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Research Report

The behavioural consequences of dissociating the spatial directions of eye and arm movements

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ABSTRACT

Many of our daily movements use visual information to guide our arms toward objects of interest. Typically, these visually guided movements involve first focusing our gaze on the intended target and then reaching toward the direction of our gaze. The literature on eye-hand coordination provides a great deal of evidence that circuitry in the brain exists which can couple eye and arm movements. Moving both of these effectors towards a common spatial direction may be a default setting used by the brain to simplify the planning of movements. We tested this idea in 20 subjects using two experimental tasks. In a "Standard" condition, the eyes and a cursor were guided to the same spatial location by moving the arm (on a touchpad) and the eyes in the same direction. In a "Dissociated" condition, the eye and cursor were again guided to the same spatial location but the arm was required to move in a direction opposite to the eyes to successfully achieve this goal. In this study, we observed that dissociating the directions of eye and arm movement significantly changed the kinematic properties of both effectors including the latency and peak velocity of eye movements and the curvature of hand-path trajectories. Thus, forcing the brain to plan simultaneous eye and arm movements in different directions alters some of the basic (and often stereotyped) characteristics of motor responses. We suggest that interference with the function of a neural network that couples gaze and reach to congruent spatial locations underlies these kinematic alterations.

1. Introduction

During everyday reaching movements, we typically look toward the object we intend to interact with. In fact, when subjects are presented with several visual targets for eye and hand movements, they virtually always move both their eyes and limb to the same target, even without receiving specific instructions to do so (Gielen et al., 1984). The motor control literature contains a large amount of evidence indicating that there is a very close relationship between the control of eye and arm movements within the brain.

Many behavioural studies have revealed examples of the link between the control of eye and limb movements. For example, examinations of visually guided reaching have demonstrated that reaching movements are less accurate when we do not look at the target for the arm movement (Prablanc et al., 1979; Vercher et al., 1994; Henriques et al., 1998). In addition, the spatial location of eye fixation strongly

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influences target selection for reaching movements (Scherberger et al., 2003). There is also evidence that arm movements performed simultaneously with eye movements alter the kinematic characteristics of the eye movements. For example, peak eye velocity has been shown to be higher for saccades that accompany limb movements than for saccades performed on their own (Epelboim et al., 1997; Snyder et al., 2002). Neggers and Bekkering (2000, 2001) have also reported an interesting phenomenon of eye-hand coordination that they have termed “gaze anchoring”. Subjects were instructed to make simultaneous eye and arm movements to visual targets. However, the subjects were further instructed to initiate secondary saccades to any new targets that appeared during ongoing reaching movements without changing the course of their limb. The authors found that subjects were unable to initiate saccades towards the secondary targets until the ongoing arm movement to the first target was completed, suggesting that the brain actively stabilizes our gaze during reaching movements. Dynamically, visual tracking of a target can be improved when an individual simultaneously tracks the target with their hand (Koken and Erkelens, 1992; Steinbach and Held, 1968). Also, while smooth pursuit eye movements generally require the presence of a visible target, subjects can smoothly pursue movements of their own hand in the dark (Gauthier and Hofferer, 1976), indicating that the oculomotor system receives proprioceptive information about limb movements even when the moving arm is not visible. These examples of how characteristics of eye and arm movements are influenced by one another suggest that the neural circuitry controlling eye and arm movements are linked together.

Shared neural circuitry could underlie some of the mutually influential effects of eye and hand movements. For example, subcortically, the activity of a small population of superior colliculus (SC) and reticular formation cells is related to arm movements (Werner, 1993; Werner et al., 1997b), and in some cases the temporal pattern of this activity correlates well with electromyographic recordings from arm muscles (Stuphorn et al., 1999, 2000; Werner et al., 1997a). In the cerebral cortex, gaze-related modulation of activity can be observed in premotor (Boussaoud et al., 1998; Boussaoud and Bremmer, 1999; Mushiake et al., 1997) and parietal reach-related cells (Batista et al., 1999; Battaglia-Mayer et al., 2001). Also, some neurons within the supplementary eye field (which is generally considered an eye movement-related region) are more active for saccades accompanied by arm movements than for saccades alone (Mushiake et al., 1996). Further dramatic evidence of a possible coupling of eye and arm movements by neural circuitry was demonstrated in a clinical examination of a patient with parietal cortex damage who demonstrated “magnetic misreaching” (Carey et al., 1997). In this case study, the patient was unable to reach away from the location of foveal fixation, indicating that the parietal region could have a role in suppression of neural circuitry that typically acts to couple the spatial locations of eye and arm movements.

Typical visually guided movements possess stereotyped characteristics. For example, the eyes tend to begin their movement before the onset of the arm movement (likely in part due to the differences in inertia between these two effectors) (Prablanc et al., 1979), hand-path trajectories tend to be fairly straight in allocentric coordinates (Morasso, 1981; Sergio and Scott, 1998), and velocity profiles of both the eye and the arm tend to be unimodal and bell-shaped (Abend et al., 1982; Morasso, 1981). If the putative circuitry coupling the eyes and the arm does indeed exist, then it is likely involved in producing the well-stereotyped characteristics of visually guided movements, as well as linking the movement direction for both effectors. This may occur perhaps as a means of optimizing the accuracy of arm movements, or of simplifying the motor planning. Therefore, disrupting this default eye-hand circuitry by spatially dissociating the directions of eye and arm movements should result in changes to some or all of these stereotyped properties of visually guided movement. This hypothesis was tested in the current study by examining the behavioural consequences of dissociating the directions of eye and arm movements during well-trained, simple, visually guided reaching movements. Although visual stimuli and feedback were identical in the two conditions, we observed significant effects of dissociating eye and arm movement directions on the characteristics of motor output from both the eyes and the arm. Specifically, moving the eyes and arm in opposite directions significantly altered basic movement properties, including the curvature of hand paths and the peak velocities of both the eyes and the arm.

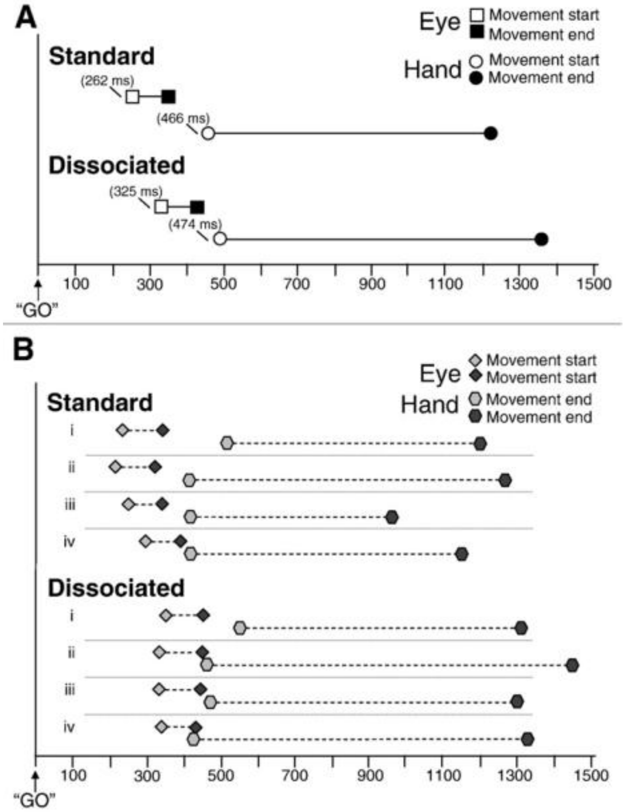

Fig. 1 – (A) An illustration of mean reaction and movement times for all subjects after the go signal for the eye and arm in the Standard and Dissociated conditions. (B) Reaction and movement times for four individual subjects (i, ii, iii, and iv) for the eye and arm in the Standard and Dissociated conditions.

2. Results

Two experimental conditions were examined. In the Standard condition, subjects moved their eyes and their arm in the same direction. In the Dissociated condition, subjects moved their eyes to a cued spatial location, but their arm to a location 180° in the opposite direction. Visual cues and feedback were identical in the two conditions. The effects of each condition on movement kinematics are described in the following sections.

2.1. *Reaction and movement times of the eye and arm*

The latency of eye movements (i.e. reaction time) significantly differed between the Standard condition and the Dissociated condition ($F_{1,1052}=140.9$, $p<0.001$), despite the fact that the eye movement requirements of the two conditions were identical. The mean eye reaction time (eye RT) for the Standard condition was 262 ms ± standard deviation of 87 ms. Mean eye RT in the Dissociated condition was significantly slower at 325 ± 125 ms (Fig. 1). In contrast, no significant effect of condition was observed on arm reaction time (arm RT). Mean arm RT in the Standard condition was 466 ± 151 ms and 474 ± 165 ms in the Dissociated condition. Thus, a significant difference between the eye and arm movement onsets was observed ($F_{1,1052}=70.8$, $p<0.001$) such that during the Standard condition, eye movements preceded arm movements by 180 ± 138 ms, while in the Dissociated condition, eye movement onset only occurred 119 ± 179 ms before arm movements.

An effect of condition on the time it took subjects to complete arm movements (i.e. movement time) was also observed ($F_{1,1152}=86.0$, $p<0.001$). Mean arm movement time (arm MT) during the Standard condition was 744 ± 213 ms. Mean arm MT in the Dissociated condition was significantly longer at 885 ± 249 ms. There was no significant effect of condition on eye movement time (eye MT). Mean eye MT in the Standard condition was 88 ± 17 ms and was 88 ± 18 ms in the Dissociated condition. Average reaction and movement time results are summarized in Fig. 1A. Fig. 1B demonstrates examples of reaction and movement time data from individual subjects. In addition, Fig. 2B provides a comparison of mean latencies, movement times, and velocities for the eye and arm in both conditions.

2.2. *Peak velocity of eye and arm movements*

In general, the velocity profile of eye movements was bell-shaped and unimodal with a steep acceleration phase to a peak velocity followed by a steep deceleration phase. The velocity profiles of arm movements were also unimodal (see Fig. 2B for group mean velocity profiles). A significant effect of condition on peak velocity was observed in both eye and limb movements. The mean (±SD) peak velocity of arm movements made during the Standard condition was 12.5 ± 3.2 cm/s. Peak arm velocity in the Dissociated condition was significantly slower at 11.4 ± 3.1 cm/s ($F_{1,969}=83.4$, $p<0.001$). A significant

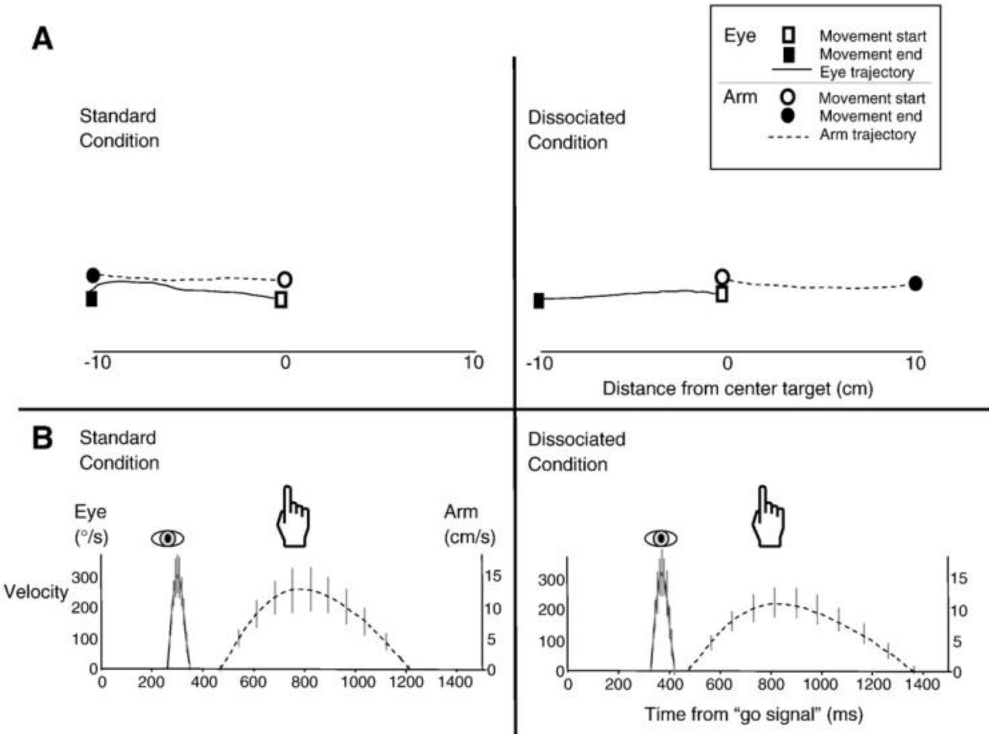

Fig. 2 – (A) Sample trajectory data for the eye and arm in individual trials of the Standard (left) and Dissociated (right) conditions. The trajectory data demonstrates that eye and arm movements were made in the same direction in the Standard condition but in opposite directions in the Dissociated condition. (B) Mean velocity profiles (solid line for the eye and dashed line for the arm) for group data from both conditions. Error bars represent standard deviation.

effect of condition on peak eye velocity was also observed. The mean peak velocity of eye movements during the Standard condition reached 304 ± 87 °/s. Interestingly, the peak velocity of the eye reached during the Dissociated condition was 310 ± 83 °/s, which was significantly *faster* than the velocity reached in the Standard condition ($F_{1,891} = 4.14$, $p < 0.05$).

2.3. Curvature of trajectories

The curvature of arm and eye movement trajectories for each trial was assessed using calculations of linearity ratio (see methods). Perfectly straight movements would have a ratio of 0.0, while a semicircular path would have a ratio of 0.5. Trials containing multiple movements or corrections were removed from the analysis. Therefore, all hand paths included in the analysis for both conditions formed one continuous movement. In general, hand-path and eye-path trajectories were fairly straight in both conditions (Fig. 3A and Fig. 4A, respectively). However, both hand-path and eye-path linearity ratios were significantly greater than zero for both conditions (hand Standard: $t_{956} = 64.70$, $p < 0.001$; hand Dissociated: $t_{502} = 52.75$, $p < 0.001$; eye Standard: $t_{736} = 36.38$, $p < 0.001$; eye Dissociated: $t_{636} = 32.95$, $p < 0.001$), indicating that neither effector produced perfectly straight movements. Significant differences in the curvature of hand paths made during the two experimental conditions were observed ($F_{1,811} = 145.24$, $p < 0.001$). The mean linearity ratio of hand paths for all target locations was 0.0285 ± 0.013 in the Standard condition and 0.049 ± 0.021 (i.e., more curved) in the Dissociated condition. Post-hoc comparisons of hand-path curvature at individual target locations also revealed significant differences related to condition in all of the movement directions tested (Fig. 3B). Specifically, the mean curvatures of movements to the upward target were 0.027 ± 0.013 for the Standard condition and 0.042 ± 0.020 for the Dissociated condition ($p < 0.001$). For the downward target, mean curvature of hand paths was 0.029 ± 0.014 and 0.044 ± 0.018 for the Standard and Dissociated conditions respectively ($p < 0.001$). The mean linearity ratio for the left target in the Standard condition was 0.034 ± 0.017 and 0.053 ± 0.027 in the Dissociated condition ($p < 0.001$). For the target located on the right, mean curvature of movements was 0.028 ± 0.013 and 0.043 ± 0.019 for the Standard and Dissociated conditions respectively ($p < 0.001$). Thus, the hand-path curvatures were 1.5 to 2 times greater during the Dissociated conditions across targets. The calculation of linearity ratio

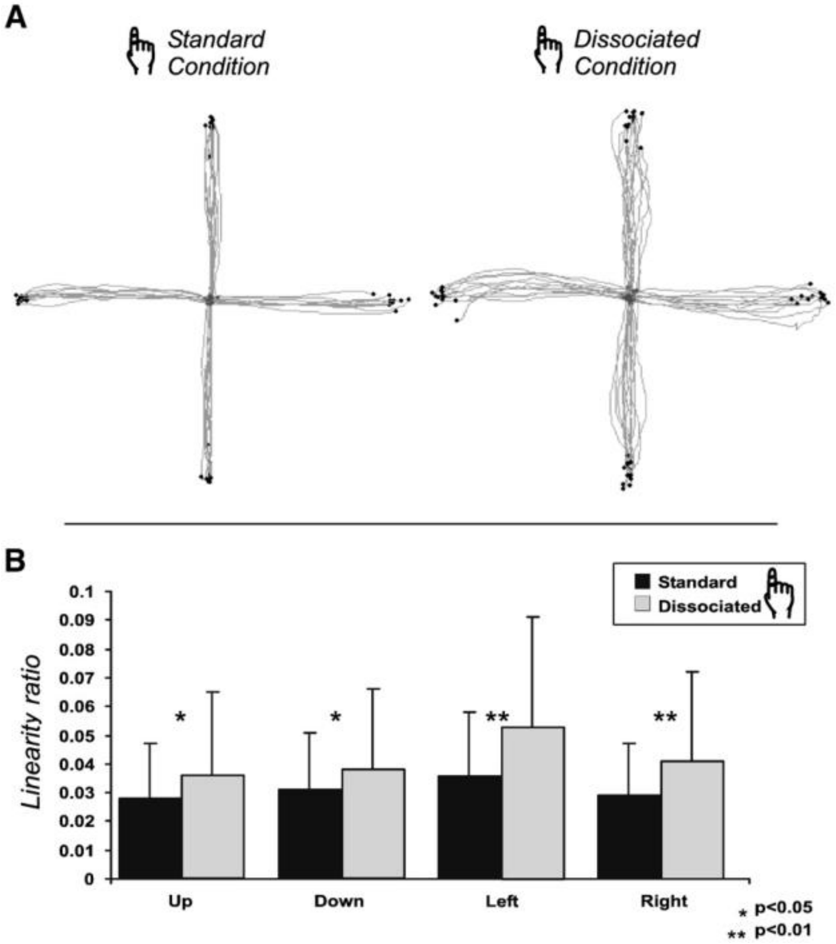

Fig. 3 – (A) Sample hand-path trajectories for one subject in single blocks of the Standard condition (left) and Dissociated condition (right). (B) Histogram illustrating the mean linearity ratios of hand-path trajectories made to each target location for all subjects in both conditions. Error bars represent standard error of the mean.

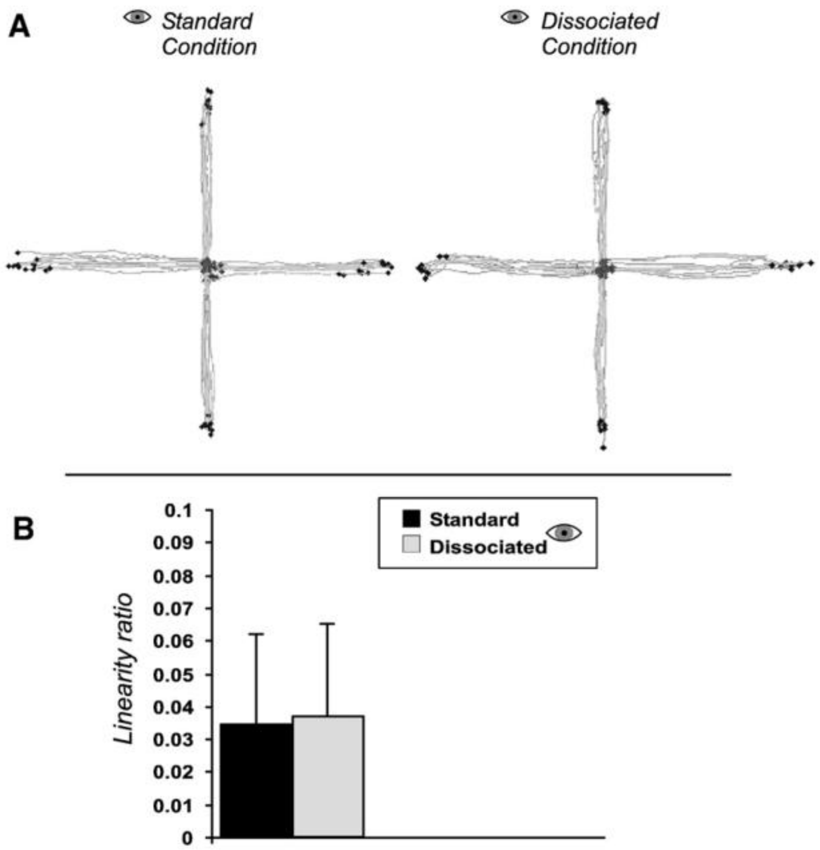

Fig. 4 – (A) Sample eye-path trajectories for one subject in single blocks of the Standard condition (left) and Dissociated condition (right). (B) Histogram illustrating the mean linearity ratios of eye trajectories for each condition (not significantly different). Error bars represent standard error of the mean.

indices does not take the direction of hand-path curvature into account. Upon examination of the arm trajectories of individual movements made by each subject, there does not appear to be a systematic nature to the direction of curvature for the arm movements. However, this observation was not directly quantified. An example of the variability of movement curvature direction for a single subject can be seen in Fig. 3A. The results of the hand trajectory linearity ratio index comparisons for all directions are summarized in Fig. 3B. We observed that the curvature of eye movement trajectories did not significantly differ between conditions ($F_{1,596}=0.74$, $p=0.39$). The mean linearity ratios of eye trajectories were 0.035 ± 0.027 and 0.037 ± 0.029 in the Standard and Dissociated conditions respectively (Fig. 4B).

In a secondary analysis, correlation coefficients were calculated between group mean linearity ratios and the trial number of arm movements made in the Dissociated condition. No significant correlation was observed ($R=-0.07$, $p=0.54$) indicating that participants' movements did not become progressively less (or more) curved over the course of the experimental session.

2.4. *Accuracy and precision of eye and limb movements*

Comparisons of the constant errors (horizontal and vertical components) and variable errors (horizontal and vertical components as well as resultant values) of the endpoints of arm and eye movements made in the two experimental conditions did not reveal any significant differences. Thus, overall, no systematic differences in the accuracy (i.e. Constant Error) or precision (i.e., Variable Error) of movements made by the eye or the arm were observed between the conditions examined. The results of these comparisons are presented in Table 1.

2.5. *Effects of sex and subject*

Sex and subject were included in the repeated-measures ANOVA comparisons as between-subject factors. In all of the variables examined in the sections above, there were no significant effects of sex (eye RT: $F_{1,1}=2.88$, $p=0.09$; eye-arm RT difference: $F_{1,1}=0.03$, $p=0.86$; arm MT: $F_{1,1}=2.42$, $p=0.12$; arm velocity: $F_{1,1}=2.07$, $p=0.15$; eye velocity: $F_{1,1}=1.44$, $p=0.23$; arm linearity ratio: $F_{1,1}=0.23$, $p=0.63$; constant and variable error statistics listed in Table 1). However, individual subjects displayed significant variability in many of the variables examined (eye RT: $F_{1,18}=6.52$, $p<0.001$; eye-arm RT difference: $F_{1,18}=15.1$, $p<0.001$; arm MT: $F_{1,18}=13.69$, $p<0.001$; arm velocity: $F_{1,18}=5.64$, $p<0.01$; eye velocity: $F_{1,18}=6.46$, $p<0.001$; arm linearity ratio $F_{1,18}=2.6$, $p<0.001$; VE horizontal eye: $F_{1,18}=2.73$, $p<0.001$). There were no significant effects of subject variability for most of the

Table 1 – Mean constant and variable errors for the arm and eye in the Standard and Dissociated conditions.

Variable	Effector/direction	Standard	Dissociated	Statistical comparison	Between-subjects factors	
					Sex	Subject
CE	Arm — horizontal	0.1±2.4 mm	0.6±2.5 mm	$F_{1,147}=2.22$, $p=0.14$	$F_{1,1}=0.4$, $p=0.53$	$F_{1,18}=0.8$, $p=0.70$
	— vertical	0.5±2.9 mm	−0.1±3.2 mm	$F_{1,147}=2.72$, $p=0.10$	$F_{1,1}=0.16$, $p=0.69$	$F_{1,18}=0.62$, $p=0.88$
	Eye — horizontal	−0.5±1.6°	−0.1±2.3°	$F_{1,99}=0.21$, $p=0.65$	$F_{1,1}=2.65$, $p=0.11$	$F_{1,18}=0.41$, $p=0.98$
	— vertical	0.1±1.4°	−0.5±2.0°	$F_{1,99}=1.90$, $p=0.17$	$F_{1,1}=0$, $p=0.97$	$F_{1,18}=1.2$, $p=0.29$
VE	Arm — horizontal	3.6±1.9 mm	3.5±1.8 mm	$F_{1,147}=0.04$, $p=0.83$	$F_{1,1}=2.15$, $p=0.14$	$F_{1,18}=0.65$, $p=0.85$
	— vertical	3.3±1.5 mm	3.5±1.8 mm	$F_{1,147}=0.73$, $p=0.39$	$F_{1,1}=0.08$, $p=0.77$	$F_{1,18}=0.89$, $p=0.59$
	— resultant	3.4±1.4 mm	3.7±1.7 mm	$F_{1,147}=2.63$, $p=0.11$	$F_{1,1}=1.91$, $p=0.17$	$F_{1,18}=1.45$, $p=0.12$
	Eye — horizontal	0.9±0.4°	0.9±0.5°	$F_{1,99}=0.27$, $p=0.61$	$F_{1,1}=2.34$, $p=0.13$	$F_{1,18}=2.73$, $p<0.001$
	— vertical	1.1±0.7°	1.4±1.1°	$F_{1,99}=0.26$, $p=0.61$	$F_{1,1}=0.32$, $p=0.58$	$F_{1,18}=0.61$, $p=0.87$
	— resultant	0.8±0.4°	0.8±0.3°	$F_{1,99}=0.17$, $p=0.69$	$F_{1,1}=1.81$, $p=0.18$	$F_{1,18}=1.55$, $p=0.10$

measurements of accuracy and precision of the endpoints of movements (Table 1).

3. Discussion

This study examined the behavioural consequences of dissociating the spatial directions of eye and arm movements. This dissociation resulted in changes to stereotyped characteristics of movements made by both effectors. These data support our hypothesis that dissociating the movement directions of the eyes and arm causes a disruption in a default brain network which normally acts to couple eye and arm movements. In the following sections, we contextualize these results and discuss where in the brain such a default network may reside.

3.1. *Movement latency, duration, and velocity*

The mean onset of eye movements made in the Dissociated condition was significantly later than those made in the Standard condition. This delay suggests that dissociating eye and arm movement directions requires additional planning compared to movements of both effectors in the same direction. Past studies have revealed close relationships between several kinematic aspects of saccadic eye movements. Correlations exist such that saccadic duration, average velocity and peak velocity all increase as the amplitude of the saccade increases (Bahill et al., 1975; Baloh et al., 1975). The relationship between these parameters is referred to as the “main sequence” (Bahill et al., 1975). Interestingly, we observed that peak eye velocity was significantly faster in the Dissociated condition compared with the Standard condition, in spite of the fact that the amplitude of eye movements made in each condition did not significantly differ.

While this observation seems counterintuitive, Epelboim et al. (1997) observed that differences in saccadic duration (between two different tasks) were only significant for saccades that were greater than 20° in amplitude. Saccadic eye movements made in the present study were approximately 15° in amplitude, which may explain why we failed to observe changes in saccadic duration related to condition.

The difference in peak eye velocities we observed could be an effect of dissociating eye and arm movements on the main sequence. These results suggest that separating eye-arm coordination triggers changes in the basic properties of the control of eye movements.

Our data do not allow us to draw specific conclusions regarding why peak eye velocity is higher in the Dissociated condition. However, it is possible that eye movements are sped up to compensate for the longer eye reaction time during the Dissociated condition. In spite of a longer eye latency in the Dissociated condition, the eye typically still arrived at the target location prior to the onset of arm movement (which was not significantly delayed), meaning that visual information was stabilized before arm movements were made without requiring a delay in arm movement onset. Thus, the increased eye velocity could be a means of compensating for the increased neural planning required to dissociate the eye and arm.

3.2. *Curvature and variability of hand paths*

In general, the hand paths made during arm movements in both conditions tended to be fairly straight. The tendency for subjects to follow roughly straight hand paths is a highly predictable characteristic of reaching movements (Morasso, 1981; Abend et al., 1982; Sergio and Scott, 1998). Under conditions in which externally imposed forces alter reaching trajectories subjects tend to gradually adapt their movements so that relatively straight trajectories are once again achieved (Lackner and Dizio, 1994; Shadmehr and Mussa-Ivaldi, 1994). Indeed, even when perceived arm trajectory curvature is altered, subjects adapt their movements such that the perceived trajectory is relatively straight even if this means that the actual arm trajectory becomes more curved (Flanagan and Rao, 1995; Wolpert et al., 1995), indicating that this tendency to follow roughly straight hand paths is not a result of anatomical constraints such as joint angles or muscle insertions. This invariance of movement path linearity is likely a product of a control rule imposed by the central nervous system to simplify the planning of reaching movements.

In the current study, the required arm movements made to individual target locations were biomechanically identical in the two experimental conditions. However, we observed that hand paths in the Dissociated condition were significantly more curved than those produced in the Standard condition. Since no correlation between movement curvature and experimental trial number was observed, it is unlikely that the increased curvature observed in the Dissociated condition results from a relative lack of experience with the task (compared with the Standard condition). If inexperience were the cause of the greater curvature in the Dissociated condition, one would expect that curvature would have decreased over the course of the experiment. The greater movement curvature observed in the Dissociated condition suggests that dissociating the direction of eye and arm movements during visually guided reaching disrupts the control processes that underlie the brain's well-documented tendency to form roughly straight reaching movements. Thus, while we are able to perform non-standard tasks in which the eye and arm are not moved to the same spatial location, this ability might come at the cost of introducing noise into a putative neural system that more commonly acts to couple these two effectors, and uses rules (i.e., such as the production of a straight hand path) to make planning of visually guided movements as efficient as possible. We suggest that in the present study, the additional processing resources required for uncoupling the movement directions of the arm and eye reduce the motor system's ability to maintain neurally imposed constraints that typically accompany standard reaching, leading to an alteration in the basic kinematics of eye and hand movements.

3.3. *Possible subcortical and cortical networks involved in coupling and decoupling eye and arm movements*

The existence of neural circuitry that acts to obligatorily couple the eye and arm would make sense from an evolutionary perspective. This kind of circuitry would allow animals to quickly and efficiently capture prey, based on visual information, by coupling a motor response with the direction of gaze. Given the potential adaptive benefit of this coupling, it is likely that the brain structures involved in this process would have evolved early in vertebrate history and would be highly conserved. The superior colliculus fits these criteria in that its homolog (i.e., the optic tectum) is apparent in virtually all vertebrates and appears to be organized similarly to mammalian super colliculi (Gaither and Stein, 1979). In anuran amphibians, the optic tectum is crucially involved in orienting the animal's gaze toward potential prey and then initiating a motor response to this gaze location (Carr, 2006; Ewert et al., 2001; McConville et al., 2006). The superior colliculus may have a similar role in generating signals that are important for the coordination of eye and arm movements in primates. Aside from this region's well-documented role in orienting gaze (Crawford and Guitton, 1997; Klier et al., 2001), it also contains cells with patterns of activity that correlate with electromyographic recordings from arm muscles (Stuphorn et al., 1999; Werner et al., 1997a). Importantly, arm-related activity in these cells is modified by the direction of gaze (Stuphorn et al., 2000). Therefore, these arm- and gaze-related cells in the superior colliculus are a strong candidate for involvement in potential brain circuitry that coordinates eye and limb movements (for example, see Stuphorn et al., 2000; Neggers and Bekkering, 2001; Lünenburger et al., 2001; Snyder et al., 2002) and perhaps these cells underlie part of a system which acts to couple gaze and reach by default.

Although brain circuitry that links gaze and reach likely exists, it is clear that it can be over-ridden, since most people are able to decouple eye and arm movements. The superior parietal lobule (SPL) and its extensive, reciprocal connections with the dorsal premotor area (PMd) of the frontal lobe have a well-documented involvement in visually guided reaching movements (Batista et al., 1999; Battaglia-Mayer et al., 2001; Boussaoud et al., 1998; Crammond and Kalaska 1994; Johnson et al., 1999; Shen and Alexander 1997; Snyder et al., 2000). These two regions are excellent candidates for areas containing circuitry for dissociating the eyes and arm. Within the SPL, an area encompassing the medial intraparietal area (MIP) and the dorsal aspect of the parietal occipital area (PO), there are reach-specific neurons that encode movement predominantly in an eye-centered reference frame (Batista et al., 1999; Buneo et al., 2008;Cohen and Andersen, 2002). This reference frame is maintained throughout the entire planning stage of an arm movement (Buneo et al., 2008). While these cells are not involved in the planning of saccadic eye movements, many of them do fire around the time of a saccade, possibly indicating cross-coupling between the reach and eye movement systems that could aid eye-hand coordination (Snyder et al., 2000) and potentially, the ability to dissociate the directions of eye and arm movements. Furthermore, in a compelling clinical observation, it has been noted that patients with magnetic misreaching (a disorder that results from bilateral damage to the SPL), cannot decouple reach and gaze directions, resulting in the inability to accurately reach for non-foveated targets (Carey et al., 1997; Jackson et al., 2005). This gaze-biased misreaching can also be observed to a lesser extent in optic ataxic patients (Pisella et al. 2006; Sergio et al. 2009) For its part, PMd has a role in the learning and performance of non-standard visuomotor movements (i.e., responses in which the targets of eye and arm movements are spatially dissociated from one another). Specifically, in tasks that spatially dissociated the location of visual cues and the targets of reaching, others have observed that the directional tuning of individual PMd cells initially coincides with the direction of the visual cue, and then subsequently with the direction of the movement target, prior to arm movement initiation (Crammond and Kalaska, 1994; Shen and Alexander, 1997; Johnson et al., 1999). This observation suggests that these cells are specifically involved in planning arm movements away from where the eyes are looking. Importantly, it has also been documented that damage to PMd prevents the successful performance of tasks involving a spatial dissociation between gaze and limb movement (Passingham, 1988). These characteristics of PMd and SPL strongly suggest roles in the ability to uncouple eye and arm movements.

In addition to these cortical regions, the cerebellum also likely contributes to the ability to spatially dissociate the eyes and arm. Adaptation to visuomotor perturbations (including those that require the directions of eye and arm movement to be dissociated) relies in part on cerebellar processing of mismatches between the predicted and actual sensory outcomes of motor commands (Tseng et al., 2007). In addition, cerebellar activity increases as these types of non-standard visuomotor tasks are acquired (Miall et al., 2001; Della-Maggiore and McIntosh, 2005). Interestingly, the amplitude of cerebellar activity has also been shown to partially depend on the degree to which eye and arm movements are spatially congruent. In particular, regions of the cerebellum are more active during conditions in which the eyes and arm must be moved in independent directions relative to those in which the eye and arm movements spatially correspond (Miall et al., 2001). These findings suggest an important role for the cerebellum in the acquisition and performance of tasks in which movements of the eyes and arm are dissociated.

3.4. *Study limitations*

We cannot entirely rule out the possibility that the kinematic differences associated with the two conditions in this study are related, in part, to differences in task difficulty. Producing non-congruent eye and arm movements is not as natural as guiding the arm and eyes to the same spatial location. A training session cannot entirely compensate for a lifetime of performing standard eye-hand movements (in which the targets of both the eyes and the arm are the same). Therefore, the Dissociated task could be considered more difficult to perform than the Standard task, and kinematic differences could partly result from this non-equivalence. However, analysis of the endpoint data from eye and arm movements made in each condition indicated that subjects demonstrated equivalent precision and accuracy in both conditions, suggesting a similar level of proficiency in each experimental condition. Therefore, we believe that a valid argument can be made that a large part of the kinematic differences observed between the two conditions studied here result from the requirement of simultaneously planning movements of the eye and arm in different directions versus planning these movements to a congruent location.

3.5. *Conclusions*

These data demonstrate that dissociating the spatial direction of movements of the eyes and the arm leads to changes in kinematic properties such as hand-path curvature, eye reaction time, peak eye velocity and arm movement time. Thus, while we are capable of separating the directions of gaze and reach, these data demonstrate that such actions necessitate the disruption of a putative brain system that more commonly acts to couple the eyes and arm, a system guided by control rules employed to make visually guided reaching as efficient as possible.

4. Experimental procedures

4.1. *Subjects*

Twenty right-handed adult volunteers participated in the experiment (10 males mean age 28.5±7.2 years, 10 females mean age 26.4±5.7 years). The handedness of subjects was verified using the Oldfield Handedness Inventory (Oldfield, 1971). None of the subjects had a history of neurological problems. All subjects provided informed consent.

4.2. *Apparatus (Fig. 5A)*

Subjects sat in an adjustable chair with their heads supported in a chin rest to minimize head movements made during the experiment (Fig. 5A). Targets for movement were projected down onto an opaque horizontal surface in front of the subject. The display surface was located approximately midway between the subject's shoulders and xyphoid process. Subjects moved their right index finger on a digitizing touchpad tablet (37.5 cm by 31.1 cm, sampling rate 100 Hz, spatial resolution 3 mm, Keytech Magic Touch). The tablet was located below the surface onto which visual targets were projected (approximately midway between the subject's xyphoid process and waist) and was therefore not visible to subjects. Subjects wore a thin cloth glove to minimize the friction of movements made on the surface of the tablet. Subjects could comfortably reach the entire surface of the tablet. Both the tablet and the projection above it were aligned

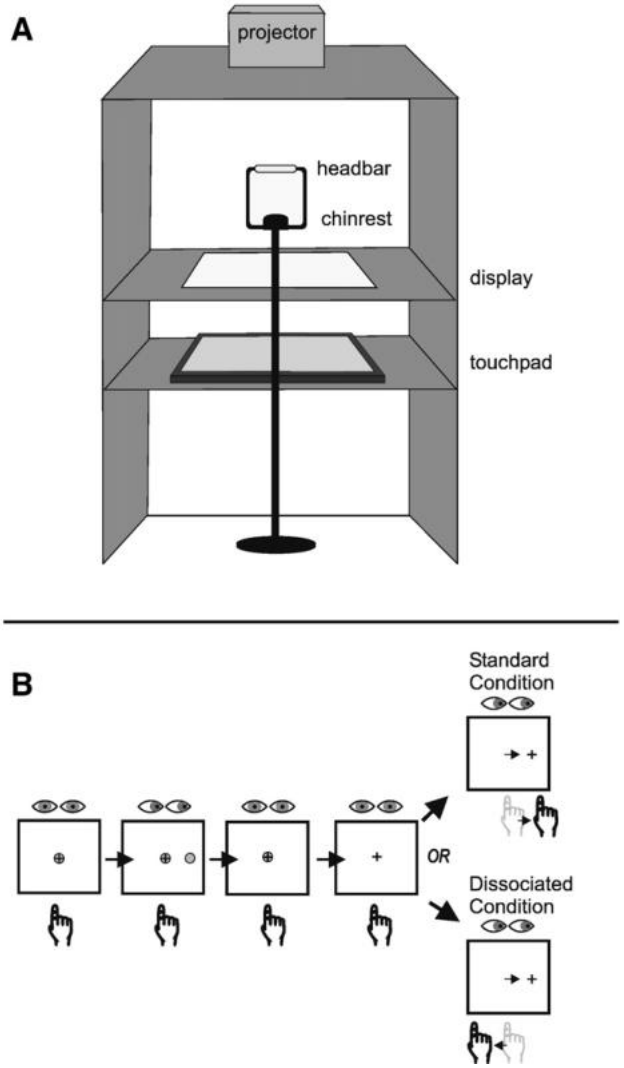

Fig. 5 – (A) Simplified illustration of the experimental set-up. Subjects were seated in front of the apparatus with their head in the chin rest, and slid their finger over the touchpad. The position of their finger was shown as a cross-hair on the display, which also showed the targets. With this arrangement, they could not see their arm. (B) Schematic representation of the eye and arm movements required in the Standard and Dissociated conditions.

with the midsagittal plane of the subject. Vision of the hand and arm was blocked by the opaque projection surface. Movements of the subject's right index finger on the tablet controlled the position of a cursor projected onto the projection surface. In order to ensure that the amplitude of finger movements on the touchpad and cursor movements viewed on the display were equivalent; the experimental set-up was calibrated so that the size of the projection display and the size of the touchpad were equal. The touchpad was calibrated using the standard Keytec calibration method. Eye movement data was sampled at 250 Hz, with a spatial resolution of approximately 0.5°, using a head-mounted, video-based eye-tracker that recorded the horizontal and vertical components of eye movement by tracking pupil position (Eyelink 2, SR Research). The eye-tracker was calibrated using the standard Eyelink calibration method with 9 calibration targets projected onto the horizontal display surface at the beginning of each experimental session. The eye-tracker was then re-calibrated at the start of each block of data collection to correct for any drift.

4.3. *Behavioural paradigm*

During experimental trials, subjects were required to make coordinated eye and arm movements from a central position on the digitizing tablet to one of four peripheral locations around this central target. Subjects were instructed to make movements of both their eyes and arm as quickly and accurately as possible and to avoid making corrective movements with either effector.

Subjects performed two different visually guided reaching conditions (described in the following section and illustrated in Fig. 5B). In both conditions, each trial began with the appearance of a grey central target (diameter = 1.60 cm) which the subjects had to fixate. Using movement of their right index finger on the digitizing tablet, subjects had to move a blue cross-shaped cursor (width = 1.28 cm) into the central target and hold it there for 1000 ms. After this center-hold period, a grey peripheral target (diameter = 1.28 cm) appeared in one of four locations (0, 90, 180, or 270°) around the center target. Peripheral targets were located 10 cm away from the center target (at a visual angle of approximately 15°). After the peripheral target appeared, subjects acquired the target location by briefly moving their eyes to the peripheral target and then back to the central target location. (Note that subjects were required to acquire the target location at this time to help them focus on the optimal performance of the coordinated eye and arm movement at the end of the trial, rather than on an unnecessary constraint of having to maintain fixation after the presentation of a peripheral stimulus.) The peripheral target was extinguished 1000 ms after its initial appearance. Then, after a variable delay (1500 ±500 ms), the center target was extinguished, providing subjects with a "go signal". At the go signal, subjects moved both their eyes and the cursor (via arm movements on the tablet) to the remembered location of the cued peripheral target. Subjects then held this eye and hand position for 1000 ms before the cued peripheral target reappeared providing subjects with feedback regarding the accuracy of their movements. Feedback regarding movement accuracy was provided in order to make the tasks as easy to learn and perform as possible, thus helping to minimize differences in task difficulty between the two conditions.

4.4. *Experimental conditions (Fig. 5B)*

4.4.1. *Standard condition*

After the go signal, subjects moved both their eyes and the cursor (via arm movements on the digitizing tablet) to the remembered location of the cued peripheral target. The position of the subject's hand on the tablet and the location of the cursor on the projection surface were congruent. Thus, eye and arm movements were made in the same direction.

4.4.2. *Dissociated condition*

As in the Standard condition, after the go signal, subjects moved both their eyes and the cursor to the remembered location of the cued peripheral target. However, at the go signal, an algorithm was applied so that movement of the cursor on the projection surface was in a direction 180° opposite to that of movement of the finger on the digitizing tablet (e.g., to achieve a rightward displacement of the cursor, subjects were required to make leftward hand movements on the tablet). Therefore, subjects successfully performed trials in this condition by moving their eyes to the remembered location of the cued target and their arm in a direction opposite to this cued location.

Note that the requirements of eye movements made during both conditions were identical. However, required limb movement direction differed depending on which condition was being performed. In addition, blocking the subjects' vision of their own arm and having the cursor move toward the cued target location for both conditions ensured that visual stimuli associated with both experimental conditions were identical. Each condition was presented in blocks of 40 trials (10 trials per target location in random order). Each block consisted of trials from one condition only.

4.5. *Training*

The experimental conditions tested here were both kept deliberately simple to help minimize effects of differing task difficulty. Subjects were also trained on each condition prior to experimental data collection to minimize learning effects (i.e. to ensure that subjects were performing stable, learned movements). Each subject received identical training during a session that took place between 1 to 7 days before experimental data collection. Subjects were shown the experimental apparatus and an illustrated description of the Standard and Dissociated conditions. After an initial demonstration by the experimenter, subjects verbally explained how to correctly perform each of the two conditions in order to verify that they had understood the instructions. Subjects then performed a block of 40 trials of the Standard condition, followed by two blocks (80 trials) of the Dissociated condition. Only subjects that demonstrated a high level of performance at the completion of training proceeded to the next stage of experimental data collection. Assessment of training efficacy was also performed by examining the reaction time learning-curve profile of each subject over the course of training in both conditions. Subjects who did not obtain a plateau in this learning-curve by the conclusion of training were excluded from experimental data analysis. In practice, the vast majority of subjects had little difficulty performing the required tasks and these criteria only lead to the exclusion of one subject (out of a total of 21 subjects recruited and trained).

4.6. *Experimental data collection*

On the day of experimental data collection, each subject performed several warm-up trials of both the Standard and Dissociated conditions. After this practice period, subjects performed 2 blocks of the Standard condition and 2 blocks of the Dissociated condition (in random order).

4.7. *Data analysis*

4.7.1. *Trial exclusion criteria*

Successful trials were ones in which eye and arm reaction times were between 150 and 2000 ms. Also, the movement time of the limb could not exceed 3000 ms. During successful trials, subjects only made a single eye and arm movement (any corrective movements were excluded from the analyzed movement trajectories). Trials in which either the eye or arm reversed movement direction were excluded. Also, trials in which eye movements tracked the location of the cursor (via multiple eye movements) were excluded from the analysis. In total approximately 7% of trials in the Standard condition and 10% of trials in the Dissociated condition were excluded from the final analysis based on these criteria.

4.7.2. *Reaction time, movement time and velocity*

Velocity of eye and arm movements made during each trial was calculated. Reaction times were calculated as the time after the go signal at which the velocity of the effector (either eye or arm) first reached 10% of the peak velocity obtained during that trial. Movement times were calculated as the amount of time between the initial onset of movement (i.e. the reaction time) and the time at which the velocity of movement first decreased back to a value of 10% of the peak velocity. The difference between the reaction times of the eye and the arm was also calculated for each successful trial. Unfiltered data were used for scoring of movement onset and offset.

4.7.3. *Curvature of movement trajectory*

The curvature of eye and arm movement trajectories was examined by computing the "linearity index" of each movement (Atkeson and Hollerbach, 1985). Linearity indices are computed such that the largest deviation of the actual trajectory from a straight line between the start and endpoints of the movement is calculated. The linearity index is the ratio between the length of this deviation and the length of the straight line. Thus a perfectly straight movement trajectory would have a linearity index of 0 and a semicircular trajectory would have a linearity index of 0.5. Note that the linearity index is a measure of the absolute curvature of the movement and does not take the direction of curvature into account.

Note that in this analysis, comparisons of arm movements in the two conditions were made using movements made in the same direction. Thus, curvature of leftward movements of the arm in the Standard condition was compared to curvature of leftward movements of the arm in the Dissociated condition.

In a secondary analysis, Pearson product-moment correlation coefficients were calculated between group mean linearity ratios and the trial number (from 1 to 80) of arm movements made in the Dissociated condition. This secondary analysis was performed to test whether or not the mean curvature of arm movements systematically changed over time (for example, became less curved) as subjects performed the Dissociated task.

4.7.4. *Movement endpoint analyses*

The final position (horizontal and vertical coordinates) of both the eye and finger was recorded for each trial. The directional constant error (CE) was calculated for the horizontal and vertical components of each final position. Variable error (VE) of endpoint locations was calculated for both the separate horizontal and vertical components of each final location, and for the resultant of these values. Any block of eye data in which there was evidence of head movement was excluded from the comparison of eye endpoint data. In total, about one third of all eye data was excluded leaving a reduced data set of 53 blocks (rather than 80) for this particular analysis.

Comparisons of measured variables were made between conditions using Repeated-Measures Analysis of Variance (ANOVA) with subject, sex and target location incorporated as between-subject factors. Additional one-sample *t*-tests were performed to test whether mean linearity ratios for the hand and eye significantly differed from zero. Data points lying outside of 2 standard deviations of the mean for each data set were removed prior to analysis (approximately 3–5% of each set). Tukey's test was used for post-hoc analyses. All kinematic data analyses were done using custom-written software. Statistical analyses were performed using commercially available software (SPSS v12.0, SPSS Inc.).

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