

The effects of secondary task interference on shape reproduction

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Abstract The influence of a secondary task on speeded responses, and its effect on the outcome of more complex tasks has been studied in detail. However, the consequence of task interference on specific movement parameters other than speed and accuracy has been largely ignored. The current study examines how performing a secondary task impacts the drawing of an unseen shape. Without vision of the hand, 15 subjects traced a shape on a graphics tablet. The shape and cursor were projected onto a screen. The shape disappeared and the subject attempted to draw three consecutive identical shapes. In the visual single-task condition, hand positions were represented by a cursor, but the resultant drawings could not be seen; in another, there was no visual feedback. In four remaining conditions, the 15 subjects drew the previously seen shapes without visual feedback while performing a secondary task of reporting the orientation of an arrow which appeared on the screen either in random or periodic timing. Subjects indicated the direction of the arrow either verbally or manually. Shapes were analyzed for scale, error of the corner angles as compared with 90°, and drift, compared to the reference shape and across conditions. In dual-task conditions, performance of the primary, shape-drawing task deteriorated with respect to location and orientation, but not with respect to the pattern and proportion aspects of the shape. Vision was important for controlling position of the drawing, and also for controlling the shape and proportion

of the drawing suggesting separate mechanisms for the location of a drawing and its shape and proportion. Furthermore, we propose that internal representations are more important than proprioception in the shape aspect of drawing well-known figures.

Keywords Attention · Proprioception · Motor performance · Dual-task · Drawing

Introduction

Daily activities often require the simultaneous performance of more than one task: we walk and chew gum at the same time, stir the vegetables while shaking salt into the potatoes or, even where prohibited by law and common sense, talk on a cell phone while driving a car. Most people believe that dual-task performance decrements are negligible; however, laboratory results show the effects of dividing attention can be substantial, even for well-practiced, seemingly compatible tasks (Pashler 1990). Much of the dual-task literature is concerned with performance of a primary motor task (such as a sequence of button presses) concurrent with a perceptual or cognitive secondary task (such as vigilance for the presentation of stimuli), or some kind of mental load (such as word pairing or mental arithmetic). In these experiments, subjects' reaction times and sequence errors are measured in the primary task alone, and while performing the secondary task.

Dividing attention has direct costs for motor learning. Taylor and Thoroughman (2007) divided attention by providing subjects with a tone discrimination task during perturbed reaching, and Gold and Park (2009) required subjects to repeat a list of digits at a delay, either during learning or recall of the building of an object such as a pinhole camera.

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For both experiments, interference was greatest during learning, and the researchers hypothesized that some chunking occurs at the time of encoding (Gold and Park 2009). Such automaticity allows for better resource sharing when performing more than one task simultaneously (Brown and Carr 1989). As a motor sequence is learned, it becomes encapsulated into a “chunk” that can be later retrieved more easily. Secondary loads on attentional, planning and motor systems cause specific interference depending on the degree to which automaticity has been achieved (Eversheim and Bock 2001). There is some evidence that there is a timing cost even for highly stereotyped movements such as concurrent saccades and reaching (Bekkering et al. 1994), although later research by the same group identified the intention for the action as being the source of the time cost (Bekkering and Neggers 2002), rather than divided attention per se. In a different set of experiments, tool grasping was impacted by a secondary semantic task, while a tracking task deteriorated with a secondary spatial task, showing that certain particular sub-systems of a given secondary task may interfere differently depending on the nature of the primary task, which therefore demonstrates the role of cognition in dual-task performance (Creem and Proffitt 2001). In all of the preceding experiments, however, subjects have learned new skills, and it is not possible to determine if the performance cost was due to effects of late stages of learning, or performance. Equally, the secondary task is rarely motor in nature, but rather cognitive or perceptual.

To a lesser extent, other experiments have examined “real-world” dual-task situations which investigate the cost to completing a goal-oriented behavior while also carrying out a secondary task, such as golf putting while performing an auditory search task (Beilock et al. 2002), or performing a soccer slalom while identifying geometric shapes (Smith and Chamberlin 1992). These studies observe the net impact of task interference on the accomplishment of the goal. However, neither the speeded response/error designs nor the “real-world” designs reveal how the secondary task might impact individual movement parameters such as the scale, orientation or drift of component movements in a primary task. In those instances of research involving continuous performance of a dual-task, the study of the parameters of the movements has not been the explicit goal. Summers et al. (2008), for example, measured the synchronization of circles drawn simultaneously with the left and right hands while verbally responding to a random tone. They investigated the variability in the location of a drawn shape, but without reporting overall location biases. They also measured proportion, but found no significant main effect, possibly because the bimanual task was designed to be in phase. More recently, Otte and van Mier (2006) had children simultaneously perform tapping with one hand and tracing a shape in a grooved track with the

other. In that instance, tapping was the primary task, and the measures examined related to movement velocity rather than the qualities of the movement performance. Movement scale and variability have been studied for dual-task interference in postural control and gait, particularly in aging subjects. Not surprisingly, many researchers have found that the introduction of an additional task increases mean variability of center of pressure (COP), and alters other specific movement parameters of gait such as obstacle contact, as well as measures of the secondary task such as reaction time and accuracy [see Woollacott and Shumway-Cook (2002) for a comprehensive review and discussion]. However, many aspects of posture and gait are not under direct cortical control in contrast to hand movements such as reaching, grasping and manipulating. These actions require both attention and dexterity, and consequently, may reveal greater performance decrement under the load of a secondary task than do posture or gait.

Previous research from Henriques et al. (2004) suggested that errors in the reproduction of felt shapes from individual line segments are due to higher cognitive processes. In one experiment, subjects used a robot manipulandum to “feel” the virtual borders of an irregular, closed shape then reproduced the shape using the same manipulandum: the subjects could not see the hand or manipulandum. Subjects tended to draw the shape about 15% larger than the reference shape. In terms of location, right-handed subjects tended to draw the shapes further from their body and to the left, and left-handed subjects drew the shapes closer to themselves. Last, subjects tended to make the inner angles of the shapes more regular than they actually were, leading the researchers to hypothesize that regular shapes may be more compactly stored in memory. For our current study, we simplified the shapes, and added a secondary task. Thus, we hypothesized that any additional performance decrement would be due to a competition for attentional resources during either motor planning, or execution.

To better understand processes and mechanisms involved in the continuous performance of a primary task, we asked subjects to draw three reproductions of a shape while simultaneously reporting the orientation of a series of visual stimuli. The task of drawing quadrilaterals allowed us to examine well-known movement sequences having clear and specific measures for accurate completion (straight lines, 90° corners, equal-length sides and consistent location): moreover, subjects did not need to learn how to draw the shape. We hypothesized that with the secondary load, shapes would be less square both in terms of proportion and size, and the location of the shape would drift more than in conditions without load. Last, we varied the method of response between verbal and manual modes. We hypothesized that if any effect on the drawing is shared

by both response modalities, it is likely that the effect is attributable to the impact of perceptual processes; alternatively an effect in only one response modality indicates the effect may be caused by the planning and execution of the response modality.

Methods

Subjects

Fifteen healthy right-handed subjects (10 male, 5 female, ages 17–40 years, mean age 23.3) with normal or corrected to normal vision, participated in six conditions discussed below. Twelve new subjects and three from the previous experiment (10 male, 5 female, age 17–24 years, mean age 20.5) with normal or corrected to normal vision, participated in the control conditions of responding manually or verbally to the secondary task only. The subjects were volunteers who gave informed consent and the experiments were conducted in accordance with the provisions of the York University Human Participants Review Subcommittee.

Apparatus

In all conditions, subjects were seated comfortably at a desk equipped with a Wacom graphics tablet, (23.5 × 43.3 × 5.8 cm.) sampling at 50 Hz, connected to a PC (Fig. 1). The center of the drawing surface was situated 30 cm from the body midline at table height. The computer display, with a resolution of 1,270 × 764 pixels, was projected onto a screen 67 cm in front of the subject, while a barrier on the desk occluded the subject's view of the room. An 8-inch-wide board just below eye level also restricted field of vision so that subjects were not able to see their hand on the tablet, and a circular mask on the screen removed immediate vertical and horizontal orthogonal references (Williamson and McKenzie 1979). Custom software was designed to provide the experimental conditions and collect the data. For the manual and verbal responding dual-task paradigms, subjects responded, respectively, on mouse buttons with the left hand or their spoken answer was recorded by an experimenter.

Conditions

All subjects participated in six separate conditions. Two conditions examined the ability to draw a shape with or without vision of the cursor. These two single-task conditions were performed without any additional load and allowed us to isolate the effect of vision in the single-task condition. Four additional dual-task conditions were

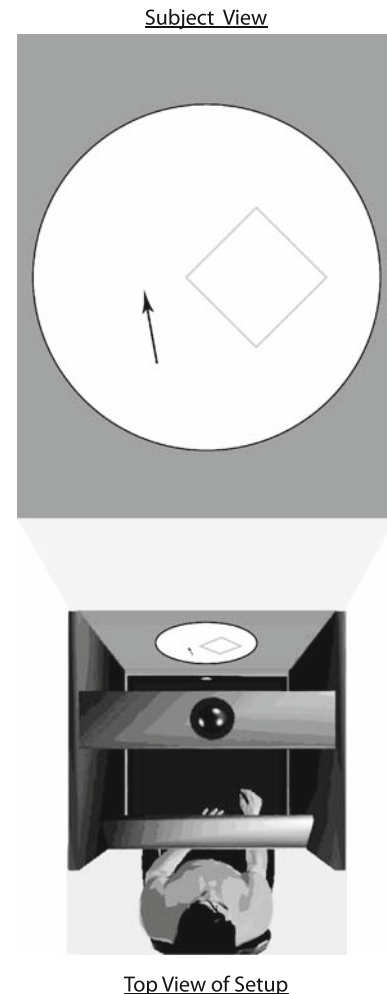


Fig. 1 Experimental apparatus and display of one template shape. On a graphics tablet, subjects traced a square or diamond displayed on a vertical screen. As the shape was drawn, an *arrow* oriented either to the left or right was displayed either at a fixed time interval or at a random time during the drawing. A horizontal bar occluded vision of the hand, and the template shape disappeared. Shapes were either 4 × 4 or 8 × 8 cm, and appeared either centered on the screen or shifted 4 cm to the right

performed both with the primary task of drawing a shape without vision of the cursor, and a secondary task of identifying the orientation of a visually presented arrow.

Single-task conditions

In the single-task, no-cursor (SNC) condition, the subject traced a template shape, then completed a second “drawing phase” without any vision of the reference shape or the cursor or hand: the screen displayed only white pixels. The second, single-task, cursor, condition (SC) was identical to the SNC condition, except that the cursor was visible during the drawing phase. For each condition, 32 trials consisting of one trace and three drawings were drawn, for a total of 128 repetitions. For all subjects the SNC

condition was provided first, since deprived of any feedback of performance, it is quite unlikely that any learning took place. For all subjects SNC and SC conditions were completed on separate days. In the drawing phase, the cursor condition allowed us to examine the subjects' performance replication of a remembered shape with vision of the end effector, while the single task no-cursor condition allowed us to view replication of a shape relying only on efference copy, proprioception, and haptic feedback.

Dual-task conditions

For the dual-task conditions, all subjects performed the tracing phase with vision of the cursor, as before; however, during the drawing phase without vision of the drawing cursor, subjects were presented with arrows displayed randomly on the screen, within an area of 19.8×6.4 cm, centered on the middle of the screen. Each arrow was 3 cm in length with a head measuring 0.5 cm across and comprising 0.5 cm of the total arrow length. The arrows were tilted either to the right or left of vertical by 3° , 5° or 10° . Subjects were told that the most important task was to accurately and precisely reproduce the reference shape.

Arrows were presented either at fixed (timed) or random intervals. Unlike PRP experiments, where the timing of the stimuli is carefully manipulated to influence the timing of a speeded response (Pashler 1994), we used fixed and random intervals to vary the difficulty of the perceptual task on correctly identifying arrow orientation. Thus, we were able to determine whether performance deficits in the primary task were attributable to attending and perceiving the arrows, or attributable to verbal versus manual responding. In the timed conditions, we presented arrows after a 1,000 ms inter-stimulus interval. In the random timed conditions, the inter-stimulus interval was random, between 500 and 1,500 ms. In either instance after the interval, the arrow was displayed until the subject responded whether the arrow was tilted to the right or left, or a for maximum time of 2,000 ms: following a response or maximum presentation time the arrow disappeared. After the next inter-stimulus interval, a new arrow appeared in a new location with a different degree of tilt. Correct and incorrect answers were recorded, as well as a failure to respond within the 2,000-ms display time. Subjects were continuously provided with new arrows after every response until they indicated the end of the primary drawing task by moving the stylus to the bottom of the tablet. As a consequence, some subjects responded to more arrows and others to fewer.

Subjects responded to the secondary task while continuing to draw reproductions of the shape. In the manual-response conditions the responses were manual, with the subject using the left hand to click a mouse positioned

beside the graphics tablet, clicking left or right buttons to indicate the corresponding arrow-tilt. In the verbal response conditions, subjects spoke the words "right" or "left" to an experimenter who then manually responded using the mouse. In this condition, the subject's left hand was placed in the lap just below the desk.

Conditions were counterbalanced across subjects with respect to timed and random arrow presentation and verbal and manual responses, giving four dual-task combinations: timed arrows, manual response (DTM); timed arrows, verbal response (DTV); random arrows, manual response (DRM); and random arrows, verbal response (DRV).

Procedure

The appearance of a blue dot (0.5 cm in diameter) on the screen indicated the start position for each trial in all conditions. Subjects positioned the stylus so that the point of the cursor was within the dot. After 1,000 ms, a quadrilateral with sides of either 4 or 8 cm appeared oriented as a square or diamond. As drawn on the tablet, the center of the drawn shape was approximately 30 cm from the subject's sternum. In order to maintain the subjects' interest, the shapes were presented pseudo-randomly with the following combinations of variables: either centered on the display and midline of the body or offset 4 cm to the right; either 4 or 8 cm, in either square or diamond orientation. All eight combinations were randomly presented in each block of eight trials. In the centered condition, all shapes were centered on the same point, regardless of size or orientation, meaning they each had a different starting point. The same was true for all right-shifted shapes. We varied the size, orientation and start location of the shapes to maintain subject interest, and presented these varied stimuli in a pseudo-randomized, counterbalanced fashion. The upper left or topmost corner of the square or diamond (respectively) was given as a starting point, and a clockwise drawing direction was arbitrarily chosen to facilitate programming and analysis of the experimental data.

Subjects used a computer cursor to trace the outline of a shape which was projected on a screen. This gave immediate visual feedback regarding performance on the tracing since subjects could compare the position of the cursor against the reference shape, although no visible path was displayed on the screen. The tracing phase provided the template shape for each trial in all conditions: these data were not analyzed, but are included in some figures to provide an index of baseline performance. At the end of the trace phase, subjects paused, and after 1,000 ms, the reference shape disappeared. The pause allowed for a clear separation of trace and drawing phases, facilitating both stimulus presentation and data collection. Subjects then made three additional continuous squares or diamonds, as

much like the trace shape as possible during a second “drawing phase”. Subjects were instructed in advance to make an additional shape if they were uncertain whether they had made two or three cycles.

Secondary task control

In order to determine whether performance in the main drawing task affected the response rate to arrow-tilt in the dual-task (mean number of responses per subject, per condition = 219.18 ± 78.50 , SD), we ran a separate group of subjects who performed 300 trials of the arrow task only, (no primary drawing task) using the same experimental setup.

Data analysis

Data points were smoothed using a first order, low-pass Butterworth filter, and line paths for each shape were selected using a Matlab custom-written GUI, and verified and corrected by hand when computer-selected corners did not correspond with the corners of the drawn shape. Statistical analysis was performed in SPSS. We assessed drawing performance using measures of size as determined by area, drift of the shape as determined by displacement of the center of area over three repetitions (left/right, up/down), mean rotation of the shape (tilt), inner angle error (squareness), and movement time. These measures were compared to those for the reference shape and with respect to those for the preceding shape in each drawing phase.

All data were compared using a 2-way within-subjects repeated measures analysis of variance (RM-ANOVA) comparing 6 conditions \times 3 cycles. By comparing the SC (single task, cursor) condition against the SNC (single task, no cursor) condition, we were able to determine to what extent vision of the cursor aided in single-task performance. The comparison of the SNC condition against the dual-task conditions allowed us to examine the effect of a secondary task on the primary task, both in the absence of vision. The “trace” phase of each trial was only used as a template, and is not included in any analysis. Greenhouse–Geisser correction was used where appropriate on the repeated measures analyses, and a modified Bonferroni correction was applied to all post hoc paired comparisons.

The area of each shape was calculated using the formula $A = (\sum x_1 \times y_2 \dots x_n \times y_{n+1}) - (\sum y_1 \times x_2 \dots y_n \times x_{n+1})/2$, to calculate the area of any polygon using Cartesian coordinates: this formula was used to allow for the inclusion and influence of every data point on the area of the drawing, regardless of its concavity or convexity relative to a straight line. We then calculated the ratio of area of the drawn shape compared to the ideal shape. A perfect sized shape would have a ratio of 1. Inner angle

error is the angle between two adjacent drawn lines subtracted from 90 (the ideal shape), with positive values indicating an obtuse inner angle, and 0 representing a 90 degree inner angle. To measure the tilt of the drawn shape, we calculated the rotation of each line segment relative to the line’s origin, and calculated the mean rotation for each shape. To measure drift in the shape reproduction, we calculated the center of area for each shape, and computed this two-dimensional location relative to the two start position centers for the shapes.

For certain trials in load conditions, subjects completely missed the corner of a shape and proceeded to the next corner (Fig. 9a, shows a typical missed-corner trial from one subject). These trials were omitted from the main analysis. The number of missed corners were summed and averaged for each subject and condition. One sample *t* tests (two-tailed) revealed the occurrence of missed corners to be reliably different from zero in all load conditions except DTM ($p > 0.1$), (DTV: $t(14) = 2.188$, $p < 0.05$; DRM: $t(14) = 2.571$, $p < 0.02$; DRV: $t(14) = 2.311$, $p < 0.04$). We analyzed these “missed corner” trials for the effect of angle of the stimulus arrow, as discussed below.

Responses to the arrow orientation on the secondary task were summed as correct, incorrect or missed for each subject and condition. *t* tests were used to compare them with the control condition, and correlations were performed to determine if the number of arrow responses impacted drift, squareness, tilt or movement time.

Results

Figure 2 illustrates changes in the size (as measured by area) of the drawing, pictured as a gray square over a wireframe representing the ideal size, normalized across small and large sizes ($F_{5,70} = 8.2$, $p = 0.002$, $\varepsilon = 0.385$). When subjects had vision of the cursor and no load (Fig. 2, single task, cursor condition, SC, they drew shapes about 33–60% smaller than all other conditions ($p < 0.013$) (as indicated by the relatively larger shaded shapes in Fig. 2) and also 14% smaller than the ideal shape ($p < 0.001$, one sample *t*-test). The DRM (dual-task random manual) condition (top, right) was drawn larger than either the SNC (single task, no cursor) or DTV (dual-task, timed verbal) conditions, and the DRV (dual-task, random verbal) condition (bottom, right) was also larger than the DTV condition (all $p < 0.016$). Vision of the cursor (in the cursor condition) helped subjects to draw shapes closer in size to the reference shape, and the random presentation of the arrow stimulus caused subjects to draw shapes approximately 6–26% larger than the timed load and no-cursor conditions, perhaps indicating that performance was affected when vigilance needed to be greater.

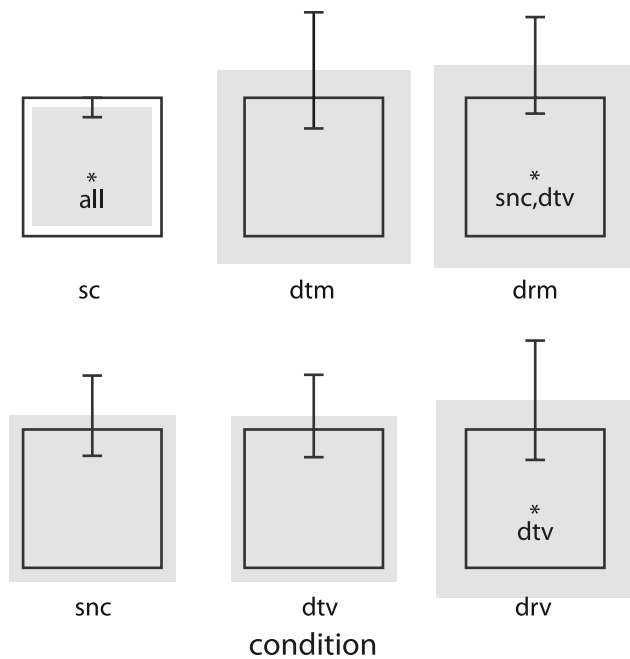


Fig. 2 The scale of the drawing as represented by area across conditions. The ideal, normalized area of shapes is represented by the black wireframe, while the actual performance is shown by the grey quadrilaterals. Error bars represent the SEM averaged across participants. Significant differences are shown with an asterisk. *sc* single task, cursor; *snc* single task, no cursor; *dtm* dual task, timed manual responding; *dtv* dual task, timed verbal responding; *drm* dual task, random manual responding; *drv* dual task, random verbal responding

Subjects tended to draw the shapes below the location of the ideal shape. To quantify this, we calculated the location of the shape as the center of the drawing as defined by the centroid of the endpoints of each line segment, and found that drift was not significant between subsequent cycles of the drawing within a single trial (i.e., between first and second repetition), but only became significant over cumulative repetitions within a single cycle (between first and third repetitions). These centers, averaged across repetitions, trials and subjects, are shown for all conditions by the squares in Fig. 3, with the origin of the axes representing the center of an ideally drawn shape, and down representing locations closer to the subject. The black square represents a shape drawn with view of the cursor: even with sight of the cursor, subjects drew the center of the shape with a downward drift ($p < 0.0001$). All other conditions without vision of the cursor were drawn significantly lower than the cursor condition ($F_{5,70} = 8.9$, $p < 0.001$, $\epsilon = 0.517$, post hoc comparison $p < 0.001$), but there was no effect of load. In other words, hiding the cursor caused increased downward drift (closer to the subject) compared to the cursor condition, although no additional downward drift was caused by the secondary task. The DTV condition, represented by the grey circle in

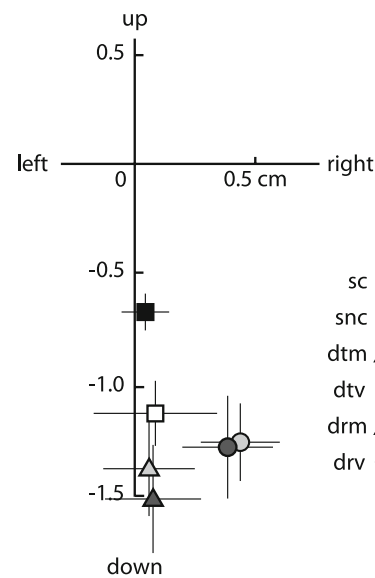


Fig. 3 Average drift of the drawing across three repetitions for all subjects (in cm). The squares represent the center of the drawn shapes, averaged across subjects and trials, with the intersection of the axes representing the ideal center of the drawn shape. Results of all subjects comparing the single-task cursor condition (black) and single task no-cursor condition (white) against manual (triangles) and verbal (circles) responding; dark grey represent fixed arrow timings, and the light grey shapes represent random arrow timings. *sc* single task, cursor; *snc* single task, no cursor; *dtm* dual task, timed manual responding; *dtv* dual task, timed verbal responding; *drm* dual task, random manual responding; *drv* dual task, random verbal responding

Fig. 3, drifted more to the right than all other conditions (5, 70) $F = 2.8$, $p < 0.041$, $\epsilon = 0.708$, post hoc $p < 0.015$) except the SNC (white square) and DRV condition (black circle).

Shapes not only drifted more without vision of the cursor and with the load of a secondary task, they also became more rotated around their central axis. The black bar in Fig. 4a shows that when subjects had vision of the cursor, the shapes were less rotated than for all other conditions except DRV. ($F_{5,70} = 3.2$, $p < 0.02$, $\epsilon = 0.842$, paired comparisons $p < 0.014$). Figure 4b shows that shapes became more rotated after the first drawing cycle ($F_{2,28} = 17.29$, $p < 0.0001$, $\epsilon = 0.576$, paired comparisons $p < 0.001$); however, the third cycle is not more rotated than the second. It is not possible with such few cycles to speculate if this lack of change between the second and third cycles represents an asymptote. The shape and proportion aspects of the drawing were also impacted by lack of visual feedback. Subjects drew shapes which were less distorted, with corners closer to 90° when they could see the cursor ($F_{5,60} = 12.7$, $p < 0.001$, $\epsilon = 0.648$, paired comparisons $p < 0.001$). Removing vision of the cursor led to distortion of the shape, however, adding an additional load did not as shown by the black bar in Fig. 5a. Also, Fig. 5b shows there was a main effect of

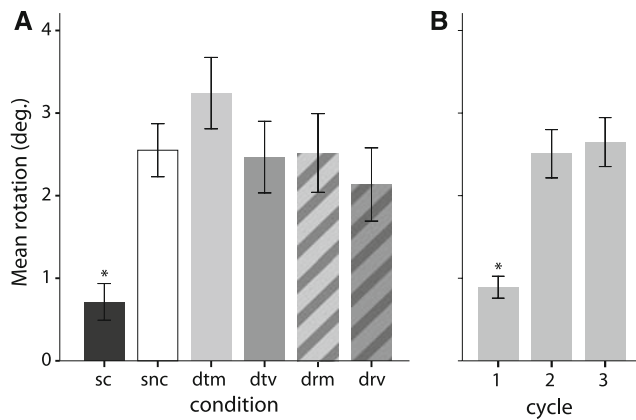


Fig. 4 The rotation of drawings around a central axis. Bars show the mean rotation, averaged across trials and subjects, with taller bars being more rotated. **a** Mean rotations across each condition. **b** Mean rotations across cycles. Error bars represent the SEM averaged across participants. Significant differences are shown with an asterisk. *sc* single task, cursor; *snc* single task, no cursor; *dtm* dual task, timed manual responding; *dtv* dual task, timed verbal responding; *drm* dual task, random manual responding; *drv* dual task, random verbal responding

cycle, with shapes becoming more distorted after the completion of the first cycle but no more so after two cycles. ($F_{2,24} = 14.4$, $p < 0.001$, paired comparisons, $p < 0.012$).

On average, subjects took about 1.2 s to draw each side of the shape (i.e. each line), but this movement time varies across conditions ($F_{5,70} = 6.91$, $p < 0.0001$, $\epsilon = 0.527$), for example Fig. 6a illustrates that movement time of the SNC and DTM conditions (white and light grey bars, respectively) were drawn around 300 ms more slowly than either the timed verbal or random verbal conditions ($p < 0.002$). In Fig. 6b, each successive cycle can be seen to be drawn more quickly than the preceding ($F_{2,28} = 34.85$, $p < 0.0001$, comparisons $p < 0.014$). These movement times may seem long in comparison with transport times of ~ 1 s for both 15- and 30-cm reaches in studies such as that by Rand et al. (2006), but it must be remembered that in the present experiment subjects are drawing rather than reaching. Thus, they have the constraint of making straight paths that correspond to the template shape and also respond to a secondary task.

Secondary task

We compared the performance of the secondary task of correctly identifying arrow orientation alone against its performance concurrent with the primary task, considering correct, incorrect and missed responses (Fig. 7). For the DTV condition, there were more correct responses and fewer missed responses for the secondary task alone (second row left, grey and white wedges, respectively). For the

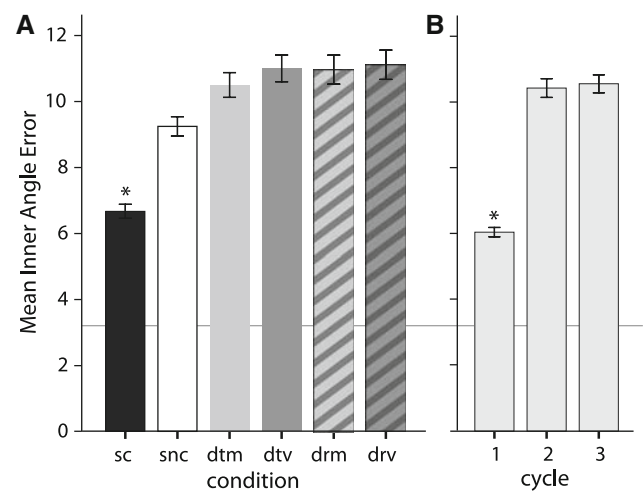


Fig. 5 The inner angle error, which is the difference between the ideal angle (90°) and that drawn by the subject, averaged across trials and subjects. The grey horizontal line shows the inner angle error for the trace condition, when subjects could see the drawing template. Mean inner angle error for the drawing are shown across conditions (**a**) and cycles (**b**). Error bars represent the SEM averaged across participants. Significant differences are shown with an asterisk. *sc* single task, cursor; *snc* single task, no cursor; *dtm* dual task, timed manual responding; *dtv* dual task, timed verbal responding; *drm* dual task, random manual responding; *drv* dual task, random verbal responding

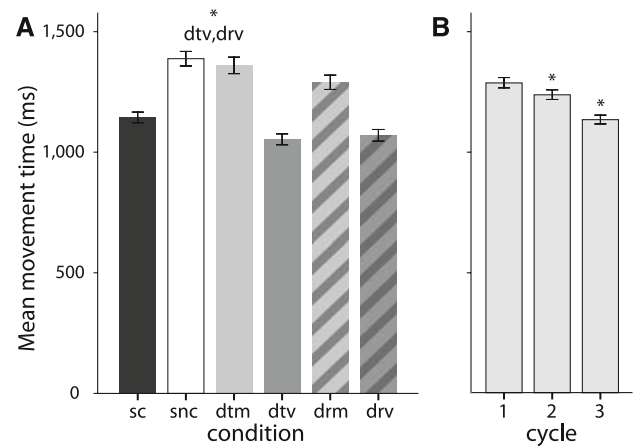


Fig. 6 Time required to draw a single side of a shape, averaged across subjects and trials. Movement times in milliseconds across conditions (**a**), and cycles (**b**). Error bars represent the SEM averaged across participants. For **a** significant differences are shown with an asterisk, for **b**, each cycle is significantly different. *sc* single task, cursor; *snc* single task, no cursor; *dtm* dual task, timed manual responding; *dtv* dual task, timed verbal responding; *drm* dual task, random manual responding; *drv* dual task, random verbal responding

DRV condition, there were more correct responses and fewer incorrect responses for the secondary task alone (bottom row left, grey and black wedges, respectively; all $p < 0.001$, two-tailed). Still, performance of the detection task was very good in both dual-task verbal response conditions at 92.5% for DRV and 85.7% for the DTV

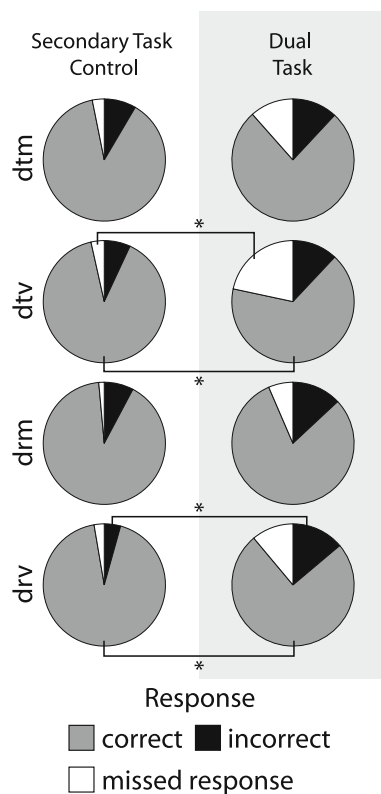


Fig. 7 Mean of correct, incorrect and missed responses to presented secondary task arrow plotted as a percentage of the total number of arrows presented. The *left group* represents the secondary task control condition in which participants responded to arrow orientations without drawing, and the *right represents* arrow responses within the dual task conditions. *dtm* dual task, timed manual responding; *dtv* dual task, timed verbal responding; *drm* dual task, random manual responding; *drv* dual task, random verbal responding

compared to a chance level of 50%. In all other conditions detection of orientation in the dual-task condition was equal to performance in the secondary task alone.

Because subjects were free to respond to as many arrow stimuli as they wished, it was possible that the number of responses may have influenced the various metrics. Correlations were not significant except between the number of responses and the measure of movement time, where we found $r > 0.93$ for all load conditions (data not shown), indicating that an increased number of responses was coupled with an increased movement time.

As one might expect, we found that subjects typically coordinated their response to the arrow-tilt so that they responded more often as they were approaching a corner of the drawing; in other words when the velocity of the drawing action was likely to be slowest, since subjects briefly came close to stopping at each corner. This is shown in Fig. 8 where we plot the number of responses in the secondary task relative to the distance to the nearest corner. Figure 8a shows the responses counted into 20-ms bins. The vertical line represents the nearest corner. The same

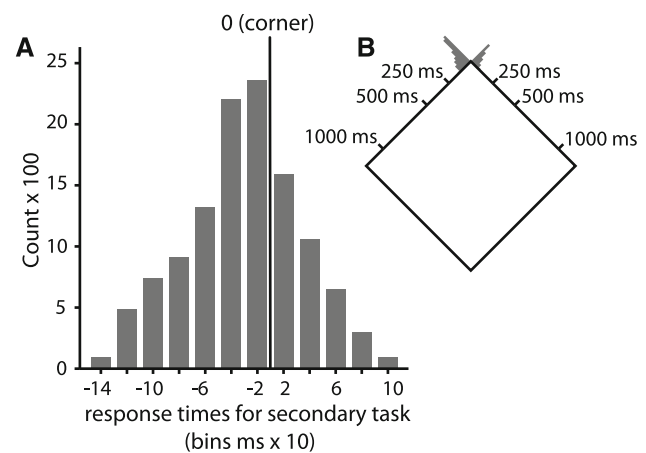


Fig. 8 a Responses to the arrow were placed into 20-ms bins, according to their appearance relative to the closest corner drawn by the subject in the shape-drawing task. The vertical line (0 corner) shows the timing of the corner relative to the arrow responses. **b** The same data shown on an idealized shape with the length of each side representing the average time taken to draw a side (1,215 ms)

data is also shown in Fig. 8b, plotted against an idealized corner on a shape with sides that would take the mean time of 1,215 ms to complete. Most responses fell into the two bins immediately before the corner, with the third most populous group occurring immediately after the corner.

In a small but significant ($p < 0.006$, t test) number of trials (140 trials, which is 7.2% of all trials) subjects missed drawing one of the corners: although these trials were excluded from the main analysis, we examined the features of these trials. Figure 9a shows a typical trial in which a subject completely missed a corner and proceeded to the next corner in the shape. In these missed-corner trials, we analyzed the remaining corners of the square to see if there were any differences between the end locations for corners that were before and after a missed corner and corners that did not flank a missed corner. Separate one-way ANOVAs were performed on the left/right and up/down coordinates and no differences were found between the means or variabilities of corners flanking a missed corner (pre- and post-corners in Fig. 9b) and corners of shapes where there were no missing lines in any of the conditions (normal corners in Fig. 9b). In other words, subjects located corners before and after a missed corner with both the same accuracy and precision as with normal corners. It is as though they had never missed the corner at all.

We considered that arrow-angles closer to vertical may have caused subjects to miss corners due to additional resources needed to identify the less oblique arrow-angles (overall, subjects were slightly less accurate for 3° arrows, $F_{2,1073} = 8.23$, $p < 0.0001$); however, all angles occurred before missed corners with the same frequency (Chi-square = 1.41, $df = 3$, $p < 0.7$). Also, subjects were less

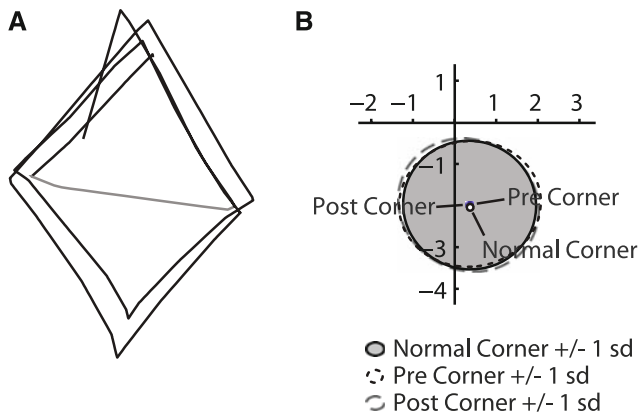


Fig. 9 **a** A typical drawing in which a subject completely missed drawing a corner due to load from the secondary task. **b** The intersection of axes shows the ideal location of a corner. The three overlapping ellipses show the variance for normal corners, corners before subjects missed a corner (*dotted line*), and corners after subjects missed a corner (*dashed line*). The *overlapping dots* show the mean values (in cm) for those same corners

likely to miss drawing the first line (0.8% compared to change rate of 8.3%) or last (5.4 versus change of 8.3%) than ones in between, (93.8 versus change rate of 83.33%, Chi-square = 9.2, $df = 2$, $p < 0.01$). In other words, subjects were less likely to miss drawing the first or last line of a drawing than one in between.

Discussion

In this study, we examined the effect of a secondary load on a continuous drawing task. Specifically, subjects had to reproduce a square shape while indicating the orientation (left or right) of briefly displayed arrows. Indicating the orientation of arrows manually or verbally allowed us to identify whether perceptual or motor demands of the secondary task caused deterioration in performance of shape drawing. We found that the addition of this secondary load affected the topokinetic aspects (scalar and positional aspects of a movement), but not the morphokinetic (shape or pattern) aspects of the primary task. Overall, subjects were reasonably good at drawing squares and diamonds, although the shape and placement of the drawings did deteriorate in some aspects when they drew these shapes without visual feedback (no cursor) and when performing the secondary task. Without vision of the cursor, shapes were drawn less square and more rotated than with vision of the cursor. The addition of a secondary task did not worsen this decrement. During concurrent performance of the secondary task, there were changes in the size and location of the drawn shapes compared to the single-task no-cursor condition. Regarding the placement of the drawn shapes, subjects drew shapes below the reference shape,

especially when made without the cursor, and slightly more so (though not significantly) in the load conditions. Shapes were drawn more to the right for the verbal responding conditions. In the load conditions, subjects sometimes missed a corner, but this did not affect the location of preceding or following corners.

Vision, attention and drift

The impact of the secondary task on the location but not on the shape of the drawing suggests that in a shape-drawing task, those parameters may be processed separately. This is consistent with findings by Brown et al. (2003) on a simpler point-to-point reaching task and by Zelaznik and Lantero (1996) in a circle drawing task. There is mounting evidence that position sense is processed separately from dynamic movement, suggesting separate mechanisms for the regulation of limb position and shape parameters in primary and/or supplementary motor cortices (Proskoe 2006).

In terms of the position aspects of the movement, even with vision of the cursor there was significant drift of the stylus toward the subject across repetitions within each trial. Drift became worse without vision of the cursor; however, in the up/down direction we found no effect of the secondary task. Most previous studies reporting drift use more than 50 repetitions without visual feedback, while in our experiment there were only 3 repetitions for each trial, and it is possible that with more repetitions we would have shown an effect of the secondary task on drift. Our starting location represents a normal workspace position for writing and typing tasks and is a common starting position in other experiments: (15–45 cm, Henriques and Soechting 2005; 30 cm, Henriques et al. 2004; 30 cm, Klatzky 1999). These studies did not report any drift, in contrast with Brown et al. (2003) who found a lateral drift from the starting location when the hand was started at approximately 30 cm from the subject, and movement speed was higher. Alternatively, the complexity of drawing a square may be so great that even with vision of the cursor, but no external reference point, the near/far position component could not be maintained.

Drawings also drifted to the right in verbal responding load conditions. A possible explanation is that motor planning and execution of speech, rather than perceptual mechanisms, competed with resources for accurate placement of the shape. In other words in the verbal conditions, only the manner of response changed so we can conclude that conflict over synergies at the level of motor production caused the disruption. A second possibility is that the placement of the left hand in the manual responding condition “anchored” the right hand. This explanation is not supported since there was no rightward drift in either the

cursor or no-cursor conditions, and in each of these conditions the left hand was not in the workspace but on the knee, immediately below the workspace. It might also be posited that a challenge to working memory may be responsible for the proprioceptive drift. A study by Desmurget et al. (2000), however, suggests that variable delay periods, even up to 20 s between target presentation and reaching, do not on average affect proprioceptive drift when vision of the hand is occluded. In the present experiment, there is only 1-s delay between the termination of the trace phase and the beginning of the drawing phase, and the mean time for the drawing phase is less than 4 s.

Following the presentation of an arrow, subjects frequently drew two or more additional sides of the quadrilateral before responding to the arrow task. At that point, they responded coincidentally at the point of minimum drawing velocity, most frequently within 20 ms of starting a new line. Subjects apparently “buffered” the response to the secondary task, holding it in memory then integrating its execution with a change of direction in the primary drawing task. The prefrontal cortex (PFC) is a good candidate for a possible site of conflict causing a performance decrement in our verbal task as it has been implicated in movement planning and execution (Bullock 2004; Averbeck et al. 2003a, b). Sohn et al. (2000) demonstrated functional connections between the superior posterior parietal cortex, (important for movement guidance) and the PFC, particularly when subjects had foreknowledge of the action to be performed. Miller and Cohen (2001) argue that the PFC modifies and integrates behavior based on “rules” in concert with extensive interconnections with sensory, association and motor cortices, as well as connections with sub-cortical structures, such as the thalamus and basal ganglia, and provides control for top-down behavior. Furthermore, they suggest that the PFC maintains a response in memory until it is executed. If the PFC is responsible for the performance decrement, why is only the verbal response modality in our task affected? The answer may lie in an interconnected structure.

The PFC is known to have extensive interconnections with the pre-supplementary movement area (pre-SMA) (Bates and Goldman-Rakic 1993), which is implicated in planning of internally guided movements (Deiber et al. 1996), especially movements prepared in advance as compared to speeded response-type movements (Krams et al. 1998). Gowen and Miall (2007) also found increased activations of the pre-SMA in an internally generated shape-drawing task. Additionally, the pre-SMA has been found to be involved in internally cued speech production (Tremblay and Gracco 2009). The verbal responding condition of our load task required movement preparation, internally generated drawing, geometric shape production, and internally cued speech production. Given the

coincidence of these activities, a possible candidate for aiding in drift control of the primary movement task is the pre-SMA. In the Tremblay and Gracco study (2009), they found no effect of attention on the pre-SMA; however, their high attention task required greater semantic processing, but did not actually require selective attention among distractors nor did it divide attention among possible targets or tasks. This internal cueing for speech preparation and response selection attributed to the pre-SMA would also explain the higher incidence of missed and incorrect responses for the DTV and DRV conditions (respectively, Fig. 7). Equally, while some literature finds specific slowing of a primary tapping task due to story telling or recitation of a word list (Hiscock and Chipuer 1986) or reading (Hiscock et al. 1989), the movement times in our dual task verbal conditions were quicker under the verbal responding conditions than either the single task, no cursor or dual task timed manual responding conditions. This enigmatic result in the present study may be the consequence of choosing and preparing a verbal response: in the aforementioned studies the response was previously selected. We propose that when subjects concurrently performed the secondary task, performance suffered additionally only for the verbal responding conditions because of the competition for resources in the distributed processing of the pre-SMA.

Vision, attention and shape

The shape and proportion components of the quadrilateral became worse without vision but no additional deterioration was observed when load was applied: the shapes did not become less square with the secondary task. Even when a corner was missed (which occurred only rarely and only in the load conditions), subjects were able to find the following corners with remarkable fidelity. It seems that, even when subjects were so distracted by the secondary task that they entirely missed a corner, the brain still maintained an accurate map of the relative locations of the remaining points: the subjects had no vision of the hand or end effector, and were therefore relying either on proprioceptive information, and/or an internal representation of the shape. It is possible that if we had used a secondary movement requiring the movement of the elbow or shoulder as opposed to just the index and middle finger, there may have been an effect on the shape components.

Separate mechanisms for location and shape parameters

In the present study, we observed drift of location but preservation of pattern and proportion aspects of drawing movements made under an attentional load. A similar effect has been observed previously under various

conditions aimed at challenging performance through removing vision, ischemic compression, vibrating the tendons, or observing patients with complete afferent neuropathies. Vision plays an important role in limb localization, but less so in maintaining the pattern and proportion of the shape. We found that subjects drifted downward when vision was removed, but there was no alteration of the pattern and proportion aspects of the shape. Similarly, in another study using repetitive circle drawing, researchers found that when vision was removed, the spatial components of the task were altered in terms of the size and location, but the shape and roundness of the figure were maintained (Zelaznik and Lantero 1996).

In order to degrade proprioceptive information during a letter-drawing task, Laszlo and Bairstow (1971) applied a blood pressure cuff to subjects' arms. They found that the shape and proportion aspects of the letters were not maintained, concluding that proprioception is necessary for the structural components of a motor task. However, Kelso et al. (1975) found that during ischemic compression, impairment of motor function occurs before loss of proprioceptive information, making it likely that both motor function and proprioception were degraded. Likewise, when another group of researchers vibrated the tendons to disrupt proprioception, they found that the 16-cm circles were drawn smaller and the location also drifted relative to un-vibrated control conditions (Verschuere et al. 1999). The circles were drawn consistently wider than tall in all conditions, indicating that although distorted overall, pattern and proportion information was preserved.

This preservation of form despite drift is also observed in patients with total sensory neuropathy. In a deafferented patient, researchers found that the proportion and pattern aspects of handwriting were preserved even when vision was removed; however, the position, scale and orientation components were compromised. Moreover, the patient was observed to drift more than controls in a repetitive ellipse drawing task, while the overall shape of the figure was preserved (Teasdale et al. 1993). Ingram et al. (2000) found that a different deafferented patient, IW, was able to adapt to a visuomotor perturbation for a single joint movement, although a cognitive load of counting backward degraded his performance. In both experiments, the patients maintained the shape aspects of the drawings, but drifted considerably. It is probable that the attention necessary for maintaining a seated posture had some impact on the outcome in terms of drift (Ingram et al. 2000), but proprioception was not necessary to make the shape accurately. In summary, drift occurs without vision, and even more so when proprioception is degraded, absent, or challenged for attentional resources as seen in load conditions in the present experiment.

Missed corners and serial action

We found that in some cases, subjects entirely missed a corner of these well-known shapes, but were unaware that they had done so. They were able to continue drawing the shape and subsequent repetitions of the shape quite faithfully. This disruption and ability for continuation suggests that each component of the shape was prepared in advance, rather than being dependent on the preceding correct action; otherwise in Fig. 9a, our subject would have continued the drawing with a diagonal up and to the left, rather than toward the apex of the diamond. Lashley (1951) proposed that before execution, sequential acts such as typing, or indeed the drawing of quadrilaterals, were prepared in the brain as complete actions. Hence, transpositions of keystrokes in typing or spoonerisms in speech show the parallel preparation of all elements in the sequence. Bullock (2004) refers to this collective preparation of the sequence before its execution as a "fluent succession of acts" and implicates Brodmann's area 46, the dorsolateral prefrontal cortex. Lashley's hypothesis has been confirmed experimentally. Averbeck et al. (2003a, b) made recordings from ensembles of neurons from the right prefrontal cortex of monkeys as the monkeys drew different shapes copied from visually presented templates. During this serial motor behavior, the neuronal ensembles displayed distinctive patterns of activation corresponding to the beginning of each line segment. Before the drawing, all line segments in the shape were represented at the level of neuron populations, with the first segment of the sequence having a relatively stronger representation after the template stimulus had been presented but before the monkeys had begun to draw. As the monkeys began drawing each segment, the neural activation corresponding to that segment increased until the hand path was partially completed, at which point the next segment began to increase in neural activity. The peak of each activation corresponded to the commencement of each successive segment.

Averbeck et al. (2003a) also found that the strength of the neural representation for line segments was stronger for early and late segments than for middle segments, correlating to the commission of more errors in the middle segments. This corresponds to the ideas of primacy and recency in the recall of serially presented stimuli (Robinson and Brown 1926), where the researchers proposed that in a memory task, both the first and most recent elements in a series were most well remembered. When our subjects mistakenly missed corners of their drawings, more than 93.8% of those missed corners were in the middle of the drawing, contrasting with 0.8% for beginning segments and 5.4% for end segments. These animal studies and our behavioral results indicate that the prefrontal cortex may be a candidate location for some of the conflict experienced by

our subjects, since it is involved in the parallel preparation of serial acts. Overall, our finding of the strong preservation of the shape of the drawing over the location of the drawing suggests that prefrontal cortex–pre-SMA networks give priority to the shape of a drawing movement.

Was drift a result of identifying arrows or the motor act of responding?

It is reasonable to consider whether drift across repetitions in conditions with load and without vision were the consequences of perceptual processes or of processes related to the preparation and execution of movement plans. For drift we found different effects for verbal and manual responding, suggesting that the effects were not due to processing, but rather a consequence of competition at the level of motor preparation and production, with verbal and manual responses competing for different resources. Furthermore, in the cases where subjects completely missed a corner, there was no correlation between missing a corner and the angle of the arrow preceding the missed corner. Although the 3° arrow was more challenging to judge correctly, it did not occur more frequently before a missed corner than other arrow-angles.

In addition to the verbal and manual differences, we also manipulated the interval of the arrow presentation between fixed and random. In the secondary-task-only control group, subjects performed equally well at identifying the arrows whether the timing of the presentation stimulus was fixed or random, with correct responses at more than 92%. Clearly, the perceptual process was not a problem, nor was coordinating the index or middle fingers to indicate the correct response in either fixed or random intervals. When subjects were faced with randomly presented arrows, while concurrently drawing a shape in the dual-task conditions, they made their shapes larger than the template shape (Fig. 2). One possibility is that the increased uncertainty of the random presentation made the coordination of the primary task of drawing and the secondary task of responding more difficult, leading subjects to delay braking of the drawing movements in order to allow for synchronization of the responding task. Another possibility is that subjects were using the presentation of the arrow as an external timing cue for judging appropriate movement amplitude; however, this seems unlikely since arrows were presented both faster and slower than 1,000 ms, and any effect of cuing from the arrows would be neutralized, and there would simply be an increase in variability.

Conclusions

When subjects performed two tasks, performance of the more complex, primary drawing task was degraded in

terms of location, but not shape and proportion components. This supports previous work showing a separate control and regulation for location and pattern aspects of limb movement. Vision played an important role in the preservation of the position, scale and orientation elements of the drawing. When vision was removed, drift across repetitions within a trial increased, and when a load was added, this drift increased to the right showing that while proprioception alone is inadequate for accurately maintaining position of a limb, proprioceptive performance deteriorates when attention is divided. For the shape and pattern components, overall performance was not degraded under the secondary load, except when subjects naively missed a corner. This finding, along with literature involving proprioceptive disruption suggests that proprioception is not necessary for producing drawing movements of known shapes, rather that internal representations of the movement may be employed.

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