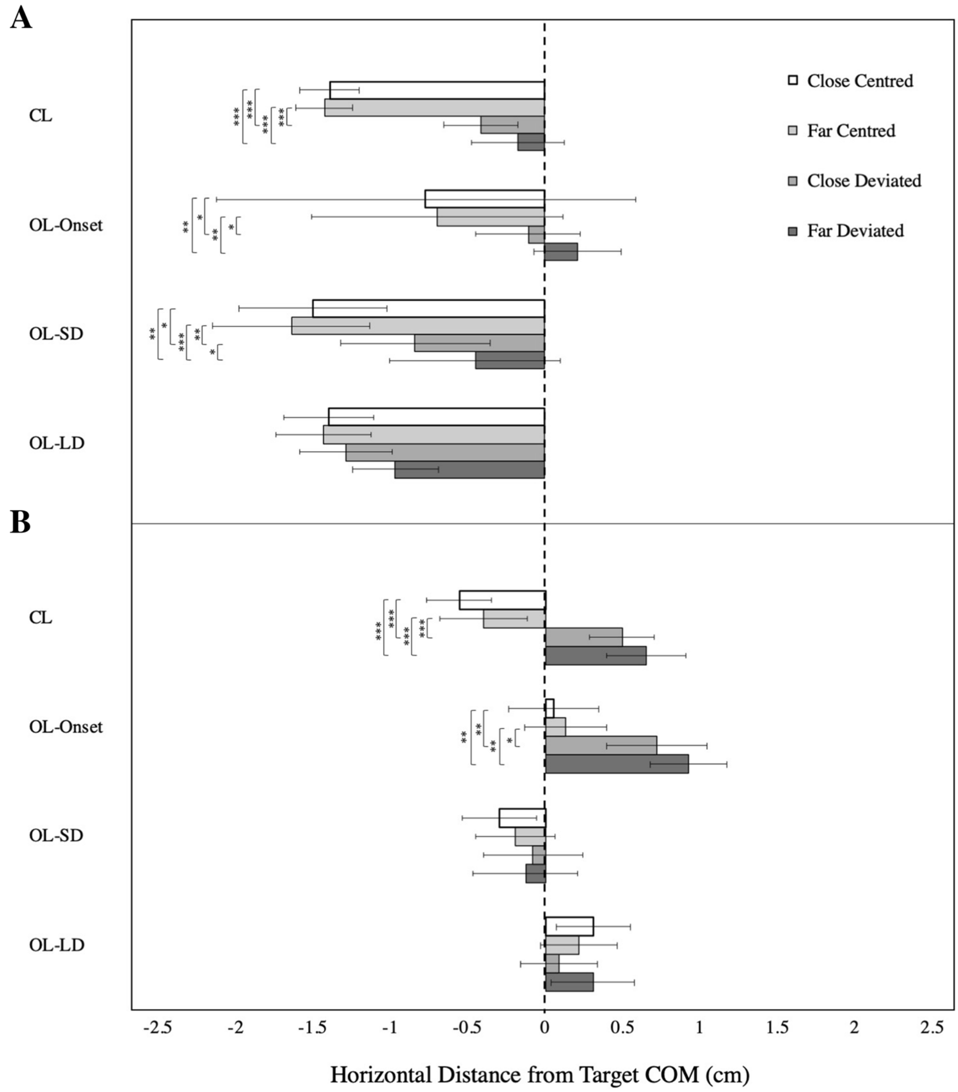
Discussion

This study explored obstacle avoidance behavior as subjects reached out and grasped a 3D target object under visually-guided (entirely closed loop or open loop with full vision prior to movement onset) or memory-guided (short-delay, or long-delay) conditions. On any given trial, subjects maneuvered their reaching arm through a pair of flanker obstacles to grasp a target object. The positions and widths of the obstacles were manipulated, though their inner edges remained a constant distance apart. Overall, we found reach and grasp behavior occurred in a manner consistent with the obstacle avoidance account of collision mitigation (Tresilian 1998), whereby reach, grasp, and gaze positions were biased away from right-sided obstacles and obstacles most obtrusive to the reaching hand. Our results show distinctive avoidance approaches undertaken depending on the availability of visual feedback. Contrary to expectation, subjects reaching to grasp the target object after a delay of 2 s in the absence of visual feedback failed to modify their final fixation and grasp positions to accommodate the different positions of obstacles. We take this result to suggest under the presumed perceptual control of the ventral stream, obstacle avoidance in the memory-guided condition after a brief delay of 2 s followed a more moderate, rather than exaggerative, strategy.

Bisection of the space between obstacles during reach

Participants in all viewing conditions displayed biases in reach behavior dependent upon the positions of obstacles. As in previous literature, our participants' reaches showed a general repulsion away from obstacles most obtrusive to the reaching hand (our Close and Far Centered obstacle positions; Chapman and Goodale 2008, 2010; Dean and Brüwer 1994; Garzorz et al. 2018; Marotta and Graham 2016; Tresilian 1998). Also consistent with previous literature, we observed subject reaches deviated away from the obstacle positioned closest to their (right) reaching arm when they reached between obstacles centered around the target object. Of note, we observed index finger bisections even further away from the right-sided obstacle when reaches occurred between obstacles deviated slightly to the right of the grasp space. We interpret this result to

Fig. 3 Average horizontal positions for the index finger (**A**) and the final fixation (**B**) at the time of grasp for each obstacle position and viewing condition. The dashed line represents the target object's horizontal center of mass. Thus, negative values are to the left of the target object's COM, while positive values are to the right. *Error bars* represent standard error of the mean



suggest that by shifting the obstacles to the right of the grasp space, we managed to reduce the salience and the relevance of the right-sided obstacle, allowing subject reaches to come closer to the non-threatening left-sided obstacle. Still, we never observed index finger bisections to the right of the midpoint between obstacles, suggestive of a prominent bias in reach away from obstacles with the most potential to obstruct the movement of the reaching arm (obstacles on the right side). Consistent with previous investigations, which demonstrate largely invariant reaches for obstacles at various positions contralateral to the reaching arm (Chapman and Goodale 2008; Marotta and Graham 2016; Mon-Williams et al. 2001; Tresilian 1998), this result emphasizes the strength of the influence of obstacles positioned on the same side as the reaching arm, when individuals make reaches within cluttered environments.

Final fixation and grasp

At the time of grasp, several variables of interest revealed differential strategies undertaken depending on the availability of visual feedback. Participants in the visually-guided (closed loop and open loop conditions with full vision prior to movement onset) and the memory-guided short-delay conditions adjusted the positions of their grasps on the target object to accommodate obstacle positions. The greatest repulsions in grasp position were made away from right-sided obstacles at centered positions. Subjects in the open loop long-delay group did not alter final index finger positions on the target object to account for obstacles in the grasp space. Rather, the index finger tended to land at one general location on the target object, regardless of obstacle position or width. Likely, participants positioned their index finger at a location on the target object that they found to be "safe" early on during experimentation and continued to output a motor plan that would allow them to end up at that position. A moderate strategy such as this is indicative of subjects relying on behavioral heuristics, where formulating a unique motor plan to accommodate the characteristics of the task environment on every single trial is computationally costly in the absence of accurate, continuous visual information. It is possible that while the open loop long-delay condition necessitated participants to keep the layout of the grasp space in memory, it also provided them with more motor preparation time. Thus, the finding that subjects in this condition did not modify their final grasp position in response to the different obstacle positions could simply be the result of better motor performance due to increased preparation time prior to initiating movement. Nonetheless, our kinematic results do not suggest poorer performance in the long-delay condition, as group differences in grip aperture, wrist velocity, and reach duration were largely not significant nor meaningful. A further investigation, including a control condition which would require participants to reach to grasp a target object in the absence of flanking obstacles, is warranted to disentangle these interpretations. Nonetheless, this result is unexpected given our hypothesis that the interference of obstacles would be exacerbated under memory guidance. This result provides unique insight into the type of perceptual strategy employed by the ventral visual stream when acting after a time delay in the absence of visual information.

Of note, in all viewing conditions, participant grasps tended to land to the left of the target object's center. In view of the patterns observed during reach, whereby subjects tended to bisect the space between centered obstacles to the left of the target's center, but to the right of the target's center when reaching between deviated obstacles, this result further highlights the influence of obstacles situated on the same side as the reaching arm on grasp performance.

In terms of the final fixation at the time of grasp, only participants who had visual feedback available throughout, or up until the point of movement onset (closed loop and open loop conditions with full vision prior to movement onset) showed adjustments in final fixations on the target object to accommodate obstacle positions, with the greatest repulsions away from right-sided obstacles at centered positions. In the memory-guided short-delay and long-delay conditions, final fixation positions on the target object were not modified according to positioned obstacles along the horizontal axis. Rather, final fixations tended to consistently land at one general location on the target object despite the positions or widths of obstacles. When acting upon remembered objects, it seems the eyes took on the predominant role in maintaining the position of the target object irrespective of positioned obstacles, while the hand took on the role of avoiding obstacles, relying largely on the guidance of proprioceptive sensory feedback. Previous studies support the use of such an oculomotor strategy as a way to reduce the load on internal cognitive resources when performing spatial memory tasks (Clark 1997; Hodgson et al. 2000; Ketcham et al. 2003; Kirsh and Maglio 1994).

Furthermore, our results provide support for the coupling of eye and hand movements during reach-to-grasp movements (Brouwer et al. 2009; Desanghere and Marotta 2011; Flanagan and Johansson 2003; de Grave et al. 2008; Johansson et al. 2001; Neggers and Bekkering 2000, 2001; Prablanc et al. 1979). In all viewing conditions, largely consistent differences between final fixation and final index finger positions on the target object were observed. Specifically, the final fixation and the final index finger were separated by approximately 1 cm regardless of obstacle position. The exception to this was that increased separation between the final fixation and final index finger position was observed when obstacles were situated at the Far Centered compared to the Far Deviated positions. This result is intuitive in that obstacles at the Far Centered position are close in proximity to the target object, demanding increased control to ensure a collision-free grasp.

Overall performance

Despite the influence of obstacles and the unavailability of visual information in particular viewing conditions, performance in all groups was quite good, showing successful grasps of the target object and minimal instances of collision. Gaze was generally directed at the target object rather than towards either flanker obstacle, consistent with results of a previous investigation in our lab showing the presence of obstacles tended to affect reach mechanics more than gaze (Marotta and Graham 2016). The motor system needs to be sensitive to environmental characteristics to effectively perform goal-directed actions, whereas the eyes are never in any physical danger of colliding with objects so can be less sensitive to the physical properties of the reaching space. In this sense, movement plans can be computed using peripheral vision exclusively (Chapman and Goodale 2008). Further investigations manipulating the salience of obstacles will increase understandings about the types of obstacles that can capture gaze.

Additional considerations

Memory-guided actions are executed countless times daily as they allow for the simultaneous involvement of the eyes and the hands in accomplishing tasks in our typically cluttered environments. The results of the present study provide new insight and direction for considering the obstacle avoidance strategies undertaken during memory-guided grasping. While we acknowledge the somewhat artificial nature of our experimental paradigm, we hope readers can appreciate the commonality and real-life applicability of such a setup, for instance, the next time one goes to maneuver between the many objects inside the refrigerator to grasp the sought-after bottle of ketchup remembered to be at the back of the first shelf. A logical next step would be for this study to be replicated with common household objects, as we understand differences in the obstacle avoidance patterns observed might emerge as the identities of potential obstacles are taken into account, relying on interactions between dorsal and ventral stream processing (Chapman and Goodale 2008; Gentilucci et al. 2001; de Haan et al. 2014; Menger et al. 2013),

The widths of obstacles did not result in exaggerated avoidance maneuvers in the context of our experimental paradigm. It seems the perceptual mechanisms of the ventral stream do not necessarily cause wider obstacles to be judged as more salient under memory guidance. Although a gap space of 20 cm between obstacles proved challenging enough, with a number of collision events recorded, it is possible wider obstacles would have incited more exaggerated avoidance strategies had the gap distance also been manipulated. Potentially, intermittently inserting narrower gap distances might provoke exaggerated avoidance behavior, as this would demand adjustments to the motor plan, utilizing accurate information about the visual scene, on a trial-by-trial basis. Along similar lines, it is possible that manipulations of the density or stability of obstacles might induce differential avoidance strategies under memory guidance, such that more care is taken to avoid knocking over a less stable obstacle or bumping one's hand into a very stiff obstacle on the way to the target object.

Conclusion

This study provides novel evidence for the obstacle avoidance strategies adopted under memory guidance. We found that memory-guided obstacle avoidance, under the presumed control of the ventral visual stream, is accomplished by adopting moderate, less variable eye–hand movements, rather than exaggerating the salience of obstacles obtrusive to the reaching hand. Future investigations are needed to examine how the properties of obstacles and the difficulty of the task might influence avoidance strategies under memory-guided conditions, pushing the boundaries of ventral stream control in obstacle avoidance paradigms.

Appendix

Table 1.

Table 1 Average maximum grip aperture (MGA), reach duration, and maximum wrist velocity

	Viewing condition				
		Closed loop (CL)	Open loop movement onset (OL-Onset)	Open loop short-delay (OL-SD)	Open loop long delay (OL-LD)
Maximum grip aperture (cm)	Close centered (CC)	9.62 (0.20)	9.59 (0.29)	9.99 (0.34)	10.51 (0.38)
	Far centered (FC)	9.52 (0.16)	9.69 (0.31)	10.07 (0.37)	10.57 (0.46)
	Close deviated (CD)	9.40 (0.16)	9.43 (0.27)	10.00 (0.35)	10.45 (0.37)
	Far deviated (FD	9.49 (0.16)	9.49 (0.31)	10.13 (0.37)	10.37 (0.39)
	Average	9.51 (0.17)	9.55 (0.29)	10.05 (0.36)	10.45 (0.40)
Reach duration (s)	Close centered (CC)	0.76 (0.02)	0.93 (0.06)	1.01 (0.09)	0.98 (0.06)
	Far centered (FC)	0.75 (0.02)	0.87 (0.05)	0.97 (0.09)	0.95 (0.06)
	Close deviated (CD)	0.74 (0.02)	0.92 (0.06)	1.03 (0.10)	1.01 (0.08)
	Far deviated (FD	0.73 (0.02)	0.94 (0.06)	0.97 (0.10)	0.98 (0.07)
	Average	0.74 (0.02)	0.91 (0.05)	0.99 (0.09)	0.98 (0.07)
Maximum wrist velocity (m/s)	Close centered (CC)	0.76 (0.03)	0.69 (0.05)	0.72 (0.04)	0.66 (0.02)
	Far centered (FC)	0.77 (0.03)	0.70 (0.05)	0.74 (0.05)	0.67 (0.03)
	Close deviated (CD)	0.74 (0.03)	0.71 (0.05)	0.68 (0.04)	0.60 (0.03)
	Far deviated (FD	0.77 (0.04)	0.70 (0.05)	0.73 (0.03)	0.63 (0.03)
	Average	0.76 (0.03)	0.70 (0.05)	0.71 (0.04)	0.64 (0.03)

Standard errors of the means presented in parentheses

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Availability of data, material, and code All data and materials as well as software application or custom code support our published claims and comply with field standards. Data and materials can be made available on request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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