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Gaze-Grasp Coordination in Obstacle Avoidance: Differences between Binocular and Monocular Viewing

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Abstract

Most adults can skillfully avoid potential obstacles when acting in everyday cluttered scenes. We examined how gaze and hand movements are normally coordinated for obstacle avoidance and whether these are altered when binocular depth information is unavailable. Visual fixations and hand movement kinematics were simultaneously recorded while 13 right-handed subjects reached-to-precision grasp a cylindrical household object presented alone or with a potential obstacle (wine glass) located to its left (thumb's grasp-side), right or just behind it (both closer to the finger's grasp-side) using binocular or monocular vision. Gaze and hand movement strategies differed significantly by view and obstacle location. With binocular vision, initial fixations were near the target's centre of mass (COM) around the time of hand movement onset, but usually shifted to end just above the thumb's grasp-site at initial object contact, this mainly be made by the thumb, consistent with selecting this digit for guiding the grasp. This strategy was associated with faster binocular hand movements and improved end-point grip precision across all trials than with monocular viewing, during which subjects usually continued to fixate the target closer to its COM despite a similar prevalence of thumb-first contacts. While subjects looked directly at the obstacle at each location on a minority of trials and their overall fixations on the target were somewhat biased towards the grasp-side nearest to it, these gaze behaviours were particularly marked on monocular vision-obstacle behind trials which also commonly ended in finger-first contact. Subjects avoided colliding with the wine glass under both views when on the right (finger-side) of the workspace by producing slower and straighter reaches, with this and the behind obstacle location also resulting in 'safer' (i.e., narrower) peak grip apertures and longer deceleration times than when the goal-object was alone or the obstacle was on its thumb-side. But monocular reach paths were more variable and deceleration times were selectively prolonged on finger-side and behind obstacle trials, with this latter condition further resulting in selectively increased grip closure times and corrections. Binocular vision thus provided added advantages for collision avoidance, known to require intact dorsal cortical stream processing mechanisms, particularly when the target of the grasp and potential obstacle to it were fairly closely separated in depth. Different accounts of the altered monocular gaze behaviour converged on the conclusion that additional perceptual and/or attentional resources are likely engaged compared to when continuous binocular depth information is available. Implications for people lacking binocular stereopsis are briefly considered.

Key words: Visual fixation, eye movements, reaching, visuomotor behaviour, stereopsis

Introduction

Most people are adept at avoiding potential obstacles during goal-directed actions in multi-object environments. When sitting at the dining table, for example, it is an everyday occurrence to successfully reach out and pick up a desired object – a salt pot, say – without colliding with any nearby non-target objects amongst the general clutter. A number of studies (e.g., Jackson et al. 1995, 1997; Tipper et al. 1997; Tresilian 1998; Kritikos et al. 2000; Mon-Williams and McIntosh 2000; Mon-Williams et al. 2001; Tresilian et al. 2001; Watt and Bradshaw 2002) have mimicked natural table-top settings of this kind to examine how reach-to-precision grasp movements are adapted in the presence of non-targets (a.k.a., 'flankers') in the workspace. These have revealed that actors have a repertoire of conservatively-principled anti-collision strategies at their disposal, with which to subtly alter spatial and/or temporal features of their movements compared to when the same goal-object is presented in isolation. One priority is usually given to maintaining a safe distance, this being achieved by programming a reach that veers slightly away from any potential obstruction(s) and an initial ('peak') grip opening that stays relatively narrow to avoid unwanted contact(s) during grasp formation. Another is to slow down and prolong the time available to acquire visual feedback, especially during the later (deceleration or grip closure) phase, which may be needed for adjusting the final approach to the intended target.

The current experiments aimed to extend this work in several important ways. Our first questions focussed on how gaze is deployed to facilitate successful grasping in obstacle avoidance. Specifically, where do adults subjects normally look when reaching to precision grasp isolated table-top objects? And do they use different gaze/fixation strategies in the presence of obstacles at different locations relative to the moving hand? These questions were prompted, in part, by our recent evidence (Melmoth and Grant 2012) supporting a long-standing suggestion that the thumb is employed as an on-line guide to initial contact when precision grasping isolated (cylindrical) table-top objects (Wing and Fraser 1983; Haggard and Wing 1997). Movement of the finger, by contrast, appeared mainly responsible for opening the initial grip aperture, while also avoiding a subsequent collision with the target's opposite, less visible, surface, both findings being in line with other recent evidence that collision avoidance is prioritized during single-object grasping too (Verheij et al. 2012, 2014a).

It is known that people fixate the intended target before and during movement of their hand towards it, often adopting a 'just-in-time' strategy, whereby gaze is directed to acquire feedback from a single grasp position shortly before contact (Land et al. 1999; Johansson et al. 2001; Flanagan et al. 2008). While gazing towards the finger's grasp position might satisfy key collision avoidance requirements in our table-top set-up, we speculated that fixations would more likely be attracted to thumb landing-site late in the movement in order to guide initial contact with the target, and had obtained some preliminary data in support of this possibility (see Fig.1).

[Figure 1, near here]

There is, however, more extensive and, apparently, contradictory evidence that the finger's landing-site – when this is the digit of first-contact – or, sometimes, the target's centre of mass (COM) are the regions selectively fixated during other precision grasping tasks (de Grave et al. 2008; Brouwer et al. 2009; Desanghere and Marotta 2011; Prime and Marotta 2013; Cavina-Pratesi and Hesse, 2013). Moreover, selection of the thumb or the finger as the guide to contact appears less dependent on whether their respective grasp-sites are visible and, hence, available for fixation (de Grave et al. 2008; Melmoth and Grant, 2012; Voudouris et al. 2012a), but more on the end-point grip orientation adopted, a postural constraint also known to be influenced by the presence of obstacles (Rosenbaum et al. 2001; Voudouris et al. 2012b; Verheij et al. 2014b). In this context, Mon-Williams and McIntosh (2000) have speculated that choosing the thumb or finger as the guide for coordinating grasping in multiple-object scenes might depend on the relationship between obstacle proximity to each digit's preferred contact-site. Their specific suggestions were that an obstacle located close to the thumb contact-side of the target might result in thumb guidance and fixation of its landing-site or, perhaps, the gap between this site and the nearby obstacle, and *vice versa* for an obstacle located near the finger's grasp position. Indeed, there are strong hints in the literature that collision avoidance strategies, such as reducing the peak grip, are enhanced when obstacles are located near the finger, compared to thumb, path to table-top objects (e.g., Jackson et al. 1995; Tresilian 1998; Mon-Williams et al. 2001), so gaze deployment may differ according to these flanker locations as well.

Our second questions related to other issues relevant to the mechanisms of hand action control in three-dimensional (3D) multi-object environments. Specifically, does the additional 3D scene and object information provided by binocular vision (e.g., from vergence and disparity; Mon-Williams and Dijkerman 1999; Bradshaw et al. 2004; Melmoth et al. 2007; Anderson and Bingham 2010) afford greater efficiencies for obstacle avoidance and, hence, lower the risk of collision, compared to the less 'certain', reduced-3D-cue conditions of monocular viewing? Given that binocular advantages have been repeatedly demonstrated for movement execution (increased speed, accuracy and precision) when normal adults are required to grasp objects presented in isolation (e.g., Servos et al. 1992; Servos and Goodale 1994; Watt and Bradshaw 2000; Bradshaw and Elliot 2003; Loftus et al 2004; Melmoth and Grant 2006), the likely answer would seem to be 'yes'. This conjecture is supported by the fact that the normal 'automaticity' of obstacle avoidance is contingent on intact dorsal stream-posterior parietal cortical functioning (McIntosh et al. 2004; Schindler et al. 2004; Rice et al. 2006), probably involving areas with privileged access to binocular 3D (e.g., near-space, absolute and dynamic disparity) information useful for hand movement programming and on-line guidance (Quinlan and Culham 2007; Verhagen et al. 2008, 2012; Gallivan et al. 2009; Srivastava et al. 2009; Cottereau et al. 2012).

But it is only partly supported by results obtained in the two studies that previously examined the issue. Jackson et al (1997) reported that the key advantages of binocular vision were only evident when adults reached-to-grasp an object in the presence of flankers. Their consistent findings were that monocular peak grip apertures were *selectively* increased for movements performed in a cluttered workspace, rather than to an isolated target, this greater risk of collision being further associated with *selectively* prolonged deceleration times (after peak velocity) indicative of increased 'uncertainty' approaching the goal-object when obstacles were present. Watt and Bradshaw (2002), though, found that general problems associated with monocular viewing – including wider peak grips and longer deceleration times (expressed as a percentage of movement duration after peak deceleration) – occurred to a similar extent when participants grasped objects presented alone or with one, two or even four non-targets nearby. The reasons for this discrepancy are not immediately clear as aspects of experimental design in the two studies were similar.

Our particular interest in this arises, in part, from the fact that a significant minority of adults lack binocular 3D vision, for reasons that include the persistent consequences of childhood amblyopia or eye-related disorders of more recent onset. Moreover, adults with binocular dysfunctions due to these conditions exhibit similar deficits when reaching to grasp isolated objects (e.g., Grant et al. 2007; Melmoth et al. 2009; Pardhan et al. 2011) to those of normal subjects forced to perform equivalent actions using one eye alone. This raises final questions as to whether sub-optimal gaze strategies are adopted when binocular vision is reduced or absent and whether this contributes to poorer hand action control. One possibility is that when the available 3D cues are monocular and mainly pictorial in nature, rather than fixating on a specific digit contact-site, gaze is preferentially directed to the target's COM. Such a 'decoupling' between fixations and grasp-points occurs during movements to remembered targets (Flanagan et al. 2008; Prime and Marotta 2013) and when subjects are just required to extract perceptual information about objects without a specific intention to act (Brouwer et al. 2009), processes thought to engage ventral, rather than dorsal, stream cortical representations.

Our present experiments were designed to answer these questions by combining gaze and hand movement recordings during reach-to-precision grasps performed under (blocked) binocular or monocular viewing conditions, otherwise analogous to the 'dining table' setting, outlined above.

Participants were given a brief (1 sec) preview of the task, allowing sufficient time for them to encode the visual scene and fixate the target, which was a household object (resembling the salt pot), before the imperative signal to begin their hand movement. This goal-object was presented at the same location within the upper comfortable range of adult arm's length, necessitating fairly large amplitude movements and affording substantial time to use feedback in order to acquire it. On different trials, the target was presented alone or with an obstacle – a real wine glass, to which a particularly high cost of collision would likely be ascribed (Tresilian 1998) – as a flanker, placed on its 'thumb-side' or 'finger-side' on the same horizontal plane or just behind it in the depth plane, this latter being hypothesized to pose a particular problem for avoidance with monocular viewing. The specific object-obstacle distances employed were different in each case, but were based on the spatial extents of the thumb and finger paths during typical movements to the isolated target and on reviews of equivalent data from previous related studies (e.g., Jackson et al. 1995, 1997; Tipper et al. 1997; Tresilian 1998; Kritikos et al. 2000; Mon-Williams and McIntosh 2000; Mon-Williams et al. 2001; Tresilian et al. 2001; Watt and Bradshaw 2002), indicating that the wine glass would be treated as an obstacle to the movements on each flanker trial without physically impeding them.

Materials & Methods

Participants

Thirteen adults (median age 23 years, 7 males) participated in the experimental procedures, conducted in accord with Declaration of Helsinki and local City University London ethical approval. Subjects were selected on the basis that they were strongly right-handed ($\geq$ +80), as assessed by an abbreviated version of the Edinburgh Handedness Inventory (Oldfield 1971); right eye dominant for monocular sighting; had normal or corrected-to-normal vision through contact lens wear; and possessed high-grade (at least 40 arc secs) binocular stereo acuity (Randot, Stereoptical Inc., Chicago, USA).

Procedures

The workspace was a black table (60 cm wide x 70 cm deep), well illuminated from above. Subjects sat at the table gripping a circular (3 cm diameter) button between thumb and index finger. The button was positioned 12 cm from the near table edge along their mid-sagittal plane, and served as the start and finish hand location for each trial. To facilitate the gaze recordings, head movements were constrained by an adjustable chin-rest. The same cylindrical object (4.8 cm diameter x 10 cm high) was the target on all trials. It was placed on a plinth (30 cm wide x 20 cm deep x 10 cm high) at a midline distance of 40 cm from the start button, such that its geometric COM was typically ~10-20 cm below eye level. The target was presented in isolation (control condition) or with the potential obstacle flanking it in one of three possible locations on the plinth, chosen so that they posed no physical obstruction to the moving hand. These locations were centered 6.5 cm (~9^o) to the left ('thumb side') of the target; 13 cm (~18^o) to the right ('finger side') of the target; or 10 cm directly behind it. Additional to our review of previous literature, we chose to double the relative separations between the target and the left/thumb-side *versus* right/finger-side obstacle locations, to allow sufficient space for the maximal deviations of each digit away from their contact sites to occur at peak grip and which are typically double the relative distance for the finger compared to the thumb (see Melmoth and Grant, 2012). Consistent trial-to-trial object and obstacle placements were achieved by aligning their lower centres with 0.5 cm diameter stickers attached to the upper plinth surface. When unoccupied by the obstacle, the stickers on either side of the target would have been within the subject's field of view.

Subjects closed their eyes between trials and opened them on verbal command from the experimenter who simultaneously triggered the hand movement recording. This contained a programmed delay of 1 sec permitting a preview of the scene, before an auditory tone was delivered as the cue for the subject to begin their reach. Participants were instructed to pick up the target at about half its height using a precision grip, place it on the table to their right, and return their hand to the start button. They were told to move as naturally as possible, with the specific counsel to avoid contact with the wine glass, when present. A number (typically 3-5/view) of practice trials were given prior to the main experiment, to ensure that the instructions were properly followed. Subjects completed 2 blocks of 20 experimental trials (4 obstacle conditions x 5 repeats); one block performed with normal binocular viewing and the other with their right (dominant) eye alone (left eye occluded with a black patch). Obstacle presentations in each block were in different pseudo-randomized orders, with viewing order counter-balanced between subjects. Obstacle avoidance was uniformly successful: none of the subjects collided with the wine glass in any of its 3 positions under either viewing condition.

[Table 1, near here]

Hand movement recordings and data processing

Participants wore passive lightweight infrared reflective markers attached to the thumbnail, index fingernail and to the head of the radius of the wrist of their right hand. Another marker was fixed to the centre of the upper surface of the goal object. Instantaneous movements of these markers in 3D space were tracked by three motion-capture units (ProReflex, Qualysis AB, Sweden) at a sampling rate of 66

Hz. The system was calibrated to a spatial resolution of <0.25 mm prior to each session, with the *x, y*, *z* coordinates of the markers representing their lateral, forward, and vertical axes, respectively. Recorded data were processed off-line using purpose-written routines in MATLAB software, which generated a number of dependent kinematic measures and 'profiles' of each movement.

We used established definitions (e.g., Melmoth and Grant 2006, 2012) to describe the movement onset (planning/programming) and duration (execution) times, along with different spatial and temporal features of the reach and the grasp expected to be altered by the demands of obstacle avoidance (see Table 1). In brief, the reach was analyzed from both its programmed (peak reach velocity; time to peak velocity; hand path length; lateral deviation) and later guidance components (final approach time), with a similar division between the programmed (time to peak grip; peak grip aperture) and feedback phases (grip closure time; grip size at contact; on-line grip adjustments immediately before or after contact; grip application time) applied to parameterization of the grasp. We also included three versions of the more general 'deceleration time' measure of feedback control (from peak velocity or from peak deceleration to object lifting and this latter as a percentage of total movement duration; Table 1) for direct comparability with Jackson et al (1997) and with Watt and Bradshaw (2002), respectively. In addition, several 'end-point' grip parameters (Table 1), including the digit making first-contact with the target; the contact asynchrony between the two digits (in which positive values represent thumb-first and negative values finger-first contacts); and the final grip orientation (in which 90^o is parallel to the subject's midline axis and 0^o corresponds to the horizontal plane) were determined from the locations of the thumb- and finger-tips at initial object contact and at the moments of minimum velocity of each digit, with reference to the *x,y* origin of the marker centred on the target. In this way, we could determine which spatiotemporal aspects of the two movement components were affected by the different obstacle locations and viewing conditions.

Gaze recordings and data processing

Gaze tracking used an infrared pupil-corneal reflex video-camera system (ISCAN RK-464, Iscan Inc., Burlington, USA) operating at a frame rate of 50Hz, to record the visual fixations of the subject's right (dominant) eye on each trial. The infrared source of this equipment was placed on the table ~20 cm (or ~30^o) to the left of the plinth from the subject's viewpoint and far enough away from the target (see Fig.4), that it was unlikely to be considered an obstacle and its reflections on the subject's corneal surface could not be interrupted by the path of their moving limb. Gaze directions were permanently recorded on DVD via a video camera mounted on a tripod over the subject's left shoulder, with a cross superimposed on the image defining their instantaneous point-of-regard (POR). The system was calibrated prior to each block of trials and at intervals of 6-7 trials within each block, as a check on tracking accuracy. The calibration procedure required the subject to sequentially fixate the centre and four corners of a rectangular surface (20 cm wide x 15 cm high) positioned on the same horizontal viewing plane as the target's centre. The rectangular device was then replaced by the target itself, and subjects were instructed to repeatedly move their gaze up and down the centre of the object (i.e., passing from the marker on its upper surface through its COM to the base of the target), and then to repeatedly look up and down its left-(thumb)-side and right-(finger)-side edges. These procedures resulted in determination of the POR with an accuracy of ±0.5 degrees of visual angle at the mean average viewing distance of ~50 cm (i.e., equivalent to 4-5 mm on the target).

The DVD footage of each subject's gaze data was first segmented into individual trials, from the first appearance of the POR at eye-opening to lifting of the object from the plinth, using VirtualDubMod (http://virtualdubmod.sourceforge.net) video-editing software. Purpose-written routines were used to record the x, z coordinates of the POR frame-by-frame for each trial. Dependent measures were the number and location of fixations occurring on each trial relative to the various x, z coordinates derived from the most temporally contiguous calibration procedure. Fixations were defined as stable points-of-regard within 0.5 degrees of visual angle (the limit of spatial accuracy of the system) between consecutive tracking frames. Gaze locations on the target were specified by dividing it into three equal (left, middle, right) vertical strips across its width. The two borders of the middle strip contained the object's COM, with the left and right sides including the thumb- and finger- contact sites, respectively. Formulae were applied to calculate the x, z positions of the tracked POR in each frame in relation to these boundary lines and to the target's COM. Fixations falling exactly on the borders of the middle strip were, conservatively, assigned to the central target zone. Gaze locations were analyzed for 5 specific time points in each trial with reference to the hand movement recording data obtained from the same trial. These were: (1) the first fixation on the target (which invariably occurred during the 1 sec interval between eye-opening and the auditory cue to move); and the fixations occurring at the moments that were temporally most contiguous with; (2) hand movement onset; (3) peak reach velocity; (4) peak reach deceleration; and (5) initial object contact.

Hand and gaze data analyses

Median values were calculated for each dependent measure of the hand actions in each subject by trial type and entered into separate two-factor (2 views x 4 obstacles) repeated-measures ANOVA, with application of the Huynh-Feldt correction for lack of sphericity, as necessary. Post hoc tests of significant main effects of obstacle were followed up using the Bonferroni adjustment for multiple pair-wise comparisons, with 1-way ANOVA employed to elucidate any view x obstacle interactions. Probabilities of $p<0.05$ were accepted as significant. Variants of these procedures were also applied to the gaze data, as given in the following text.

Results

We begin by summarizing the hand movement data obtained from our current subject group. We then examine their patterns of gaze deployment and relate these to our primary questions of how they were coordinated with their reach-to-grasp by viewing condition and obstacle location.

[Table 2, near here]

Reach-to-grasp performance: main effects of view and obstacle location

Table 2 presents the main effects of binocular *versus* monocular viewing and of obstacle location on our subject's hand movement kinematics. Times spent to movement onset in responding to the auditory 'go' signal and in the very first part of the reach up to peak velocity were unaffected by any experimental factor, suggesting that participants were in a similar state of preparedness after the preview. But their overall movement execution times (Fig.2) were affected by their view of the tasks ($F_{(1,12)}=29.8$, $p<0.001$). This occurred because movement durations were significantly prolonged (by ~125 ms) with monocular compared to binocular vision, due to increased time spent decelerating (on all 3 measures) and with contributions to this from each of its sub-phases, including the final approach to the target after peak deceleration and in closing and applying the grip (all $F_{(1,12)}\geq 9.2$, $p\leq 0.01$). With monocular viewing, participants also formed significantly wider (i.e., less accurate) grips at peak aperture and at initial object contact, and they made more on-line adjustments to their digit positions before and after contact than when binocular information was available (all $F_{(1,12)}\geq 9.3$, $p\leq 0.01$). We thus replicated data from a number of previous studies showing general advantages of binocular vision over one eye alone, especially for programming the grasp and for on-line movement guidance.

[Figures 2 & 3, near here]

In line with this, several programmed features of reach performance were affected equally under both views by the need to avoid the obstacle (Table 2; all $F_{(3,36)}\geq 5.7$, $p\leq 0.003$). Post hoc comparisons showed that all of these were solely caused by enhanced avoidance of the right/finger-side obstacle. With the wine glass in this location, subjects reduced their peak reach velocity (by $\leq$40 mm/s) while covering a slightly shorter (by ~7.5 mm) distance to acquire the target compared to when it was alone or the obstacle was located elsewhere ($p<0.01$ for all comparisons). Indeed, the subject's reach trajectories (Fig. 3) were notably straighter in this condition with reduced lateral deviations, that sometimes even veered slightly to the *left* of their midline (i.e., resulting in negative values for this parameter), compared to the more rightward curved paths produced on other trials, and they also selectively delayed (by ~50 ms) the opening time of their peak grip ($p<0.05$ for all comparisons).

These effects are all mutually consistent with maintaining a safe distance, as were differences in final grip orientations that occurred across all obstacle locations (Table 2; $F_{(3,36)}=24.9$, $p<0.001$), regardless of view. In fact, this parameter was the only one significantly affected by positioning the wine glass close to the left (thumb-) side of the target, whereby avoidance was achieved by applying the digits in a slightly ($p=0.048$) more counter-clockwise orientation (mean = 57.5^{o}) compared to the isolated object condition (mean = 54.7^{o}); that is, with the thumb rotated away from the obstacle. Although it was the more horizontal (i.e., rotated clockwise away from the obstacle) orientations (of 48-52^{o}) adopted in the finger-side and behind conditions that contributed most (both $p<0.001$) to the main flanker effect on this end-point grip parameter.

Binocular advantages for collision avoidance

There were also main effects of obstacle presence in prolonging movement durations ($F_{(3,36)}=4.2$, $p=0.025$), associated with the finger-side and behind wine glass locations. But more importantly, given our experimental questions, there was a significant obstacle by view interaction for this ($F_{(3,36)}=6.1$, $p=0.005$) and for several other measures, all of which were indicative of more proficient binocular performance. Specifically, this interaction resulted from greater effects of the finger-side and behind locations (both $p\leq0.001$) in prolonging monocular *versus* binocular execution times (by ~150-160 ms) compared to the smaller increases (both $p\leq0.032$) in monocular movements (of ~100-125 ms) occurring in the isolated target and thumb-side flanker conditions (Fig.2). Similar interactions occurred for the same reasons in relation to deceleration times (in milliseconds), both for the periods after peak velocity (c.f., Jackson et al. 1997; $F_{(3,36)}=3.6$, $p=0.025$) and after peak deceleration ($F_{(3,36)}=3.0$, $p=0.043$), although this latter, expressed as a percentage of movement duration (c.f., Watt and Bradshaw 2002), did not achieve significance ($F_{(3,36)}=2.3$, $p=0.11$). Further comparisons showed that the placing the wine glass behind the target caused added 'uncertainties' for on-line grasp control, because this location was solely responsible for the main effects of obstacle on increased grip closure times and adjustment rates occurring mainly with monocular viewing (Table 2).

In addition to these apparent advantages for on-line movement guidance, there was a further obstacle by view interaction for the programmed peak grip aperture ($F_{(3,36)}=3.9$, $p=0.026$). This arose because, whereas our subjects kept their peak grip equivalently narrow under both views when avoiding the finger-side and behind obstacles, they opened their digits equally wider (by 4-7mm) on monocular compared to binocular thumb-side flanker and target only trials (both $p<0.005$). That is, our subject's average avoidance behaviour with respect to maintaining a *safe distance* from the obstacles at each location when initially opening their digits was no different when using binocular or monocular vision. It is notable, however, that between-subject standard deviations were generally greater for most parameters during monocular movements (Table 2), an increased variability (i.e., reduced precision) that also applies to within-subject performance across repeated equivalent trials as well (e.g., Melmoth and Grant 2006). Because this propensity could increase the *risk* of collision, we sought evidence of obstacle x view interactions in further (unplanned) ANOVAs of the mean standard deviations by trial-type across subjects for some selected spatial parameters associated with this aspect of obstacle avoidance. These revealed significant interactions for two key measures of the reach (hand path length and lateral deviation; both $F_{(3,36)}>3.2$, $p<0.04$), but not for the grasp (e.g., peak grip aperture; end-point grip orientation). In both cases, the interaction was driven by greater within-subject variability on monocular compared to binocular trials involving the finger-side (x1.75-2.5) and behind (x1.25-1.5) obstacle locations, with no equivalent monocular effects (x0.9-1.15) for either the thumb-side or no obstacle conditions.

[Figures 4 & 5, near here]

Gaze-Hand Coordination

Gaze tracking was compromised in one subject due to loss and instability of point-of-regard data. Of the remaining participants, 10 made a number of separate (3-10) saccades and fixations on each trial, while the other 2 subjects locked their gaze, after the first fixation, on essentially the same target location near its COM, regardless of the view or obstacle conditions. This created a dilemma as to whether to include these 2 statistical 'outliers' in the analyses. The findings presented focus on the ~2500 fixations recorded in the 10 subjects who showed variety in their patterns of gaze deployment. Results of additional analyses that incorporated data from the two unusual subjects are also given in relation to our main findings, to indicate that their initial exclusion did not unduly influence the outcomes. Possible reasons for their marked 'centre-looking' behaviour are considered in Discussion.

As represented in Figures 4 and 5, the vast majority of all fixations were on the goal-object, from its initial acquisition shortly after the 'eyes open' instruction, to the point of first-contact by one or both digits. But gaze directions in the majority of subjects showed systematic changes in relation to different stages of their reach-to-grasp movements; participants typically (on ~62% of trials) fixated the middle region of the target (i.e., in the vicinity of its COM) at reach onset, but then increasingly shifted their gaze towards its thumb-side (and, particularly, away from the finger-side) as their reach progressed, so that fixations were more often near the eventual landing-site of the thumb at peak deceleration and stayed there during grip closure until initial object contact. When subjects looked directly at the obstacle (Fig.4B), which they did on 33.2% of the trials in which it was present, this occurred only once and typically in the period from just before hand movement onset to just after its peak velocity. They rarely directed their gaze at the wine glass during the late deceleration/grip closure phase of the movement (just 3 times, all on 'monocular-behind' trials) and only once fixated the gap between the obstacle and its nearest potential grasp-point (on a 'binocular thumb-side' trial).

[Figures 6 & 7, near here]

Effects of viewing condition and of obstacle location

ANOVA confirmed that gaze deployment changed with time between the first and last fixations during both binocular ($F_{(8,72)}$=8,7, *p*<0.001) and monocular ($F_{(8,72)}$=3.3, *p*=0.006) reach-to-grasps. However, as shown in Figure 5, the late shift in gaze towards the target's thumb-side appeared to be more marked with binocular than monocular viewing, as also indicated by a strong 3-way (view x time x gaze location) trend in the data ($F_{(8,72)}$=2.1, *p*=0.079). Inclusion of the other 2 subjects increased the proportion of overall mean fixations on the middle region of the target (by ~5-10%) from movement onset onwards, as would be expected, and mainly at the expense of the thumb-side averages, which were reduced at object contact to 44% and 33% for binocular and monocular viewing, respectively. But it did not materially affect the view-dependent trend in altered gaze location with time ($F_{(8,88)}$=2.0, *p*=0.088).

To examine this interaction further, we made separate plots of the locations of the first and last fixations on the target on each trial for each of the 10 subjects under each view. Figure 6 compares these data, with the elliptical regions depicting the majority ($\geq$90%) of the gaze locations in each case and with the mean fixation positions within these regions of 'best fit' shown for the two time points by view. As indicated here and in Table 3, the subject's first fixations were quite widely dispersed on the target (covering ~15-20% of its total surface area), but with their average locations within just a few mm ($\leq 0.5^{o}$) of the object's COM – both in its horizontal (x) and vertical (z) axes – irrespective of view. Fixations at initial object contact, by contrast, were more tightly focused and shifted in both a leftward and upward direction (all *p*<0.025), with those on binocular trials showing both a much smaller dispersion (view x time interaction; $F_{(1,9)}$=7.7, *p*=0.022) and greater total leftward/x-axis shift (~12 mm/3°) towards the thumb-side of the target (view x time interaction; $F_{(1,9)}$=37.6, *p*<0.001) compared to those made with monocular vision, these being still deployed more often within the target's central zone (c.f., Fig.5B). Again, inclusion of equivalent data from the 2 'outliers' did not affect the findings of significantly smaller final dispersion areas ($F_{(1,11)}$=6.0, *p*=0.032) or greater x-axis gaze shifts ($F_{(1,11)}$=18.5, *p*=0.001) on binocular *versus* monocular trials.

On average, the 10 participants made 1 additional fixation when viewing monocularly (7.1 ± 0.93 sd) compared to binocularly (6.0 ± 0.63 sd), with increased fixations also occurring on trials in which the wine glass was in the behind (6.9 ± 0.91 sd) or finger-side (6.6 ± 0.89 sd) positions compared to when it was absent (6.1 ± 0.71 sd), yielding main effects for both view ($F_{(1,9)}$=32.2, *p*<0.001) and obstacle ($F_{(3,27)}$=4.1, *p*=0.028). While these effects remained equally statistically significant across all 12 subjects, they were most likely trivial consequences of their increased hand movement durations – and, hence, gaze-tracking recording times – under these conditions. More interestingly, further analyses uncovered some subtle influences of obstacle location. First, separate ANOVA conducted for each view revealed significant effects on gaze locations (both $F_{(6,54)} \geq 3.7$, *p*=0.006; and $F_{(6,66)} \geq 3.5$, *p*≤0.009 for all 12 subjects) which occurred for the same reasons and in accord with one suggestion of Mon-Williams and McIntosh (2000); that fixations were attracted slightly more (by 9-11%) towards the target's left or thumb-side in the presence of the thumb-side obstacle *and* more towards (by 5-8%) its right or finger-side in the presence of the finger-side obstacle compared to the isolated object condition. Second, there was an obstacle x view interaction ($F_{(3,27)}$=5.1, *p*=0.015; and $F_{(3,33)}$=5.0, *p*=0.011 for all 12 subjects) for fixation numbers. This was mainly due to their *selective* increase on monocular-obstacle behind trials, a contributory factor being that gaze was attracted to the wine glass itself much (2-3x) more often in the majority of participants than when it was elsewhere during monocular viewing (Fig.7).

The digit(s) of first contact and their relationship with final gaze locations

As demonstrated by the mainly positive values obtained for contact asynchrony of the end-point grip (Table 2) and consistent with general use of the 'thumb as visual guide', the overall majority of first-contacts with the target were made by the thumb (63.5%) with similar smaller proportions of finger-first (20%) or simultaneous 'pincer' contacts by both digits (16.5%). There was, however, a main effect of view on mean contact asynchronies ($F_{(1,9)}$=4.9, *p*=007), whereby binocular vision was associated with consistently smaller (and less variable) positive (thumb-first) values for this parameter than when using one eye alone. Indeed, with monocular vision, the average contact asynchrony across participants was negative for the behind obstacle location. This resulted in a digit contact-type by obstacle interaction for monocular viewing ($F_{(6.54)}$=5.7, *p*=0.001) due to finger-first contacts being markedly increased on trials (n=18/50; 36%) in which the wine glass was behind the target compared to the other three (10-22%) obstacle conditions (all *p*<0.025). On 50% of these 18 monocular-behind trials, the last fixation was also on the target's finger-contact side, a 5-fold increase on the overall mean (~10%; Fig.5B) of such final gaze locations. This suggests increased adoption of a 'finger as visual guide' strategy to ensure that this digit avoided collision with the behind flanker located quite close to its grasp point towards the rear of the object on these trials in which reliable target-obstacle depth information was reduced.

Nonetheless, with binocular – but not monocular – viewing, there was also a near-significant digit contact-type by final gaze location interaction ($F_{(4,36)}$=3.0, *p*=0.067). The main contributor to this across all 12 participants was a roughly 2-fold increase in the relative proportion of synchronous pincer grips accompanying thumb- (23%) compared to finger-side (12.5%) final fixations at object contact. Since pincer-grip size is near-perfectly matched to the target's width, this would suggest that last-fixation directed towards the thumb's grasp position on the object represented a better gaze strategy for end-point grip precision than last-fixation on the finger contact-site. It is further consistent with the more accurate mean grip sizes at initial contact (Table 2) achieved with binocular compared to monocular vision by our participants, regardless of obstacle presence or location.

Discussion

Several of our current findings confirm and extend those from previous studies that have examined obstacle avoidance in reaching to precision grasp table-top objects under natural (i.e., binocular) viewing conditions. A common theme is that alterations to the movement kinematics in the presence of non-targets representing potential, rather than direct physical, obstructions to the moving limb or digits tend to be subtle, but achieve statistical traction because they are consistent and systematic within and between subjects, compared to their performance when the goal-object is presented alone. Another is that the alterations become more evident as the anticipated risk and/or cost of colliding with the potential obstacle increases, and involves decisions to maintain a 'safe distance' when planning the movement and to 'buy time' for enhancing on-line control of the moving hand by slowing down. Existing evidence (e.g., Jackson et al. 1997; Tresilian 1998; Mon-Williams and McIntosh 2000; Mon-Williams et al. 2001) further suggests that subjects ascribe a higher risk of collision and, hence, adopt more obvious avoidance behaviours, when potential obstacles are located on the same side of the goal-object through which the reaching hand would normally move to acquire it compared to flankers situated on its opposite side, even when these latter obstacles are physically much closer to the target. These spatial locations conform to the finger- and thumb-side wine glass positions, respectively, in our experiments. Indeed, our right-handed subjects reduced their peak reach velocity and produced straighter and shorter hand paths *only* when the obstacle was positioned to the right of the target. These altered reach trajectories represent sensible precautions in deviating their moving limb to a safe distance away from the obstacle to reduce the risk of collision.

But this obstacle location also resulted in a significant narrowing (c.f., Jackson et al. 1997; Tresilian 1998; Mon-Williams and McIntosh 2000; Mon-Williams et al. 2001) and delayed opening of their initial grasp at hand pre-shaping, followed by clockwise rotation of the end-point grip (Table 2), so that the finger landed more laterally on the object rather than travelling around to its rear, as in the isolated target condition. Why? We and others have shown (Schlicht and Schrater 2007; Melmoth and Grant 2012) that outward movement of the finger almost entirely accounts for the width of the peak grip aperture when subjects are preparing to precision grasp isolated table-top objects. We suggest that the smaller and later peak grips along with their altered end-point orientations in the presence of the finger-side obstacle resulted from a plan to maintain this digit at a safe distance throughout the movement, an unnecessary precaution for the thumb-side obstacle location due to the much straighter path typically adopted by the thumb in moving to its usual contact site (Wing and Fraser 1983; Haggard and Wing 1997; Melmoth and Grant 2012).

This major difference in thumb- compared to finger-side obstacle avoidance was, however, rather more marked than reported in previous work in which equivalent relative distances between the target and a (nearer) left/thumb-side *versus* (further) right/finger-side flanker were employed. Specifically, overall effects of the two obstacle locations were less and greater, respectively, than anticipated from this work. Several elements of our experimental design probably contributed to this. First, the close proximity of the obstacle when on the target's left, near the thumb's contact side, may have biased the participant's attention to that side of the goal object. In fact, post hoc analysis showed that with natural, binocular viewing, the wine glass more often attracted direct inspection (see Fig.7) when placed on the thumb- (~38%) compared to finger-side (~26%) of the target ($F_{(1,9)}=7.2$, $p=0.025$). This greater engagement of our subject's overt visuospatial attention in verifying its 'non-obstructive' location perhaps reducing a need to modify their movements. Conversely, when on the same side as their reaching limb, the wine glass remained in our subject's peripheral vision (at an eccentricity of ~18^{o}) before and during the majority of trials, while presumably also being associated with a higher cost of collision compared to the more neutral obstacles – typically wooden blocks or dowels – used in previous studies. Finally, it is also possible that our instruction to participants to place the goal-object to their right on the table after removing it from the plinth may have inadvertently biased their avoidance of the right-side obstacle location, since the ultimate intention of an action can influence its performance (Rosenbaum et al. 2001).

It has also been reported before (e.g., Tresilian 1998) that a potential obstacle located directly behind a goal-object mainly affects components of the grip kinematics. Our results confirm this as well (Table 2). With the wine glass behind the target, participants produced more cautious grasps, characterized by smaller peak grips followed by slower closure of their thumb and finger, compared to when the goal-object was alone, and even when binocular disparity information about relative target-obstacle depth was available to them. Their end-point grips were also systematically rotated clockwise, away from the obstacle, presumably because it posed a potential obstruction to the usual finger contact site towards the object's rear.

Against this background, the present study aimed to examine three main questions.

Does the additional 3D information provided by binocular vision afford benefits for obstacle avoidance compared to the reduced-3D-cue conditions of monocular viewing?

Performance was faster, more accurate and less variable when binocular vision was available for evaluating the scene and assembling the motor plan during the initial preview and for grasping the isolated target (c.f., Servos et al. 1992; Watt and Bradshaw 2000; Loftus et al 2004; Melmoth and Grant 2006). Indeed, there are potential advantages of two eyes over one for each of these processes, from access to extra binocularly-specific depth cues for more reliable statistical encoding of the target's 3D location and intrinsic properties (Landy et al. 1995; Keefe and Watt 2009) – to which the visuomotor system seems to attach a greater weighting during the formulation of appropriate motor responses (Knill 2005; Makris et al. 2013) – to their increased efficiency in mediating feedback for correcting movement errors on line (Servos and Goodale 1994; Jackson et al. 1997; Bradshaw and Elliot 2003; Greenwald et al. 2005). That we replicated evidence of these advantages over monocular vision, particularly for grip planning and guidance, was important, because our design employed only one target object which was always presented at the same location under only 4 different trial conditions. Participants, therefore, had ample opportunity to learn the properties of this small stimulus set on monocular blocked trials from the array of pictorial cues available to them, conditions which can reduce the consequences of removing binocular information during movement programming (Marotta and

Goodale 2001; Melmoth and Grant 2006; Keefe and Watt 2009). Following this argument, one might attribute the fact that movement onsets and times to peak reach velocity, which are accepted indicators of the programming efficiency, did not differ between obstacle conditions or views (Table 2) to such task familiarization. It should be noted, however, that these two particular parameters do not always exhibit the benefits of binocular vision that are consistently found for kinematics specifically associated with the end-phase reach or with the grasp (e.g., Servos et al. 1992; Watt and Bradshaw 2000, 2002; Marotta and Goodale 2001; Melmoth and Grant 2006; Keefe and Watt 2009).

In accordance with the intuition that such benefits might be accentuated in a more complex multi-object scene – that is, over and above those occurring when the target was alone – we obtained evidence for three main problems associated with monocular obstacle avoidance. First, reach paths were more variable with monocular than binocular vision for the right/finger-side and behind obstacle locations, this less consistent performance potentially increasing the collision risk. Second, deceleration times throughout the period after peak reach velocity were extended for these same two obstacle locations, perhaps reflecting a need to ameliorate the increased risk by exercising extra caution while navigating to the target. Third, and as we originally hypothesized, the behind-the-target-in-depth obstacle location posed additional problems for monocular viewing, during which our participants were denied access to potentially important motion parallax cues to relative target-obstacle depth (Watt and Bradshaw 2003) due to their head-restraint, and so were forced to rely mainly on pictorial 3D information. In line with evidence that binocular disparity processing has special significance for controlling the grasp (e.g., Bradshaw et al. 2004; Melmoth et al. 2007, 2009), these additional problems were manifest by selective increases in grip closure times and in late adjustments to the digit positions, compared to all other task conditions. We note that all of the above effects were also relatively subtle, even with a real wine glass as the flanker, and involved some movement parameters and/or a behind obstacle location not examined in otherwise similar previous (Jackson et al. 1997; Watt and Bradshaw 2002) or contemporaneous (Gnanaseelan et al. 2014) work that found little or no difference in binocular compared to monocular avoidance of less salient non-target objects.

Where do subjects normally look when reaching to grasp an isolated table-top object? And do they alter their gaze strategy in the presence of obstacles at different locations relative to the moving hand?

Our present study, as before (Melmoth and Grant 2012), used a cylindrical table-top target which was usually contacted first by the subject's thumb. With normal binocular viewing, our current participant's gaze clearly shifted horizontally as their hand movement progressed such that, on average, they were often looking towards the left/thumb grasp-side of the target just before and at initial object contact. This finding supports a generalization of the just-in-time principle for visually guided grasping to our particular ‘dining table’ set-up, whereby the object’s thumb-side was most often fixated late in the movement *because* the thumb was most often the digit that contacted it first. Importantly, this strategy would be further consistent with specific monitoring of the reducing (near/crossed) disparity between the moving thumb-tip and its fixated grasp-point, as the key source of information underlying the advantage of binocular vision for controlling the final approach to the target (Bradshaw et al. 2004; Melmoth et al. 2007; Anderson and Bingham 2010). The thumb is also known to move more directly to its landing site in our set-up, a site that was closer to the subject’s body than the finger’s grasp point. Other evidence, however, indicates that neither the relative directness of the digit’s trajectories (Volcic and Domini 2014) nor the proximity of their grasp points (Voudouris et al. 2012a; Cavina-Pratesi and Hesse 2013) strongly influence final fixation locations on the target or the particular digit that makes first-contact with it, so these factors are less likely explanations for the binocular gaze-grasp coordination that we observed. Another finding with normal viewing was that, on average, our subject’s gaze also shifted vertically during their hand movement so that final fixations were not exactly on the thumb’s landing site, but just above it; that is, this grasp site was generally within their lower, para-foveal vision. This was unexpected, but conforms to a suggested lower field advantage for visually guided movements associated with over-representation of the lower visual quadrant in several key areas of the dorsal stream ‘action’ pathway (Previc, 1990; Danckert and Goodale 2001).

Neither the presence nor location of the obstacle had major effects on the overall gaze strategy adopted when our subjects were viewing binocularly. We did, however, obtain support for the specific conjecture of Mon-Williams and McIntosh (2000) related to a likely flexibility in deploying the gaze for obstacle avoidance, in that final fixations were found to be attracted slightly, but significantly, more *towards* the left or the right sides of the target when the wine glass flanked its left/thumb- and right/finger-sides, respectively. This flexibility is evident in other aspects of our data; after all, gaze did not *always* shift to the left side of the target (Fig.5), but remained on its middle strip in a roughly equal number of trials. Indeed, the final fixations of one subject (S8) were on its right/finger-side on an unusually high proportion (30%) of binocular trials (Fig.6) and this was accompanied by an unusually high prevalence (40%) of finger-first contacts. From this we conclude that she quite commonly guided this digit, rather than her thumb, just as the finger’s grasp-side usually attracts late fixations when it is the chosen digit of first-contact in some other experimental designs (de Grave et al. 2008; Brouwer et al. 2009; Cavina-Pratesi and Hesse 2013).

The arguments erected above are linked to the fact that only the thumb's contact site on the goal-object was visible, which seems an obvious reason for selecting this digit for guidance rather than the finger. Yet there is clear evidence that occluding vision of the preferred grasp-site of first-digit contact on an object, including vertically-oriented cylinders, does not alter this preference or discourage subjects from looking towards it (de Grave et al. 2008; Voudouris et al. 2012a). These findings and the flexibility in gaze deployment that we observed suggest alternative explanations for the digit selected for first-object contact. A possibility is that the selection is for the one judged to be associated with minimizing the risk of colliding with the target and knocking it down during the attempted grasp. That is, the preference would be contingent on multiple factors related to the goal-object itself and its immediate environment, as well as differences in individual perceptions (e.g., subject S8) of the task specifics. Perhaps had we precariously balanced our target cylinder towards the back of the plinth, where thumb-first contacts could easily push it over the edge, more of our participants would have chosen to guide their finger to its safer, though invisible, contact-site.

Are different (sub-optimal) gaze strategies adopted under monocular viewing conditions that might contribute to poorer hand action control in single or multi-object scenes?

There were two major differences in the patterns of gaze deployment between normal and monocular viewing. One was that subjects looked more towards the target's COM throughout their hand movement when vision was restricted to one eye, such that leftward/thumb-side shifts in gaze were significantly reduced compared to when binocular disparity information was available (Table 3). By one account, this monocular fixation strategy could be conceived as more concerned with continuously up-dating information about the properties of the goal-object than with visually guiding the thumb, even though this was still, most often, the digit of first-contact. Fixation of an object's COM is reported to occur during its purely visual analysis (Brouwer et al. 2009) and in memory-guided grasping (Prime and Marotta 2013), both of which are associated with ventral stream processing mechanisms. Together these considerations suggest greater engagement of object-based processing during monocular viewing involving ventral/perceptual areas which, by themselves, have been shown to be poorly suited to the more automatic demands of on-line hand movement control in multi-object scenes (McIntosh et al. 2004; Schindler et al. 2004; Rice et al. 2006). That this predominant monocular gaze strategy was sub-optimal is supported by our above findings of significant binocular advantages for obstacle avoidance and by the fact that fixation near the thumb's grasp-site in the binocular condition was associated with generally improved end-point grip precision, as indicated by better calibration of grip-to-object size and thumb-finger contact synchrony.

The other difference was that gaze patterns were *selectively* altered in the monocular viewing-obstacle behind condition compared to all other task combinations. In this condition, fixations shifted more often towards, and ended on, the right side of the target, and were accompanied by increased finger-first contacts (e.g., negative mean contact asynchronies; Table 2) suggesting frequent guidance of safer finger placement to avoid hitting the wine glass when it is was close to this digit's usual grasp-point in depth. This approach also appeared quite effortful, though, in that, compared to all other tasks, the location of the wine glass was checked by direct fixation most often on monocular-behind trials (Fig.7) including, uniquely, on a few occasions during the very late deceleration/grip closure period, which was selectively prolonged and contained the most grip corrections.

Our gaze recordings were subject to some limitations that warrant consideration in these contexts. First, they were derived from tracking only the subject's right (dominant) eye. It is conceivable that this introduced biases in gaze directions resulting from (unmonitored) vergences during binocular viewing and/or from deviation (phoria) of the left eye that might naturally occur because it was behind a patch in the monocular condition. Were this deviation to have been in a consistently inward direction (i.e., esophoria) across subjects, the goal-object's apparent visual direction would be shifted slightly to the right, which corresponds to the more central (rightward) location of their mean final fixations with monocular compared to binocular vision. But, in agreement with recent evidence, no such gaze bias between views was present at first fixation or during the early phase of the subject's hand movements when such potential effects of phoria appear to have an influence (Gnanaseelan et al. 2014), so this is unlikely to account for our main findings regarding the later view-dependent gaze shifts. Second, the frame rate (50 Hz) used was relatively low and not electronically synchronized with the hand movement recordings (at 66 Hz). Although consequences were that the gaze location at any key 'moment' in the hand action on any given trial could be temporally non-contiguous by up to 3.33 ms and had to be extrapolated backwards in time from the gaze frame showing initial target displacement by digit contact (e.g., Fig.4D), none of these main findings are contingent on resolutions of <3.33 ms between the recordings. Third, we used an eye tracking system that is really designed to monitor gaze in the frontoparallel plane rather than in 3D space. The great majority of fixations recorded, however, were on the goal-object, which was situated on approximately the same 2D plane as that used to calibrate the system, as was the obstacle when it was in the two horizontal (thumb- and finger-side) locations. Only fixations on the wine glass in the behind location differed substantially from this plane and, under these circumstances, the subject's point-of-regard was clearly directed to a position well above the target (see Fig.4B), something that only occurred under this particular task condition.

We note, though, that the average number of fixations recorded across all trials, including when the target was presented alone, was around 3-times greater than usually reported in similar work involving the grasping of flatter 3D objects (e.g., Brouwer et al. 2009; Desanghere and Marotta 2011). It is possible that this latter technical limitation resulted in over-estimation of fixation numbers due to some local 3D 'instability' in determining our subject's point-of-regard. Because of this, we re-analyzed the data using a more conservative value of a 1 degree visual angle between consecutive gaze recording frames as the definition of stable points-of-regard, a procedure that reduced our estimate of the mean fixation numbers by a factor of ~25%, but made no difference to our main conclusions regarding the differences in binocular *versus* monocular gaze deployment.

These issues bring us now to deferred discussion of why two of our participants showed a further limitation, by just looking at the same central location on the goal-object for the entire duration of every single trial. A 'centre looking' approach is often used in the multiple-object tracking paradigm devised by Pylyshyn and Storm (1988). In performing this task, subjects commonly fixate the central region of 'empty space' between several moving targets, a gaze strategy reported to enhance tracking accuracy and to be consistent with a 'multifocal' division of attention (Tombu and Seiffert 2008; Fehd and Seiffert 2010). Such divided attentive tracking has further been shown to involve perceptual grouping of the targets into a coherent 'virtual' object (Yantis 1992) from which its COM is derived and to generate cortical activations that extend beyond parieto-frontal eye movement networks into ventral stream object processing-related areas (Culham et al 1998). One possibility is that our two extreme participants always, for whatever reason(s), employed an analogous strategy of dividing their attention equally to keep track of the two significant 'targets' either side of their central focus – that is, their moving thumb- and finger-tips. Indeed, such divided-attention could also account for the predominant 'centre looking' behaviour adopted by the majority of our other subjects when using one eye and is, perhaps, favoured by the fact that their monocular gaze shifted by the same degree as with normal viewing in the vertical (z axis) dimension of the target during the hand movement (Table 3), so that initial contacts by both digits also occurred within lower parafoveal vision.

This alternative account, however, converges on the same general conclusions to those above; that such monocular gaze strategies likely involve additional, effortful, neural resources, with the relative disengagement of automatic dorsal stream mechanisms implied by this contributing to generally poorer hand action control when continuous binocular vision is not available, conditions in which reach-to-grasp movements are also, selectively, susceptible to dual-task (cognitive) interference (Singhal et al 2007; Pardhan and Zuidhoek 2013). It would be interesting to determine whether people lacking normal binocularity for developmental or later acquired reasons exhibit impaired reach-to-grasp collision avoidance behaviours – as reported when such individuals step over obstacles (Buckley et al 2010) or drive on a 'slalom' course (Bauer et al 2001) – and whether sub-optimal gaze shifts during their hand movements contribute to any such difficulties.

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References

Anderson J, Bingham GP (2010) A solution to the online guidance problem for targeted reaches: proportional rate control using relative disparity τ. Exp Brain Res 205:291-306.

Bauer A, Dietz K, Hart W, Schiefer U (2001) The relevance of stereopsis for motorists: a pilot study. Graefe's Arch Clin Exp Ophthalmol 239:400-406.

Bradshaw MF, Elliot KM (2003) The role of binocular information in the 'on-line' control of prehension. Spat Vis 16:295-309.

Bradshaw MF, Elliot KM, Watt SJ, Hibbard PB, Davies IT, Simpson PJ (2004) Binocular cues and the control of prehension. Spat Vis 17:95-110.

Brouwer A-M, Franz VH, Gegenfurtner KR (2009) Differences in fixations between grasping and viewing objects. J Vision 9:1-24.

Buckley JG, Panesar GK, MacLellan MJ, Pacey IE, Barrett BT (2010) Changes to control of adaptive gait in individuals with long-standing reduced stereoacuity. Invest Ophthalmol Vis Sci 51:2487-2495.

Cavina-Pratesi C, Hesse C (2013) Why do the eyes prefer the index finger? Simultaneous recording of eye and hand movements during precision grasping. J Vision 13:1-15.

Cottereau BR, McKee SP, Ales JM, Norcia AM (2011) Disparity-tuned population responses from human visual cortex. J Neurosci 31:954-965.

Culham JC, Brandt SA, Cavanagh P, Kanwisher NG, Dale AM, Tootell RBH (1998) Cortical fMRI activation produced by attentive tracking of moving targets. J Neurophysiol 80:2657-2670

Danckert J, Goodale MA (2001) Superior performance for visually guided pointing in the lower visual field. Exp Brain Res 137:303-308.

de Grave DDJ, Hesse C, Brouwer A-M, Franz VH (2008) Fixation locations when grasping partly occluded objects. J Vision 8:1-11.

Desanghere L, Marotta JJ (2011) “Graspability” of objects affects gaze patterns during perception and action tasks. Exp Brain Res 212:177-187.

Fehd HM, Seiffert AE (2010) Looking at the center of the targets helps multiple object tracking J Vis 10:1-13.

Flanagan JR, Terao Y, Johansson RS (2008) Gaze behavior when reaching to remembered targets. J Neurophysiol 100:1533-1543.

Gallivan JP, Cavina-Pratesi C, Culham JC (2009) Is that within reach? fMRI reveals that human superior parieto-occipital cortex encodes objects reachable by the hand. J Neurosci 29:4381-4391.

Gnanaseelan R, Gonzalez D, Niechwiej-Szwedo E (2014) Binocular advantage for prehension movements performed in visually enriched environments requiring visual search. Frontiers Human Neurosci doi: 10.3389/fnhum.2014.00959

Grant S, Melmoth DR, Morgan MJ, Finlay AL (2007) Prehension deficits in amblyopia. Invest Ophthalmol Vis Sci 48:1139-1148.

Greenwald HS, Knill DC, Saunders JA (2005) Integrating visual cues for motor control: a matter of time. Vision Res 45:1975-1989.

Haggard P, Wing AM (1997) On the hand transport component of prehensile movements. J Mot Behav 29:282-287.

Jackson SR, Jackson GM, Rosicky J (1995) Are non-relevant objects represented in working memory? The effect of non-target objects on reach and grasp kinematics. Exp Brain Res 102:519-530.

Jackson SR, Jones CA, Newport R, Pritchard C (1997) A kinematic analysis of goal-directed prehension movements executed under binocular, monocular, and memory-guided viewing conditions. Vis Cogn 4:113-142.

Johansson RS, Westling G, Bäckström A, Flanagan JR (2001) Eye-hand coordination in object manipulation. J Neurosci 21:6917-6932.

Keefe BD, Watt SJ (2009) The role of binocular vision in grasping: a small stimulus-set distorts results. Exp Brain Res 194: 435-444.

Knill DC (2005) Reaching for visual cues to depth: the brain combines depth cues differently for motor control and perception. J Vis 5:103-115

Kritikos A, Bennett KMB, Dunai J, Castiello U (2000) Interference from distractors in reach-to-grasp movements. Q J Exp Psychol 53A:131-151.

Land MF, Mennie N, Rusted J (1997) The roles of vision and eye movements in the control of activities of daily living. Perception 28:1311-1328.

Landy MS, Maloney LT, Johnston EB, Young M (1995) Measurement and modeling of depth cue combination: in defense of weak fusion. Vision Res 35:389–412

Loftus A, Servos P, Goodale MA, Mendarozqueta N, Mon-Williams M (2004) When two eyes are better than one in prehension: monocular viewing and end-point variance. Exp Brain Res 158: 317-327.

Makris S, Grant S, Hadar AA, Yarrow K (2013) Binocular vision enhances a rapidly evolving affordance priming effect: behavioural and TMS evidence. Brain Cogn 83:279-287.

Marotta JJ, Goodale MA (2001) The role of familiar size in the control of grasping. J Cogn Neurosci 13:8-17

McIntosh RD, McClements KI, Dijkerman HC, Birchall D, Milner AD (2004) Preserved obstacle avoidance during reaching in patients with left visual neglect. Neuropyschologica 42:1107-1117.

Melmoth DR, Grant S (2006) Advantages of binocular vision for the control of reaching and grasping. Exp Brain Res 171:371-388.

Melmoth DR, Grant S (2012) Getting a grip: different actions and visual guidance of the thumb and finger in precision grasping. Exp Brain Res 222:265-276

Melmoth DR, Storoni M, Todd G, Finlay AL, Grant S (2007) Dissociation between vergence and binocular disparity cues in the control of prehension. Exp Brain Res 183:283-298.

Melmoth DR, Finlay AL, Morgan MJ, Grant S (2009) Grasping deficits and adaptations in adults with stereo vision losses. Invest Ophthalmol Vis Sci 50:3711-3720.

Mon-Williams M, Dijkerman HC (1999) The use of vergence information in the programming of prehension. Exp Brain Res 128:578-582.

Mon-Williams M, McIntosh RD (2000) A test between two hypotheses and a possible third way for the control of prehension. Exp Brain Res 134:268-273.

Mon-Williams M, Tresilian JR, Coppard VL, Carson RG (2001) The effect of obstacle position on reach-to-grasp movements. Exp Brain Res 137:497-501.

Oldfield RC (1971). The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologica 9:97-112

Pardhan S, Zuidhoek S (2013) Dual cognitive task affects reaching and grasping behavior in subjects with macular disorders. Invest Ophthalmol Vis Sci 54:3281-3288.

Pardhan S, Gonzalez-Alvarez C, Subramanian A (2011) How does the presence and duration of central visual impairment affect reaching and grasping movements? Ophthal Physiol Optics 31:233-239.

Previc FH (1990) Functional specialization in the lower and upper visual fields in humans: its ecological origins and neurophysiological implications. Behav Brain Res 13:519-575.

Prime SL, Marotta JJ (2013) Gaze strategies during visually-guided versus memory-guided grasping. Exp Brain Res 225:291-305.

Pylyshyn Z, Storm R (1988) Tracking multiple independent targets: evidence for a parallel tracking mechanism. Spat Vis 3:179-197.

Quinlan DJ, Culham JC (2007) fMRI reveals a preference for near viewing in the human parieto-occipital cortex. NeuroImage 36:167-187.

Rice NJ, McIntosh RD, Schindler I, Mon-Williams M, Demonet JF, Milner AD (2006) Intact automatic avoidance of obstacles in patients with visual form agnosia. Exp Brain Res 174:176-188.

Rosenbaum DA, Meulenbrook RJ, Vaughan J, Jansen C (2001). Posture-based motion planning: applications to grasping. Psychological Review 108:709-734.

Schlinder I, Rice NJ, McIntosh RD, Rossetti Y, Vighetto A, Milner AD (2004) Automatic avoidance of obstacles is a dorsal stream function: evidence from optic ataxia. Nat Neurosci 7:779-784.

Schlicht EJ, Schrater PR (2007) Effects of visual uncertainty on grasping movements. Exp Brain Res 182:47-57.

Servos P, Goodale MA, Jakobson LS (1992) The role of binocular vision in prehension: a kinematic analysis. Vision Res 32:1513-1521.

Servos P, Goodale MA (1994) Binocular vision and the on-line control of human prehension. Exp Brain Res 98:119-127.

Singhal A, Culham JC, Chinellato E, Goodale MA (2007) Dual-task interference is greater in delayed grasping than in visually guided grasping. J Vis 7:1-12.

Srivastava S, Orban GA, De Mazière PA, Janssen P (2009) A distinct representation of three-dimensional shape in macaque anterior intraparietal area: fast, metric and coarse. J Neurosci 29:10613-10626.

Tipper SP, Howard LA, Jackson SR (1997) Selective reaching to grasp: evidence for distractor interference effects. Vis Cognit 4:1-38.

Tombu M, Seiffert A (2008) Attentional costs in multiple-object tracking. Cogn 108:1-25.

Tresilian JR (1998) Attention in action or obstruction of movement? A kinematic analysis of avoidance behavior in prehension. Exp Brain Res 120:352-368.

Tresilian JR, Mon-Williams M, Coppard VL, Carson RG (2001) The effect of obstacle position on reach-to-grasp movements. Exp Brain Res 137:497-501.

Verhagen L, Dijkerman HC, Grol MJ, Toni I (2008) Perceptuo-motor interactions during prehension movements. J Neurosci 28:4726-4735.

Verhagen L, Dijkerman HC, Medendorp WP, Toni I (2012) Cortical dynamics of sensorimotor integration during grasp planning. J Neurosci 32:4508-4519.

Verheij R, Brenner E, Smeets JBJ (2012) Grasping kinematics from the perspective of individual digits: a modelling study. PLoS One 7 (3):e33150. doi:10.1371/journal.pone.0033150

Verheij R, Brenner E, Smeets JBJ (2014a) The influence of target object shape on maximum grip aperture in human grasping movements. Exp Brain Res

Verheij R, Brenner E, Smeets JBJ (2014b) Why does an obstacle just below the digits’ paths not influence a grasping movement while an obstacle to the side of their paths does? Exp Brain Res 232:103-112.

Volcic R, Domini F (2014) The visibility of contact points influences grasping movements. Exp Brain Res 232:2997-3005.

Voudouris D, Smeets JBJ, Brenner (2012a) Do humans prefer to see their grasping points? J Motor Behav. 44:295-304.

Voudouris D, Smeets JBJ, Brenner (2012b) Do obstacles affect the selection of grasping points? Human Movement Sci. 31:1090-1102.

Watt SJ, Bradshaw MF (2000) Binocular cues are important in controlling the grasp but not the reach in natural prehension movements. Neuropsychologica 38:1473-1481.

Watt SJ, Bradshaw MF (2002) Binocular information in the control of prehensile movements in multiple-object scenes. Spat Vis 15:141-155.

Watt SJ, Bradshaw MF (2003) The visual control of reaching and grasping: binocular disparity and motion parallax. J Exp Psychol Hum Percept Perform 29:404-415.

Wing AM, Fraser C (1983) The contribution of the thumb to reaching movements. Q J Exp Psychol 35A:297-309.

Yantis S (1992) Multielement visual tracking: attention and perceptual organization. Cog Psychol 24:295-340.

Table 1: **Definitions of reach and grasp parameters**

Dependent Measures	Definition
General Kinematics	
Movement onset time (ms)	From auditory "go signal" to wrist velocity first exceeding 50mm/s
Movement duration (ms)	From movement onset to object lifting (target displaced $\geq$ 10 mm)
Deceleration time (1) (ms)	From peak reach velocity to movement end (object lifting)
Deceleration time (2) (ms)	From peak deceleration to movement end (object lifting)
Deceleration time (2) %	The post-peak deceleration time as a percentage of movement duration
Reach Parameters	
Peak reach velocity (mm/s)	Maximum wrist velocity before object contact
Time to peak velocity (ms)	From movement onset to maximum wrist velocity
Hand path length (mm)	Length of wrist trajectory from movement onset to end
Lateral path deviation (mm)	Average deviation of the wrist trajectory in the lateral (x) axis from a straight line between its start and the target's centre
Final approach time (ms)	From peak deceleration to initial object contact (target displaced $\geq$ 1 mm)
Grasp Parameters	
Peak grip aperture (mm)	Maximum aperture between thumb and finger before object contact
Time to peak grip aperture (ms)	From movement onset to maximum grip aperture
Grip closure time (ms)	From maximum grip aperture to initial object contact
Grip size at contact (mm)	Aperture between thumb and finger at initial object contact
Grip application time (ms)	From initial object contact to lifting
On-line grip adjustments	Additional opening or alterations in digit positions occurring between peak aperture and object lifting
End-Point Grip Parameters	
Digit of First Contact	Digit nearest the target centre at initial contact
Contact Asynchrony (ms)	Difference in initial time to contact (minimum velocity) of each digit after peak grip aperture and before object lifting
Final Grip Orientation (deg)	Angle between the initial thumb and finger contact points on the object with respect to the fronto-parallel plane (x axis)

Table 2. Mean (± SD) hand movement kinematics by viewing and obstacle conditions

Dependent Measures	View	Obstacle				F-statistics	
		None	Thumb	Behind	Finger	Obstacle: ($F_{3,36}$)	View: ($F_{1,12}$)
General Kinematics							
Movement onset time (ms)	Binocular	490 ± 104	545 ± 100	507 ± 89	498 ± 108	1.3, *p*=0.3 (ns)	3.0 *p*=0.1 (ns)
	Monocular	541 ± 89	546 ± 166	537 ± 108	551 ± 126		
Movement duration (ms)	Binocular	933 ± 133	986 ± 113	960 ± 130	954 ± 131	**4.2, *p*=0.025**	**29.8, *p*<0.001**
	Monocular	1059 ± 132	1079 ± 132	1117 ± 156	1103 ± 136		
Deceleration time (1) (ms)	Binocular	604 ± 132	664 ± 111	628 ± 126	631 ± 131	**6.6, *p*=0.003**	**23.9, p<0.001**
	Monocular	725 ± 131	750 ± 133	788 ± 166	774 ± 134		
Deceleration time (2) (ms)	Binocular	449 ± 120	502 ± 77	465 ± 114	468 ± 141	**4.7, *p*=0.007**	**33.8, p<0.001**
	Monocular	577 ± 120	614 ± 132	656 ± 149	612 ± 107		
Deceleration time (2) (%)	Binocular	48 ± 8	50 ± 4	48 ± 5	49 ± 6	1.7, *p*=0.2 (ns)	**30.9, p<0.001**
	Monocular	54 ± 6	56 ± 6	56 ± 7	55 ± 5		
Reach Parameters							
Peak reach velocity (mm/s)	Binocular	976 ± 89	937 ± 86	964 ± 88	903 ± 87	**13.9, *p*<0.001**	2.7, *p*=0.1 (ns)
	Monocular	930 ± 133	922 ± 107	925 ± 103	858 ± 93		
Time to peak velocity (ms)	Binocular	328 ± 26	337 ± 40	332 ± 37	323 ± 35	0.0, *p*=0.9 (ns)	3.2, *p*=0.08 (ns)
	Monocular	333 ± 40	338 ± 54	322 ± 40	324 ± 37		
Hand path length (mm)	Binocular	403 ± 19	407 ± 25	405 ± 21	395 ± 18	**5.7, *p*=0.003**	1.8, *p*=0.2 (ns)
	Monocular	416 ± 37	413 ± 35	413 ± 35	408 ± 27		
Lateral deviation (mm)	Binocular	17 ± 16	19 ± 14	15 ± 14	8 ± 15	**14.3, *p*<0.001**	1.3, *p*=0.3 (ns)
	Monocular	16 ± 15	18 ± 10	11 ± 15	7 ± 10		
Final approach time (ms)	Binocular	298 ± 106	325 ± 49	324 ± 97	325 ± 128	2.1, *p*=0.1 (ns)	**9.2, *p*=0.01**
	Monocular	368 ± 94	379 ± 104	410 ± 140	396 ± 93		
Grasp Parameters							
Peak grip aperture (mm)	Binocular	83 ± 7	83 ± 5	81 ± 7	81 ± 6	**6.0, *p*=0.008**	**9.3, *p*=0.01**
	Monocular	90 ± 9	87 ± 8	84 ± 10	84 ± 11		
Time to peak grip aperture (ms)	Binocular	587 ± 64	620 ± 87	601 ± 74	623 ± 86	**6.3, *p*=0.003**	0.6, *p*=0.5 (ns)
	Monocular	601 ± 74	610 ± 74	608 ± 80	661 ± 83		
Grip closure time (ms)	Binocular	194 ± 74	209 ± 40	218 ± 76	198 ± 79	**3.7, *p*=0.032**	**14.8, *p*=0.002**
	Monocular	243 ± 70	251 ± 62	303 ± 119	244 ± 70		
Grip size at contact (mm)	Binocular	58 ± 4	59 ± 3	59 ± 4	59 ± 4	0.8, *p*=0.5 (ns)	**9.8, *p*=0.009**
	Monocular	63 ± 4	62 ± 4	62 ± 4	62 ± 5		
Grip application time (ms)	Binocular	152 ± 45	152 ± 32	143 ± 43	149 ± 43	0.2, *p*=0.9 (ns)	**64.7, *p*<0.001**
	Monocular	206 ± 41	218 ± 46	222 ± 55	211 ± 47		
Grip adjustments (rates/trial)	Binocular	0.1 ± 0.3	0.2 ± 0.4	0.7 ± 0.8	0.0 ± 0.0	**6.4, *p*=0.001**	**16.2, *p*=0.002**
	Monocular	0.8 ± 1.0	1.0 ± 1.4	1.6 ± 1.4	0.7 ± 0.6		
End-point Grip Parameters							
Contact Asynchrony (ms)	Binocular	15 ± 44	17 ± 40	13 ± 35	23 ± 33	0.3, *p*=0.6 (ns)	**4.9, *p*=0.007**
	Monocular	21 ± 63	42 ± 63	-21 ± 71	50 ± 60		
Final Grip Orientation (deg)	Binocular	55 ± 10	57 ± 8	52 ± 9	49 ± 11	**24.9, *p*<0.001**	0.5, *p*=0.5 (ns)
	Monocular	54 ± 8	58 ± 6	50 ± 8	48 ± 9		

Table 3. Mean (+ SD) first *versus* last fixations by viewing condition

Dependent Measures	**View**	**1st Fixation**	**Last Fixation**	**F-statistics**
Gaze Position (x axis) (mm)	Binocular	+2.8 (±6.1)	-9.4 (±6.5)	Time $F_{(1,9)}$ 8.3, ***p*=0.018**
	Monocular	+3.5 (±4.5)	+0.8 (±8.2)	View x Time $F_{(1,9)}$ 37.6, ***p*<0.001**
Gaze Position (z axis) (mm)	Binocular	+4.9 (±6.2)	+15.6 (±5.1)	Time $F_{(1,9)}$ 7.5, ***p*=0.023**
	Monocular	+4.4 (± 4.9	+15.6 (±4.1)	View x Time $F_{(1,9)}$ 0.1, *p*=0.93 (ns)
Gaze Area (mm^2)	Binocular	906 (±319)	334 (±105)	Time $F_{(1,9)}$ 15.0, ***p*=0.004**
	Monocular	794 (±339)	562 (±140)	View x Time $F_{(1,9)}$ 7.7, ***p*=0.022**

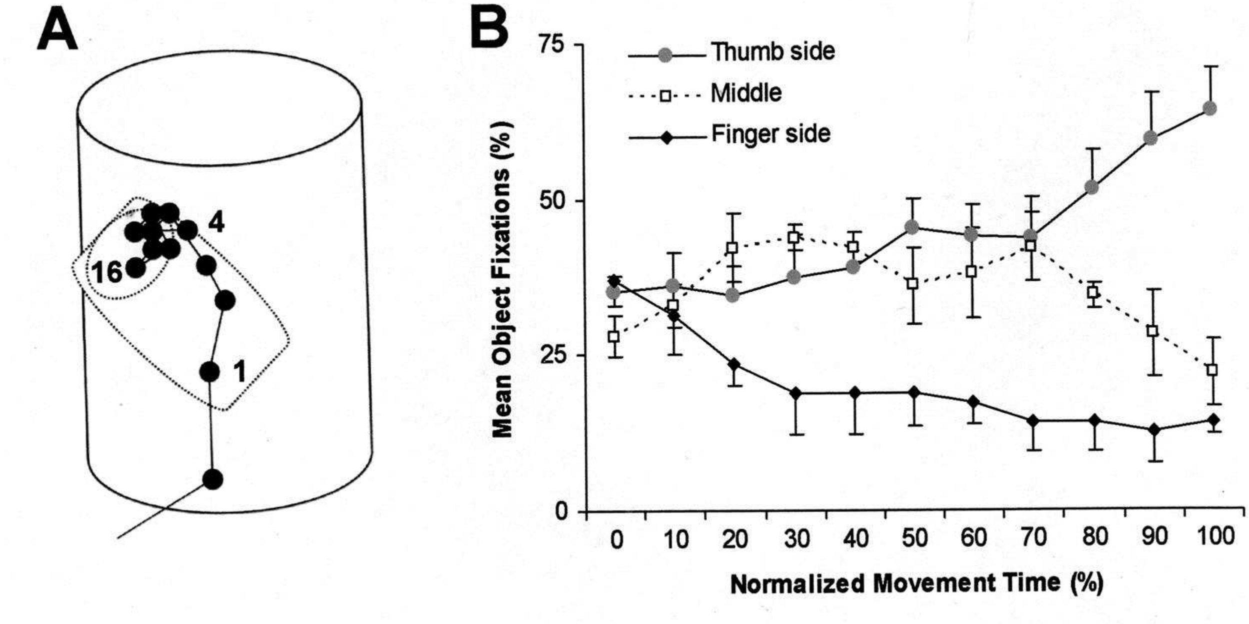

Figure 1: Changing visual fixations during precision grasping. Pilot data from 2 subjects (one right-handed, one left-handed) in which gaze deployment (by the eye ipsilateral to their preferred hand) was recorded (at 25 Hz) using a head-mounted eye-tracking system (iViewX HED, TrackSys) while they reached-to-precision grasp the same target used in the present experiments using binocular vision. (**A)** Example of sequential (frame-by-frame) fixation locations (filled circles) recorded from the right-handed subject on a representative trial. Gaze location 1 occurred (after the first fixation below it; no preview given) and just before movement onset; gaze location 16 was the final fixation at the moment of initial target contact made by the thumb (schematically outlined). **(B)** Average proportions of the fixations made by both subjects on the thumb-contact side, middle region and finger-side of the target with respect to the normalized durations of each hand movement (n=64 trials), from its onset (at 0%) to initial target contact (at 100%). Error bars, SEM. On average, gaze was increasingly directed towards the thumb side of the object, with ~50-70% of fixations on or near the thumb landing-site during the period of grip closure (between ~70-100% of movement time) compared to only 10-15% of fixations on the finger side during this same period. This was not due to attention being selectively drawn to a more salient target feature intrinsic to the thumb landing-site, since this was on opposite sides of the object for the 2 subjects due to their differing hand preference.

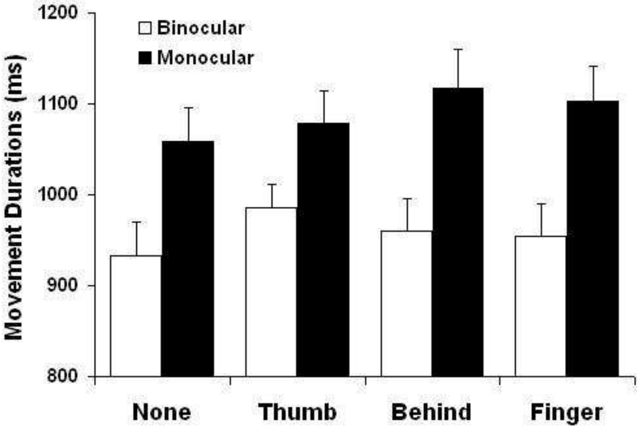

Figure 2: Average movement durations by obstacle and viewing condition. Error bars, SEM.

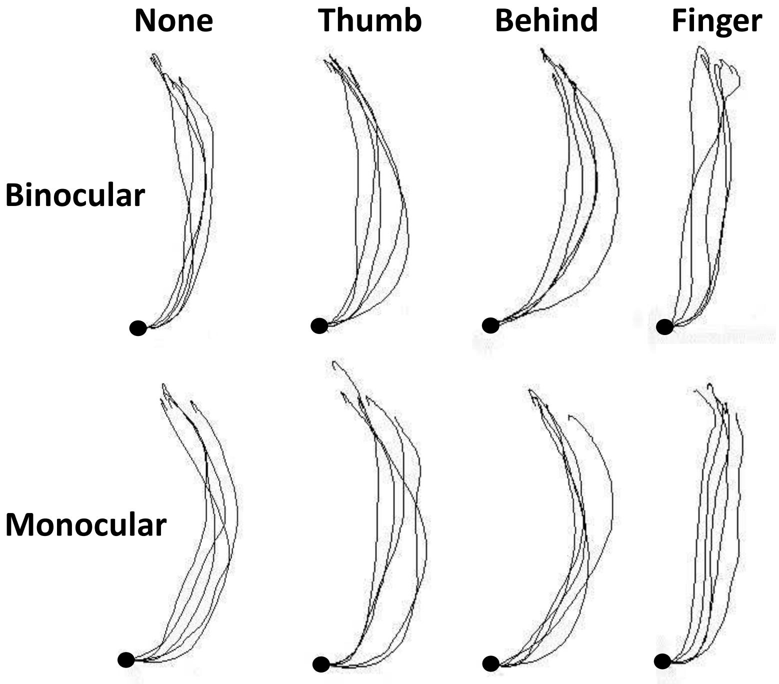

Figure 3: Representative reach trajectories by obstacle and viewing condition. Each panel shows the spatial paths of the wrist marker recorded in one subject, from his starting hand position (filled circle, bottom of traces) to the movement end-point, during each of the 5 reaches made under binocular (top row) and monocular (bottom row) viewing in each obstacle condition. Note the relative straightness of the trajectories when the wine glass was present on the finger/right side of the target.

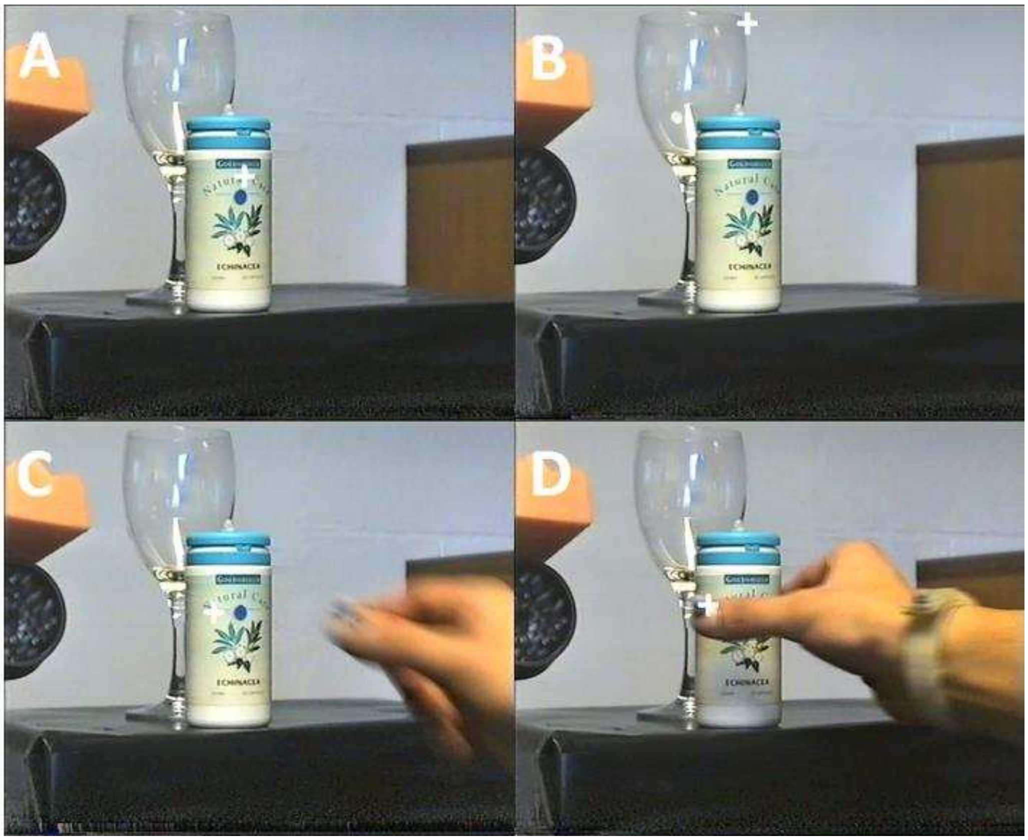

Figure 4: Representative gaze-hand recording frames. Panels show the gaze location (white cross) of the right eye in one subject at different times during a single reach-to-grasp of the target object (pill bottle) with the obstacle (wine glass) in the behind position on the raised black plinth: **(A)** movement onset; **(B)** peak velocity; **(C)** peak deceleration; **(D)** just before initial object contact. Note: fixation was were on the middle of the target close to its centre of mass in (A), on the obstacle in (B), towards the thumb-contact side of the target in (C), and just above the tip of the thumb in (D). The black structure on the extreme left in each frame is the IR source of the eye-tracking equipment; the orange structure is a shield preventing interference with the hand movement recordings from this IR source.

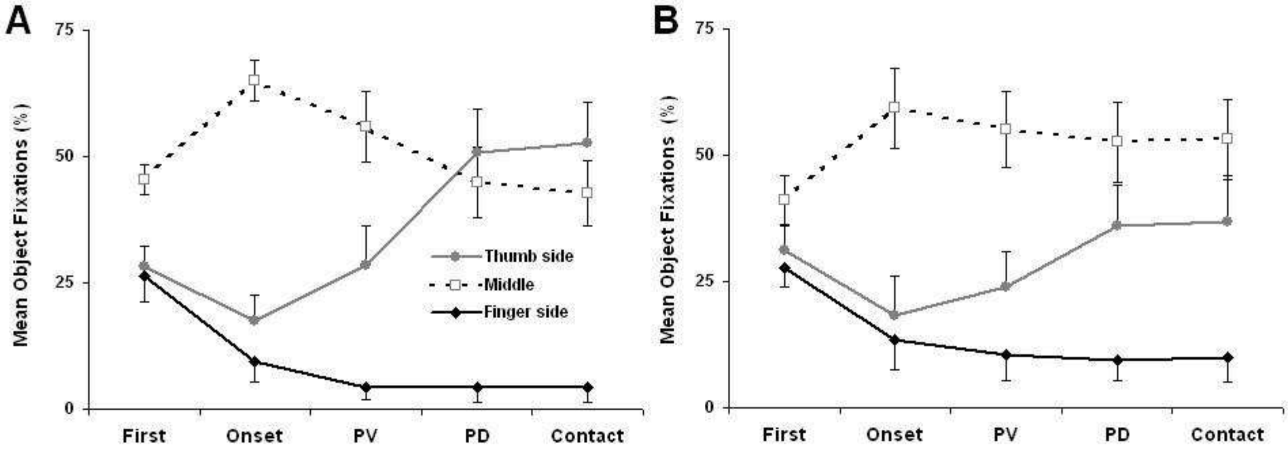

Figure 5: Changing visual fixations during precision grasping. Average proportion of gaze locations on the thumb-contact side, middle region and finger-contact side of the target at 5 landmark stages; from the first fixation on the object, and at the times of hand movement onset, its peak reach velocity (PV) and peak deceleration (PD), to the last fixation at initial object contact by one or both of the subject's digits under **(A)** binocular and **(B)** monocular viewing conditions. Error bars, SEM. Note: percentages at Onset, PV and PD do not sum to 100% under either viewing condition, because subjects were occasionally fixating the obstacle at these three time-points.

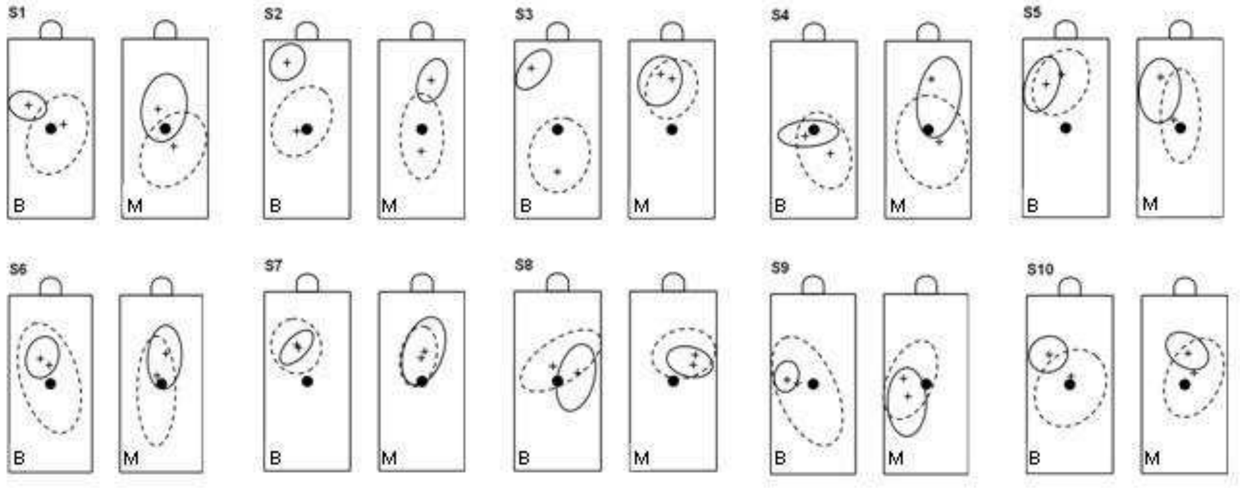

Figure 6: First compared to last fixation locations by viewing condition. Paired rectangles represent the goal object (with its central hemispheric IR marker shown on top) and show the changes in fixation pattern with binocular (B) and monocular (M) viewing that occurred for each of the 10 participants (S1-S10). The target's geometric centre of mass is indicated by the filled (black) circle. Dotted ellipses indicate the envelope of first fixations in each case, with the cross contained inside representing the mean location of the first fixation on the target prior to hand movement onset. The ellipses in continuous outline indicate the envelope of last fixations in each case, with the cross contained inside representing the mean location of the final fixation recorded at initial object contact.

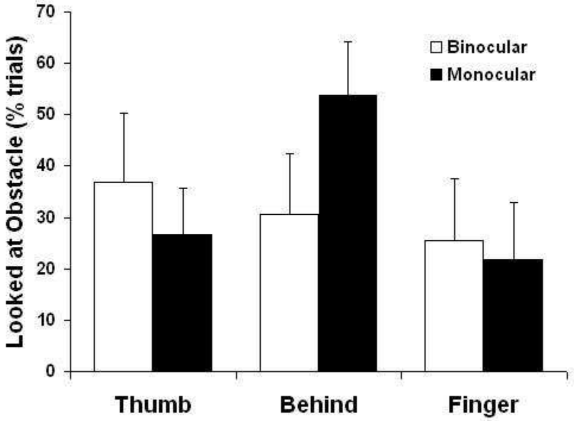

Figure 7: Average proportion of trials in which subjects fixated the obstacle. Error bars, SEM.