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Eye–hand interactions in tracing and drawing tasks

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Abstract

We report a preliminary analysis of the interactions between eye and hand during tracing and drawing of four simple shapes. Eye and hand movements were recorded using the ASL 504 system and the Flock of Birds system, respectively. During tracing, pen tip and eye were tightly coupled, with participants making a series of small saccades just in front of the moving pen, interspersed with periods of smooth pursuit. During drawing, saccades were fewer and larger and pursuit was less frequent. Observed eye–hand interactions suggested a bidirectional relationship between the eye and hand. These findings are explained in terms of the differing degree that the two tasks employ visual detail, external or internal cues and eye–hand coordination.

PsycINFO classification: 2330; 2340

Keywords: Eye–hand coordination; Drawing

1. Introduction

Eye–hand coordination is important in daily living but our understanding of its normal pattern and research into specific dysfunctions of eye–hand interactions is limited (Bekkering & Sailor, 2002; Carey, Della Sala, & Ietswaart, 2002). Technical advances have only recently allowed accurate measurement of 2-D human gaze and 3-D hand movements in manipulative tasks (e.g., block stacking: Flanagan, King, Wolpert, & Johansson, 2001; Johansson, Westling, Backstrom, & Flanagan, 2001) and in target reaching actions

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(Carey et al., 2002). This is now a rapidly developing field, and promises to provide important information on normal and impaired eye–hand coordination. There is also a growing body of research on eye–hand interaction during visually guided tracking tasks, in which moving targets for eye and hand are experimentally controlled (Engel & Soechting, 2003; Guedon, Gauthier, Cole, Vercher, & Blouin, 1998; Miall & Reckess, 2002; Miall, Reckess, & Imamizu, 2001; Vercher, Volle, & Gauthier, 1993).

Surprisingly, to date, there have been almost no studies of eye–hand interactions in tracing or drawing tasks (Bohdanecky, Indra, & Radil, 1996; Engel, Anderson, & Soechting, 2000; Miall & Tchalenko, 2001), despite the fact that writing forms a critical part of everyday activity. Adequate writing ability is a vital skill for normal independent life, and both writing and drawing are impaired in degenerative diseases including Parkinson's disease, old age, and after neurological insults and strokes (Contreras-Vidal, Teulings, & Stelmach, 1998; Smith & Gilchrist, 2005; Teulings, Contreras-Vidal, Stelmach, & Adler, 1997).

Tracing and drawing provide two contrasting settings in which to study eye–hand coordination. Tracing depends on external cues such as visual feedback from the eye which is used to monitor the pen tip position in relation to the traced line. Drawing employs internal cues such as memory to a greater extent, guiding the hand direction rather than closely monitoring and comparing its progress. The use of visual or eye position feedback may play a more significant role only at certain key points such as joining two lines at shape termination.

Those studies that have examined eye–hand coordination during object manipulation and manual reaches suggest that there are precise spatiotemporal patterns in which the eye and hand display bidirectional interactions (Ballard, Hayhoe, Li, & Whitehead, 1992; Bekkering & Sailor, 2002; Johansson et al., 2001; Neggers & Bekkering, 2000, 2001, 2002; Pelz, Hayhoe, & Loeber, 2001; Terao, Andersson, Flanagan, & Johansson, 2002). In terms of the temporal domain, the eye initially locates targets for subsequent hand action (for example, grasp points on the target object) then immediately hand–object contact is made, the eye moves to the destination, or to the locus of any obstacles along the path. The eye is apparently "locked" to the target until the hand also reaches the target, although the timing of the release of this "gaze-locking" frequently suggests predictive rather than reactive processing of ongoing hand action. In other words, the eye moves on to the next target before or just as the hand arrives, without time for the hand position to be visually addressed. The hand can also be influenced by the eye as evidenced in cases where hand movement onset is delayed until the end of a fixation (Pelz et al., 2001).

In regards to the spatial domain, saccade deviation away from distracters is greater during combined saccade and pointing tasks than when saccades are performed on their own, suggesting that the hand centred reference frame affects that of a saccade (Tipper, Howard, & Paul, 2001). Similarly, during open loop hand movements, hand amplitude increases with increasing saccade size (Van Donkelaar, 1997).

This degree of interaction between the eye and hand can vary according to the task (see Bekkering & Sailor, 2002, for a review). The two can function in a highly independent manner (Fischer, Pratt, & Neggers, 2003; Steinman, Pizlo, Forofonova, & Epelboim, 2003), or communicate and influence each others' characteristics (Engel et al., 2000; Van Donkelaar, 1999), indicating that the eye and hand function together using parallel but interacting mechanisms. Such flexibility may manifest as different patterns of eye–hand interaction between tracing and drawing, reflecting differences in the underlying neural substrates involved.

Thus, there is a strong background detailing eye–hand interactions and neural involvement during manipulative, reaching and tracking tasks. The aim of the current study was to document eye–hand interactions in normal healthy participants while tracing and drawing, so extending basic knowledge of an important human skill. Due to the different demands of the two tasks we expected there to be differences in the degree of eye–hand coordination between tracing and drawing that manifest as dissimilarities in eye movement characteristics and eye–hand interactions.

2. Methods

2.1. Participants

Eleven healthy volunteers with normal or corrected to normal visual acuity and no history of ocular or neurological abnormalities participated in the study. Mean age and standard deviation was 23.7 ± 4.1 and none were practiced artists. Each gave written informed consent to participate and the study was approved by a local ethical committee.

2.2. Experimental procedure

Two dimensional, monocular eye movements were monitored using the ASL 504 remote pan-tilt eye tracker. The system has a spatial and temporal resolution of 1° and 120 Hz, respectively. The pen movements were simultaneously monitored using the Ascension Flock of Birds. The sensor was placed on the shaft of the pen used by the participants, and an algorithm used to determine the pen tip with a reconstruction error of less than 0.25 mm.

Participants were seated 50 cm away from a near-vertical fixed work space with their head fixed using a chin rest with additional forehead restraints. Their task consisted of tracing and drawing four different shapes on this near-vertical work space. Three of the shapes were geometrical in nature (square, circle and triangle) and the fourth shape was a random blob. Circumferences of the shapes were 42 cm, 34.56 cm, 36 cm and 58.3 cm for the square, circle, triangle and blob, respectively. The different circumferences reflected the requirement to keep the shapes consistent in terms of width and height and within the calibrated area. Participants were given no specific eye or pen movement guidance, but were instructed on the starting point for each shape, movement direction (clockwise or anti clockwise) and that they were to trace the outline without removing the pen from the tracing paper. Starting points were always at the centre top (circle, triangle) or at the top left corner (square, blob).

Tracing a given shape was repeated a total of 10 times, followed by a further 10 recordings where participants were instructed to draw a similar sized shape on a blank sheet. Rest periods occurred between each shape task. Half of the tracing and drawing trials were performed clockwise and the other half were performed anti-clockwise. Each trial was performed with the elbow bent and unsupported, in a natural posture and between trials participants rested their hand and arm on the table. No participant adopted an extreme arm posture and when questioned, participants did not complain of hand or arm discomfort. Prior to performance of each block (10 trials of tracing and drawing of the same shape), calibration of eye position was conducted by instructing the participants to fixate 8 points around the periphery of the work space.

2.3. Data analysis

Horizontal and vertical eye movements, together with pen tip position in three dimensions were measured in the same near vertical work space and analysed using customized Matlab scripts. These allowed calibration of the eye and pen tip position; selection of the active drawing or tracing phase from each trial; and identification of saccades, segments of smooth pursuit, and fixation. Blinks were detected from the record of pupil diameter: for each blink all data samples with a diameter of under 30 (approx. 6 mm) and three subsequent samples were removed, effectively classified as missing data points for all further analysis. This avoided any bias of the analysis that would have been possible had we interpolated across blinks.

Fixations were identified when the gaze position had remained within 0.75 cm ($\sim$0.8°) for greater than 0.075 s, smooth pursuit was identified when velocity exceeded 5.35°/s but remained below 31.8°/s, with a minimal duration of 0.075°/s and saccades were identified when eye movements were greater than 0.8° in amplitude and 31.8°/s in velocity. Trial parameters analysed included mean pen (tangential) velocity (°/s), trial completion time, length of drawn/traced shape (cm), saccade frequency (Hz), saccade amplitude (cm) and percentage of each trial spent in fixation or pursuit. To make the analysis independent of variations in completion time or shape length, relative measures of saccade frequency and saccade amplitude were used. This was achieved by normalizing saccade frequency with respect to completion time (saccade frequency divided by completion time) or normalizing saccade amplitude with respect to average drawing length (saccade amplitude $\times$ template circumference/length of pen line).

Some individual trials were excluded because of poor quality eye data due, for example, to partial occlusion of the pupil by the eyelid or frequent blinking. Data from 10 participants were used for the square, circle and triangle analysis and data from eight participants for the blob analysis. An average of eight successful trials per participant were analysed for each traced and each drawn shape.

2.3.1. Eye–hand interactions

We were interested in examining the frequency of three types of eye–hand interaction: gaze locking (the eye remains at the target until the hand has reached the target), predictive hand processing (the eye moves away from the target before the hand has reached the target) and reductions in pen velocity that coincided with saccades. In order to achieve this we identified minima in the smoothed pen velocity trace and classified the type of eye movement occurring at that moment. For the calculation of pen velocity, the data were low-pass filtered (4th order Butterworth filter, zero phase, 2.5 Hz) and local minima detected as zero crossings in the low-pass filtered pen acceleration record (8th order Butterworth filter, zero phase, 2.5 Hz). We also measured the timing of saccades relative to each velocity minimum (when saccades occurred $\pm$0.5 s around a velocity minimum) and finally the timing of each velocity minimum relative to each saccade (when velocity minima occurred $\pm$0.5 around a saccade). These distributions can differ because there were typically many more saccades than pen velocity minima. In order to obtain an accurate assessment of eye–hand performance, while still maintaining equal data between participants, we limited our analysis to those trials and participants where the data quality was high and to simple geometrical shapes only. This detailed analysis was performed on five trials of tracing and five trials of drawing, in six participants, for the square, circle and triangle shapes.

3. Results

3.1. Effect of direction on tracing and drawing

A 2-way repeated measures ANOVA with factors of direction (anti/clockwise) and pen parameter (completion time/length of tracing) revealed no significant differences between length of tracing in the clock or anti-clockwise directions ($F(1,27) = 2.53$, $p = .12$) but that speed of tracing was significantly faster in the clockwise direction ($F(1,27) = 12.52$, $p = .01$). No significant differences between the two directions were found for length ($F(1,26) = 1.64$, $p = .212$) or speed ($F(1,26) = 1.64$, $p = .133$) in the drawing task. We collapsed data across both directions in all subsequent analysis.

3.2. Characteristics of tracing and drawing

3.2.1. Pen movement

Across all shapes, the average length of lines drawn differed significantly between tracing and drawing tasks (46.89 ± 9.13 and 43.65 ± 9.04 cm, respectively, paired samples t-test, $t = 2.62$, $p = .006$). Also, the average completion time for tracing was significantly lower than for drawing (5.3 ± 1.54 cm/s vs. 6.89 ± 2.45, $t = -6.58$, $p < .001$). There was a strong correlation between both individual participants line length and speed in the two tasks ($r = .87$, $p < .001$; $r = .81$, $p = .006$, Pearson correlation; $n = 38$).

3.2.2. Eye movements

In the following sections, parametric statistical methods have been adopted for analysis of saccade amplitude while non-parametric methods were employed for measures of saccade frequency, smooth pursuit and fixation percentage.

3.2.2.1. All shapes. A paired sample t-test revealed that saccade amplitude was significantly larger in the drawing task compared to the tracing task ($t = -6.07$, $p < .001$). Furthermore, a Wilcoxon signed ranks test with Bonferroni adjustment (significance level $< .02$) indicated that saccade frequency was significantly higher during tracing than drawing ($z = -4.62$, $p < .001$), that smooth pursuit percentage was significantly higher during drawing than tracing ($z = -2.05$, $p < .02$) but that there were no significant difference in fixation between tracing and drawing ($z = -.57$, $p > .29$) (Table 1). Therefore, during tracing participants tended to produce a higher frequency of smaller amplitude saccades and an increased amount of pursuit, whereas during drawing this pattern was reversed. These characteristics can be observed in Figs. 1–4 that show tracing and drawing samples for each shape. The circle and triangle examples (Figs. 1 and 2) particularly display the higher frequency of saccades in the tracing condition and their larger amplitude in the drawing

Table 1
Eye movement characteristics between tracing and drawing, average over all participants and all four shapes

	Saccade frequency (Hz)	Saccade amplitude (cm)	Fixation %	Pursuit %
Tracing	3.13 ± 1.7	2.16 ± 0.54	40.81 ± 16.32	27.85 ± 18.07
Drawing	2.04 ± 1.66	2.7 ± 0.85	42.52 ± 17.85	25.86 ± 20.92

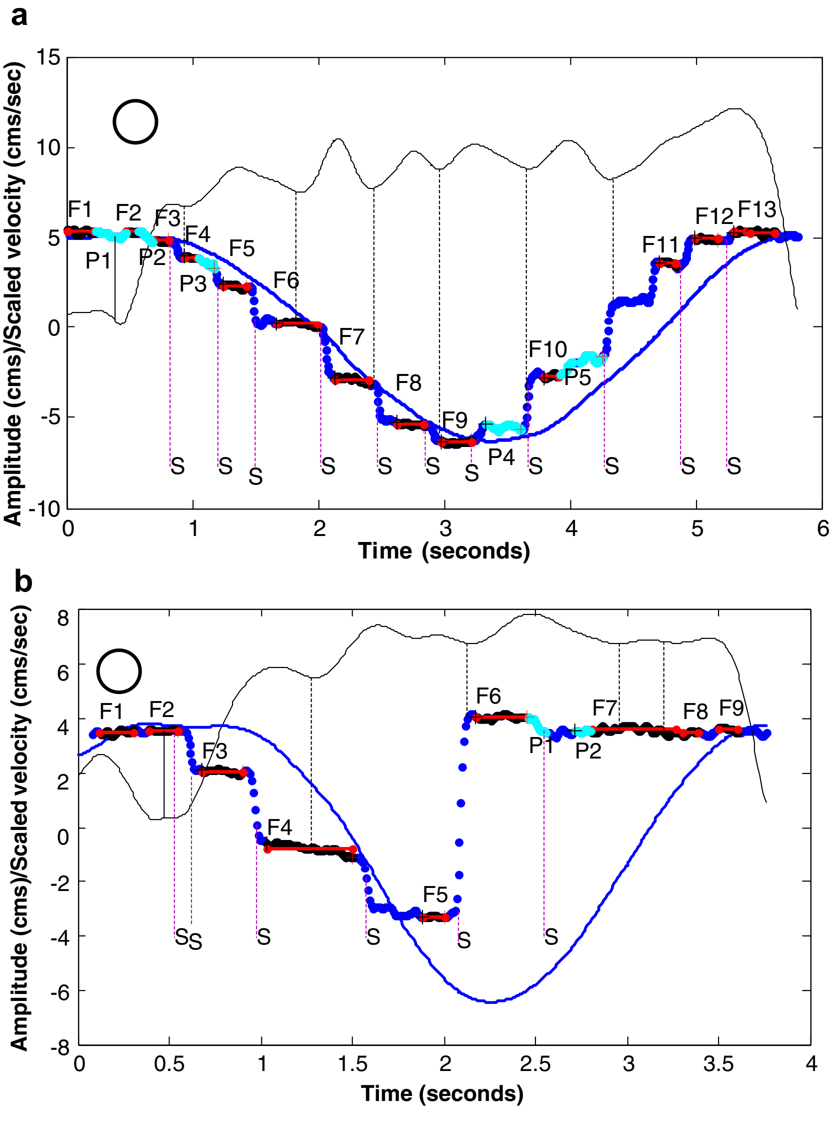

Fig. 1. Comparison between circle tracing (a) and drawing (b) within one participant. Vertical direction shown only where upward deflections indicate upward movements and downward deflections indicate downward movements. Solid black line = pen velocity; solid blue line = pen position; Turquoise = smooth pursuit segments (P1, P2, etc.); black and red = fixation (F1, F2, etc.); blue dots = saccades (S); vertical dashed black lines = dips in pen velocity; vertical purple dashed lines = saccades. Time in seconds is represented along the *x*-axis and amplitude (cm) or scaled velocity (cm/s) is represented along the *y*-axis.

condition. The higher percentage of pursuit during tracing can also be observed in the circle, triangle and blob examples (Figs. 1, 2 and 4). These figures also depict the tendency for participants to make larger and fewer saccades during the second half of each drawing, a pattern that did not vary according to trial number.

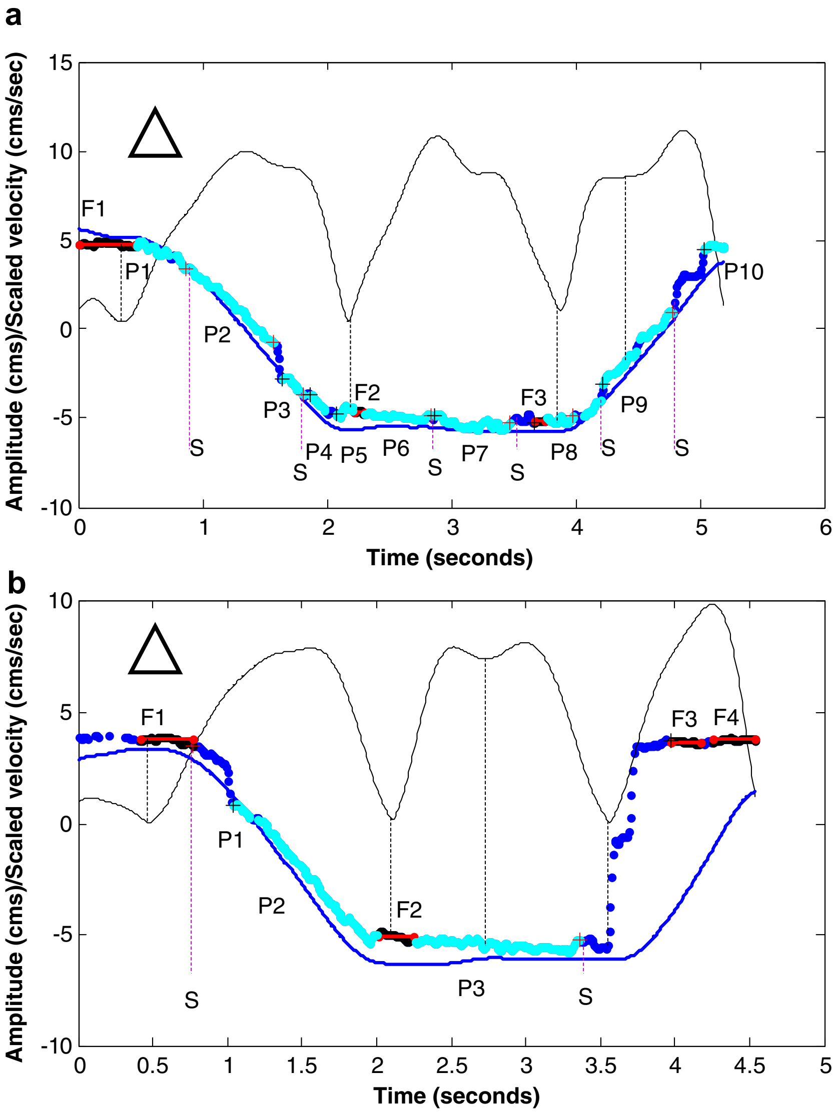

Fig. 2. Comparison between triangle tracing (a) and drawing (b) within one participant. Vertical direction shown only where upward deflections indicate upward movements and downward deflections indicate downward movements. Solid black line = pen velocity; solid blue line = pen position; Turquoise = smooth pursuit segments (P1, P2, etc.); black and red = fixation (F1, F2, etc.); blue dots = saccades (S); vertical dashed black lines = dips in pen velocity; vertical purple dashed lines = saccades. Time in seconds is represented along the x-axis and amplitude (cm) or scaled velocity (cm/s) is represented along the y-axis.

As with the pen motion, there was a strong within-participant correlation for saccade frequency, saccade amplitude, pursuit and fixation percentage between the tracing and drawing tasks ($r > .74$, $p < .02$, Pearson correlation; $n = 38$), but considerable between participant variability.

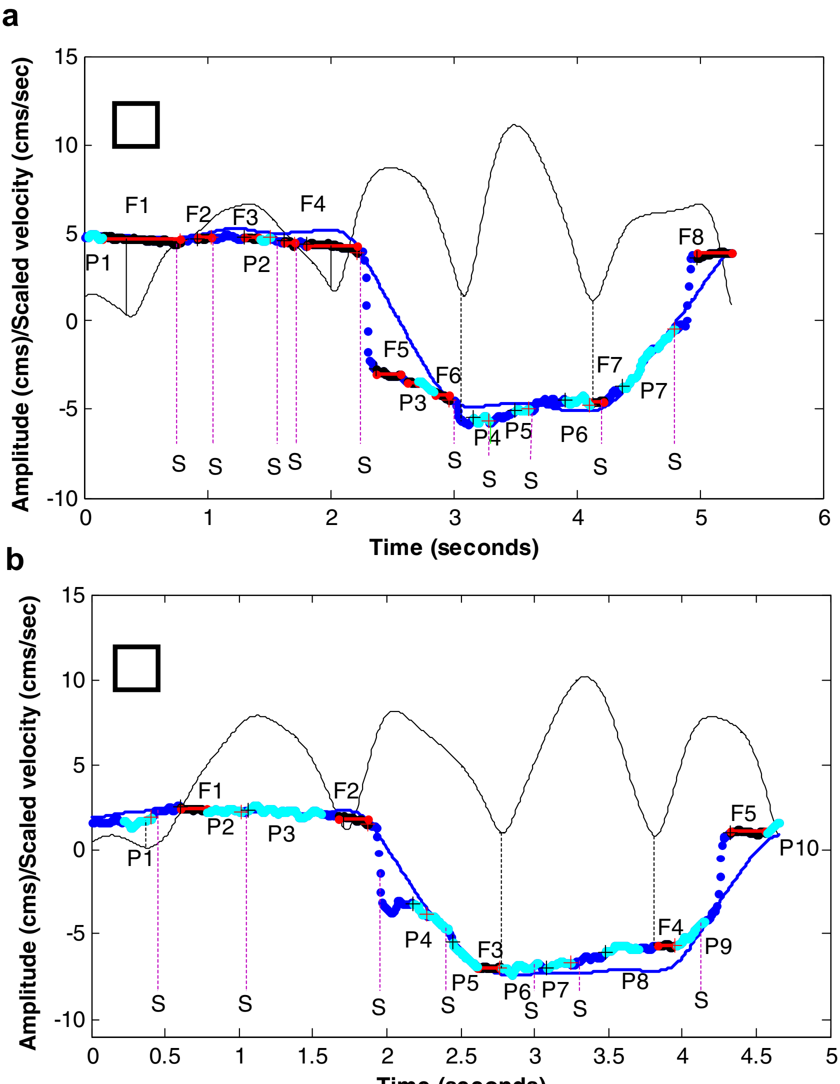

Fig. 3. Comparison between square tracing (a) and drawing (b) within one participant. Vertical direction shown only where upward deflections indicate upward movements and downward deflections indicate downward movements. Solid black line = pen velocity; solid blue line = pen position; Turquoise = smooth pursuit segments (P1, P2, etc.); black and red = fixation (F1, F2, etc.); blue dots = saccades (S); vertical dashed black lines = dips in pen velocity; vertical purple dashed lines = saccades. Time in seconds is represented along the x-axis and amplitude (cm) or scaled velocity (cm/s) is represented along the y-axis.

3.2.2.2. Individual shapes. A within factor ANOVA of saccade amplitude with factors of task (tracing/drawing) and shape (square/circle/triangle/blob) indicated a significant interaction between task and shape ($F(3,21) = 4.54$, $p = .01$). Paired t tests with Bonferroni adjustment (significance level < .01) revealed that saccade amplitude was significantly different between tracing and drawing for the circle ($t = 5.25$, $p < .01$), triangle ($t = 5.29$,

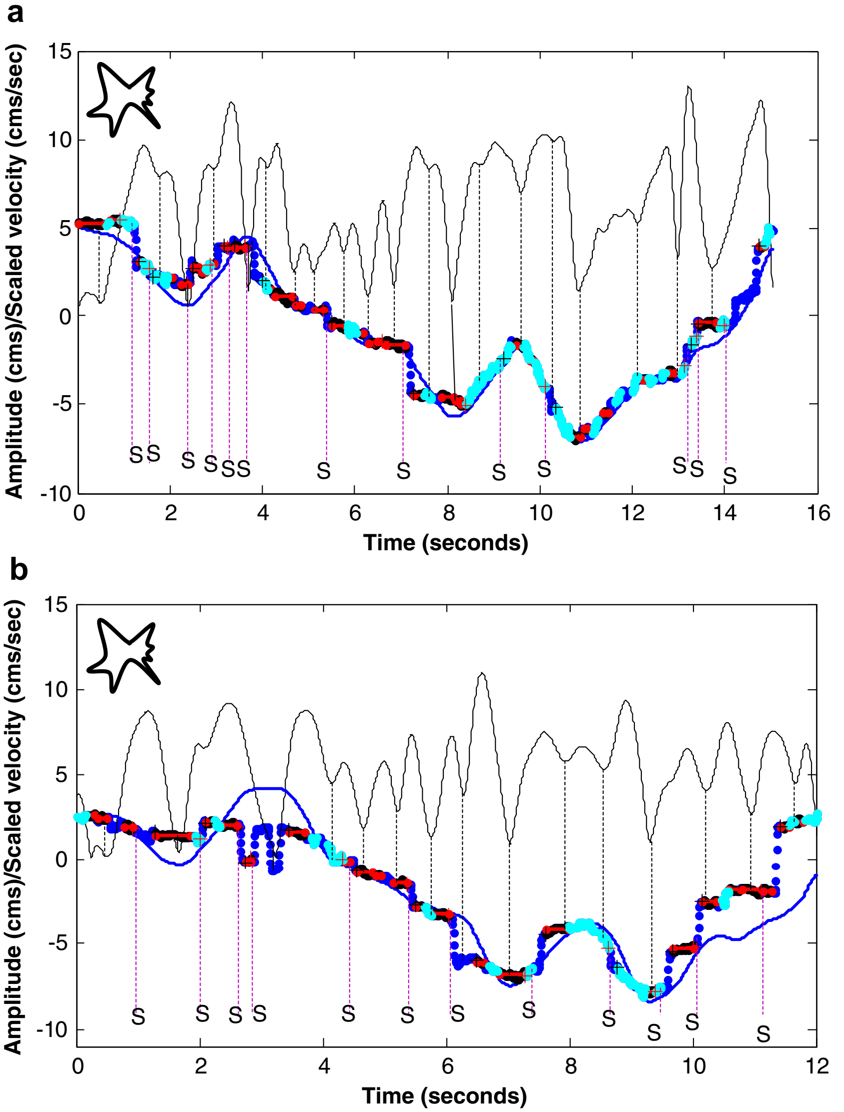

Fig. 4. Comparison between blob tracing (a) and drawing (b) within one participant. Blob configuration shown in small diagram at top left. Vertical direction shown only where upward deflections indicate upward movements and downward deflections indicate downward movements. For simplicity, labels referring to pursuit (P) and fixation (F) segments have been removed. Solid black line = pen velocity; solid blue line = pen position; Turquoise = smooth pursuit segments; black and red = fixation; blue dots = saccades (S); vertical dashed black lines = dips in pen velocity; vertical purple dashed lines = saccades. Time in seconds is represented along the x-axis and amplitude (cm) or scaled velocity (cm/s) is represented along the y-axis. Fixation and pursuit numbers have been omitted.

$p < .01$) but that there were no significant differences for square ($t = -1.53$, $p = .16$) or blob shape ($t = 2.4$, $p = .5$) (Fig. 5a). Furthermore, Wilcoxon signed ranks tests with Bonferroni adjustment (significance level < .01) indicated that saccade frequency was higher in the tracing condition for the circle ($z = -2.8$, $p = .005$) and triangle ($z = -2.8$,

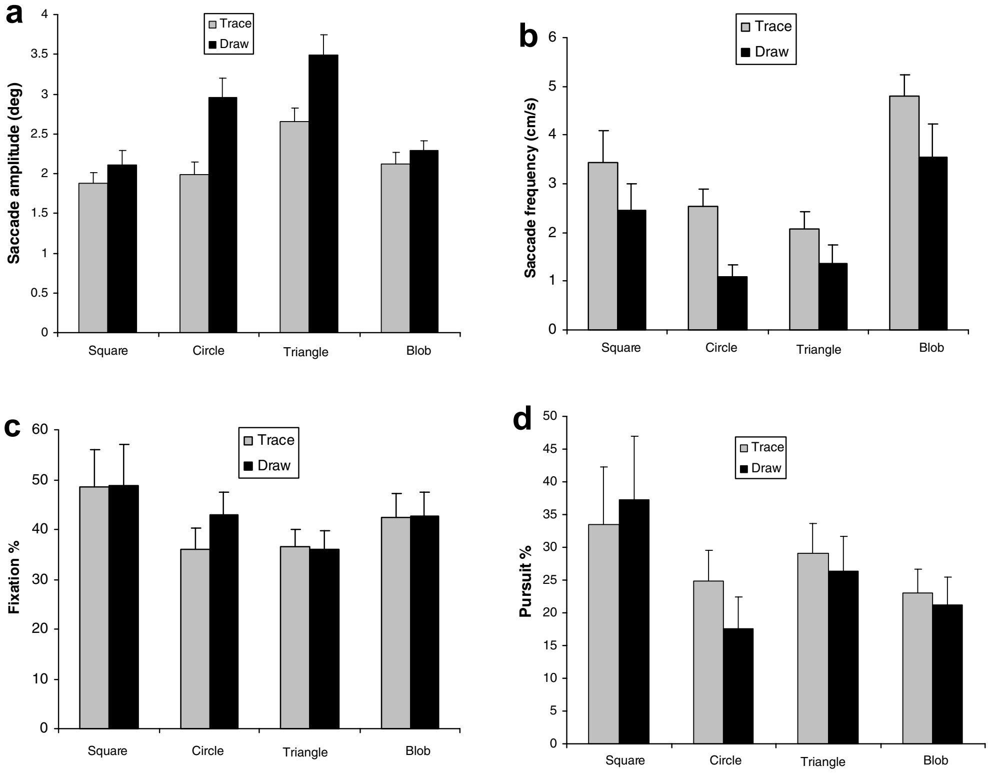

Fig. 5. Saccade amplitude (a) saccade frequency (b) fixation % (c) and pursuit % (d) for each of the four shapes in the tracing (grey bars) and drawing (black bars) tasks. Standard error bars are shown.

$p = .005$) but not the square ($z = -2.19$, $p = .03$) or blob ($z = -1.82$, $p = .07$) (Fig. 5b), that fixation percentage was significantly different between tracing and drawing only in the circle condition ($z = 2.5$, $p < .007$) (Fig. 5c) and that pursuit percentage was only significantly different between tracing and drawing in the circle condition ($z = 2.8$, $p < .002$) (Fig. 5d). Therefore, the circle and triangle shapes contributed towards the greater saccade amplitude and lower saccade frequency in drawing compared to tracing, and the difference in pursuit percentage was caused predominantly by the circle condition.

3.3. Eye–hand interactions

In both the tracing and drawing conditions, fixations were frequently made at the corners of the square or triangle, where the eye would remain until the pen tip was within approximately 1° of the eye position (Fig. 6a). This was particularly evident in the drawing condition. Pen tip velocity at these 'check points' dipped to near zero, indicating that the pen came to an almost complete stop at each corner. Smaller reductions in pen velocity that temporally coincided with saccades were also observed (Figs. 1a, 6b). We identified all saccades occurring within a window of ±0.5 s around each of the two types of pen velocity minima. Comparison of which eye movement type (fixation, smooth pursuit or saccade) occurred at these pen velocity reductions across all shapes revealed that the

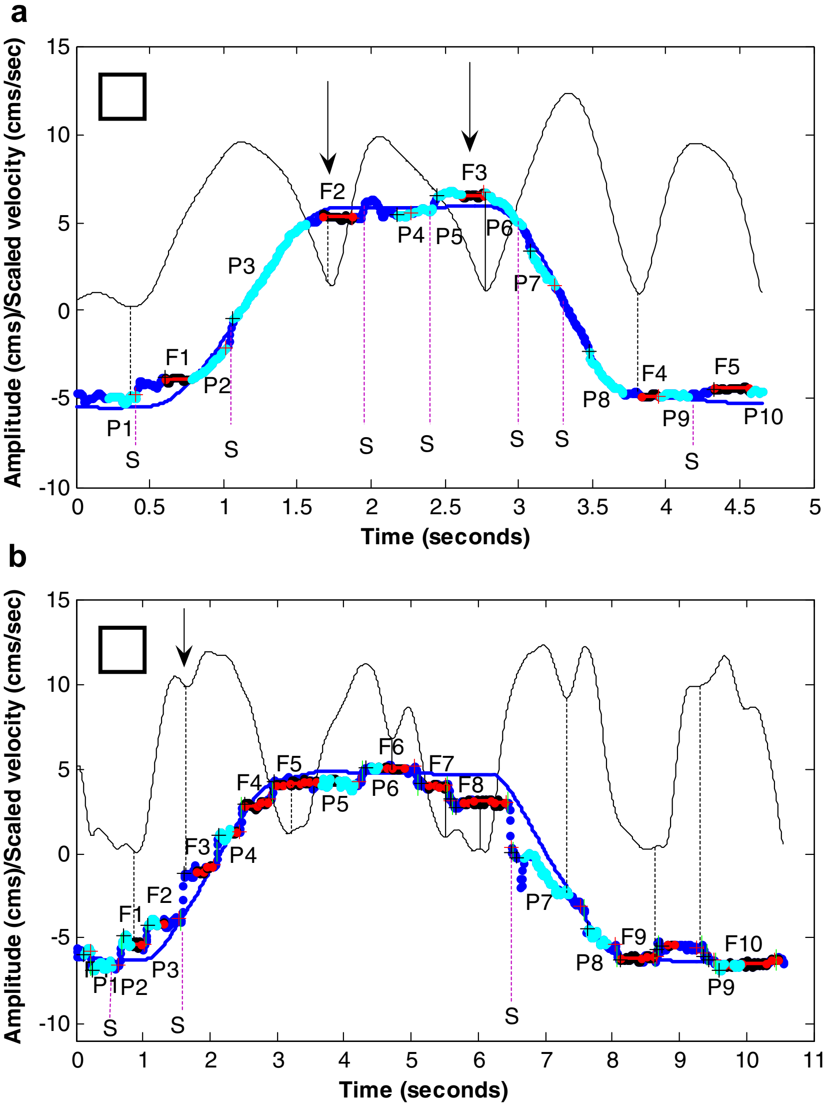

Fig. 6. Examples of (a) gaze locking (eye remains at the target until the pen has reached the target), (b) predictive hand processing (eye moves ahead of the target before the pen has reached the target), (c) dips in pen velocity while tracing (a) or drawing (b,c) the square. Examples are from different participants. Arrows indicate each example. Horizontal direction shown for (a) and (c), where upward deflections indicate rightward movements and downward deflections indicate leftward movements. Vertical direction shown for (b) where upward deflections indicate upward movements and downward deflections indicate downward movements. Solid black line = pen velocity; solid blue line = pen position; Turquoise = smooth pursuit segments (P1, P2, etc.); black and red = fixation (F1, F2, etc.); blue dots = saccades (S); vertical dashed black lines = dips in pen velocity; vertical purple dashed lines = saccades. Time in seconds is represented along the *x*-axis and amplitude (cm) or scaled velocity (cm/s) is represented along the *y*-axis.

percentage of pursuit was significantly higher than other eye movement types (Kruskal–Wallis test $X_2 = 113.29$, $p < .001$). This remained the case when the same comparisons

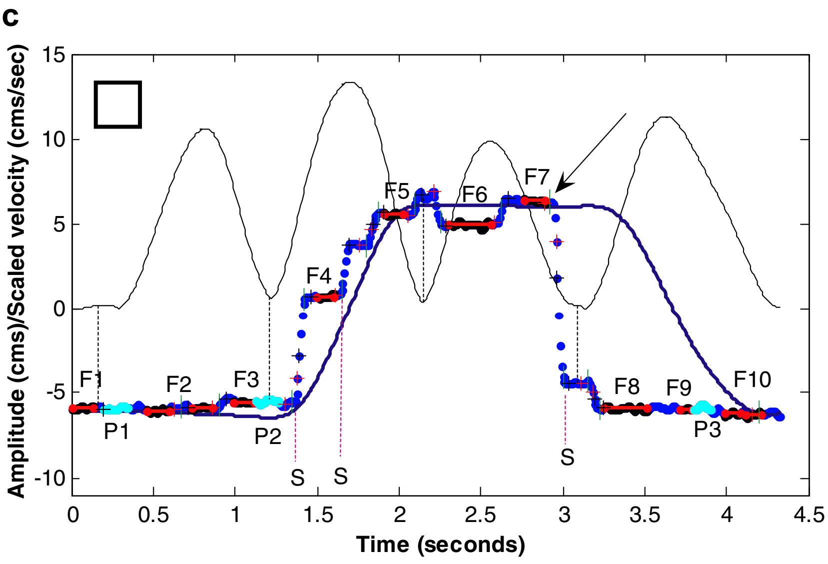

Fig. 6 (*continued*)

were made for tracing ($X_2 = 56.43$, $p < .001$) and drawing ($X_2 = 54.46$, $p < .001$) alone (Fig. 7a). Note from Fig. 5d that the total percentage of each trial spent in pursuit was between 20% and 35% so the predominance of pursuit at the dips in pen velocity is not simply because pursuit was most frequent. We compared saccade frequency during a time interval of 0–500 ms before the occurrence of a velocity minima (0 being velocity minima onset) with saccade frequency during a time interval of 0.01–500 ms following the velocity minima, across all shapes and both tracing and drawing conditions using the Mann–Whitney test. Significantly more saccades occurred following the velocity minima ($z = -2.02$, $p < .04$) (Fig. 7b). Across the two tasks, 43% and 47% of saccades occurred within ± 100 ms of the velocity minima, respectively. However, saccade frequency did not significantly differ before or after a velocity minima when compared individually for the tracing ($z = -1.44$, $p > .15$) or drawing condition ($z = -1.06$, $p > .35$). Likewise, velocity minima tended to occur prior to saccade production, although this was not significant across both tracing and drawing ($z = -0.43$, $p > .67$), or for tracing ($z = -1.59$, $p > .11$) or drawing ($z = -1.13$, $p > .26$) alone (Fig. 7c). Here, about 27% and 30% of velocity minima occurred within ± 100 ms of a saccade, respectively.

In summary, smooth pursuit eye movements more frequently coincided with pen velocity reductions than saccades or fixations. However, saccades were also frequently associated with these pen velocity dips and tended to occur following slowing of the pen, although saccades could also occur before. In almost all cases the saccades were made in a direction that progressed around the shape – so the saccade tended to increase or decrease the pen distance depending on whether the eye was ahead or behind the pen at saccade onset. Indeed, evidence for predictive hand control, where a saccade was made to a new location before the hand had reached the previous location of the eye was observed in both conditions (Fig. 6c). Inspection of many such traces suggests that this pattern was more frequently observed during the second half of each tracing/drawing.

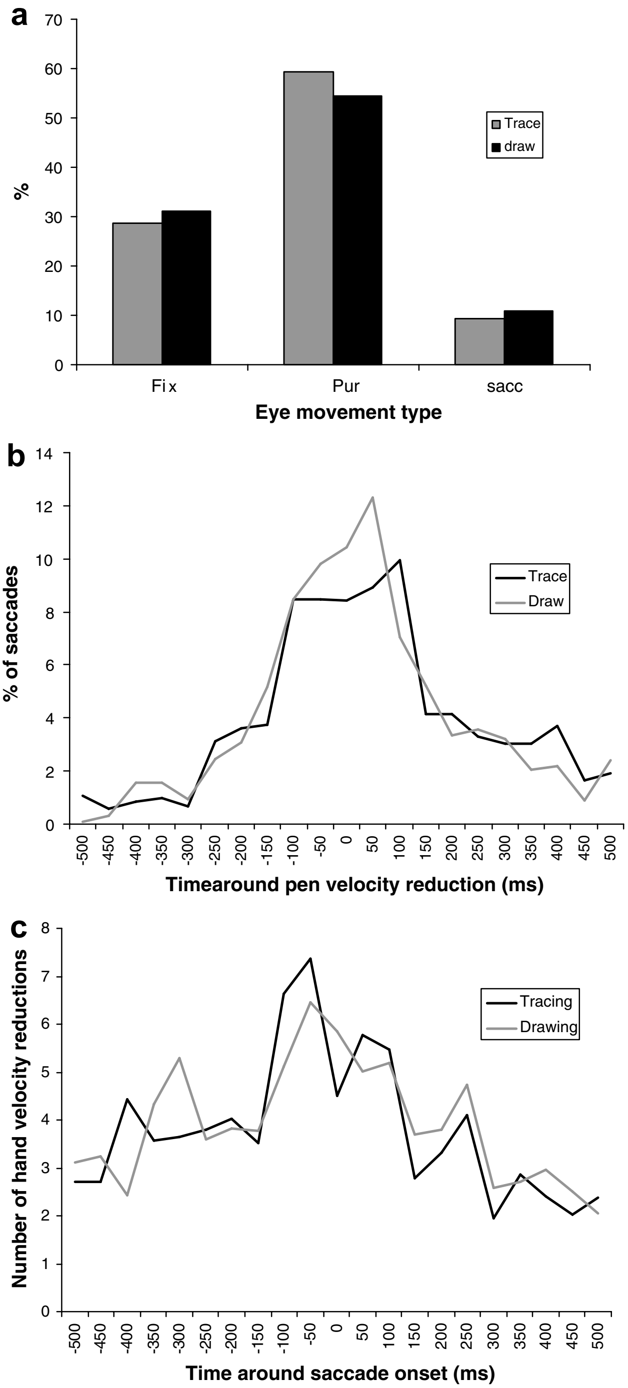

Fig. 7. (a) Percentage of each eye movement type that coincided with a pen velocity reduction; (b) percentage of saccades that occurred ±500 ms around a pen velocity reduction (0 ms); (c) number of pen velocity reductions that occurred ±500 ms around a saccade onset (0 ms).

4. Discussion

In our comparison of eye–hand coordination during simple tracing and drawing tasks we observed two main findings: (1) there are significant differences in the eye movement characteristics between tracing and drawing; (2) similar eye hand interactions occur during the tasks. We discuss these observations in terms of the varying requirements for each task.

4.1. Differences between tracing and drawing

4.1.1. Pen movement

During drawing participants were significantly faster to complete the trial and reproduced significantly smaller shapes, highlighting that tracing demanded more spatial accuracy. The use of relative eye movement measures balanced these two differences and although it is highly likely that the eye movement characteristics observed for each task are genuinely due to task differences we cannot yet rule out that they are due movement duration or drawing size. In addition, the task order (with drawing following after tracing) may have contributed towards the differences between the two tasks. Future studies will need to even out such time and size differences and counterbalance trials.

4.1.2. Eye movements

Our preliminary data display clear and statistically significant differences in eye movement characteristics between tracing and drawing tasks. Tracing was accompanied by smaller, more frequent saccades and an increased amount of pursuit indicating that this task produced tighter eye hand coupling than the drawing task. Tight coupling between hand and eye movements during tracing and combined eye–hand tracking has been observed previously (Reed, Liu, & Miall, 2003; J. Tchalenko, unpublished data).

Our data suggests that pursuit is more frequent during tracing than drawing indicating that the eye was smoothly pursuing the pen tip. Previous work has shown that during such combined eye–hand tracking where pursuit is predominant, the eye and the hand share common external cueing information or use some form of internal synchronisation (Engel & Soechting, 2003; Vercher, Gauthier, Cole, & Blouin, 1997; Vercher et al., 1993). Combined eye–hand tracking produces higher velocity smooth pursuit (Vercher et al., 1993) and the latency of the eye movement increases, whereas the latency of the hand movement decreases (Engel & Soechting, 2003). Furthermore, a greater degree of smooth pursuit is observed during combined eye–hand tracking than during eye tracking alone (Koken & Erkelens, 1992). Therefore, the observation of smooth pursuit may signal greater coupling between the eye and the hand.

The observed eye movement differences between tracing and drawing may reflect dissimilarities in either the degree of eye–hand coordination or the complexity between the two tasks. Tracing demands continual comparison between the line to be traced and pen tip, which in turn requires continual transfer of this visual information to the hand movement system. As a result one would expect close coupling between the eye and the hand which has been observed in previous tasks involving shared targets for the eye and hand (Neggers & Bekkering, 2000, 2002). In drawing, such accurate visual feedback information from the eye would be less critical and internal factors such as memory guidance of hand movement would assume greater importance. Thus, the two systems could act more independently, enabling the eyes to move further ahead and not necessarily define a path that the hand should follow. We are not arguing that the hand does not use any information from the eye during drawing, but that the degree and nature of this reliance changes. However, eye movement differences could also result from variation in task complexity as it has been shown that gaze accuracy improves as the difficulty of the task increases (Steinman et al., 2003). So it could be that increased pen-gaze accuracy would be more important during tracing to enable the pen to follow the shape contours accurately. This is suggested by the examples of the drawing task where participants frequently moved their eyes far ahead, to the end point of the shape (where vision was important) or even fixated a central location while the hand moved around the eye position (Figs. 1, 2 and 4).

Saccade amplitude and frequency differences between tracing and drawing were less apparent for the square and blob shapes. In regards to the square this may have been due to its familiarity and simplicity as the sides were all straight and either horizontal or vertical which could have led to reduced monitoring of the pen position as well as eye–hand coupling. In support of this, Bohdanecky et al. (1996) observed that tracing performance was superior for squares as opposed to triangles and circles and also for horizontal lines. This could also explain the finding that the circle shape appeared mainly to contribute to the increased amount of smooth pursuit in the tracing task, highlighting that the circle evoked greater eye–hand coupling and monitoring during tracing. In contrast to the square, the blob was a much more complex shape which may have required relatively more eye–hand coupling and decreased the differences in saccade frequency between tracing and drawing. Despite this, evidence for a weaker eye–hand relationship in the blob drawing task was still apparent from examples where the eye remained at a central location while the pen drew outward lines before returning to the eye (Fig. 4).

Finally, we found considerable variation in eye and pen movement characteristics between participants, but individual participants were highly consistent across tracing or drawing tasks. This has also been observed previously in a block copying task (Pelz et al., 2001) and may reflect differing strategies or experience of such tasks (Miall & Tchalenko, 2001). It is worth noting that we did not find any eye or hand movement differences over the individual tracing and drawing trials, suggesting that underlying mechanism of tracing or drawing did not change over the short number of trials in our study.

4.2. Eye–hand interactions

Our experiments provide evidence for a bi-directional relationship between the eye and hand during tracing and drawing tasks. During both tasks, we observed consistent fixation points at the corners of shapes that correspond with the 'check-point' or gaze-locking phenomena seen in hand reaches and manipulative tasks (Johansson et al., 2001; Neggers & Bekkering, 2001). The eyes would remain locked at these positions until the pen had reached the eye location. Gaze locking has been attributed to the requirement for visual attention to remain on the fixated target while on line foveal visual guidance of the pointing movement is being conducted (Neggers & Bekkering, 2000). Recently, an association between fixation and hand trajectory while drawing shapes has been observed: fixation location tends to be related to the location of hand trajectory where muscle control at the elbow is most demanding (Ketcham, Dounskaia, & Stelmach, 2006) and these fixations occur when movement curvature is the highest and so movement velocity the lowest

(Reina & Schwartz, 2003). This reiterates that not only does the eye supply the hand with spatial information – particularly at more demanding locations – but also that the eye moves in a feedforward manner to those locations, arriving before the hand. Interestingly, in our study a larger amount of pen velocity reductions were associated with smooth pursuit than fixation. This may be because our analysis method did not separate velocity minima (when the pen velocity reaches 0°/s) from smaller velocity reductions (where pen velocity briefly reduces but remains well above 0°/s). Smooth pursuit may be correlated more strongly with pen velocity reductions, where the eye and hand are moving together and transferring velocity information between each other. Future analysis will examine this possibility by separating the two forms of pen velocity reduction.

We did observe occasions where the eyes would move ahead of the pen, especially just before the pen reached the eye. Similar findings have been reported in a block copying task where the eyes would frequently depart from the block to be picked up before the hand had reached it (Pelz et al., 2001). In these cases predictive processing of the hand, using stored gaze coordinates would be required to reach the original fixation position. These could represent occasions where attention was freed earlier from arm movement planning and guidance in order to be available for saccade programming. Indeed, once a manual reaching movement had been planned, it can be carried out without requiring attention to the target, whereas saccades require attention to be located at the target until saccade termination (Deubel & Schneider, 2003). In contrast, examples where dips in pen velocity are synchronous with saccades could indicate attention returning to eye movement planning before the hand movement had been fully programmed. This is supported by our findings that pen velocity reductions tended to arise more frequently prior to a saccade.

We anticipated that tracing would be associated with a higher frequency of gaze locking and pen velocity reductions because of the closer eye–hand integration in this task, whereas drawing would involve more predictive processing due to less reliance on visual guidance and eye–hand integration. However, our preliminary results did not reveal any differences between tracing and drawing. If any differences do exist this may become apparent when we separate the two types of pen velocity reduction.

5. Conclusions

We have reported eye–hand coordination during simple tracing and drawing tasks. In particular, during tracing the eye and the hand are more tightly coupled than during drawing which may reflect use of optimum strategies for each task: tracing requires detailed template comparison, increased reliance on visual feedback, and therefore increased guidance of the pen tip. We intend to examine these tasks further using functional Magnetic Resonance Imaging to examine whether these behavioural differences are also apparent at the neural level. Tracing may result in higher activation of areas such as the cerebellum that are believed to be preferentially involved in combined eye and hand action (Miall, Imamizu, & Miyauchi, 2000; Miall et al., 2001) and externally cued movements (Van Donkelaar, Lee, & Drew, 2000; Van Donkelaar, Stein, Passingham, & Miall, 1999). In contrast, drawing may activate areas such as the basal ganglia which are thought to be more important for internally cued and memory guided movements (Crawford, Henderson, & Kennard, 1989; Van Donkelaar et al., 1999, Van Donkelaar, Stein, Passingham, & Miall, 2000). In this light, comparing tracing and drawing abilities in individuals with Parkinsons disease who exhibit differing responses to externally versus internally presented cues (Praamstra, Stegeman, Cools, & Horstink, 1998) could also provide insight into the neural processes underlying eye–hand coordination.

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