Oculomotor responses and visuospatial perceptual judgments compete for common limited resources

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While there is evidence for multiple spatial and attentional maps in the brain it is not clear to what extent visuoperceptual and oculomotor tasks rely on common neural representations and attentional mechanisms. Using a dual-task interference paradigm we tested the hypothesis that eye movements and perceptual judgments made to simultaneously presented visuospatial information compete for shared limited resources. Observers undertook judgments of stimulus collinearity (perceptual extrapolation) using a pointer and Gabor patch and/or performed saccades to a peripheral dot target while their eye movements were recorded. In addition, observers performed a non-spatial control task (contrast discrimination), matched for task difficulty and stimulus structure, which on the basis of previous studies was expected to represent a lesser load on putative shared resources. Greater mutual interference was indeed found between the saccade and extrapolation task pair than between the saccade and contrast discrimination task pair. These data are consistent with visuoperceptual and oculomotor responses competing for common limited resources as well as spatial tasks incurring a relatively high attentional cost.

Keywords: active vision, detection/discrimination, eye movements, spatial vision, attention


Introduction

There is considerable debate as to whether visual attention is a single unified resource, or whether in fact, judgments of different stimulus attributes (e.g., position, color and luminance) tap into distinct attentional resources. Thus, while several studies have shown comparable levels of interference between similar and dissimilar task pairings (Lee, Itti, Koch, & Braun, 1999; Lee, Koch, & Braun, 1999; Pastukhov, Fischer, & Braun, 2009), Morrone, Denti, and Spinelli (2002, 2004) report evidence to suggest that color and luminance judgments recruit distinct attentional resources. Parallel debates exist over the extent to which common attentional resources, attentional selection mechanisms (Deubel, Schneider, & Paprottta, 1998; Schneider & Deubel, 2002), and neural representations (Altmann, Grodd, Kurtzi, Bülthoff, & Karnath, 2005; Burr, Morrone, & Ross, 2001; Cavina-Pratesi, Goodale, & Culham, 2007; Collins, Dore-Mazars, & Lappe, 2007; Eckstein, Beutter, Pham, Shimozaki, & Stone, 2007; Eggert, Sailer, Ditterich, & Straube, 2002; Faillenot, Sunaert, Van Hecke, & Orban, 2001; Rice, Valyear, Goodale, Milner, & Culham, 2007; Tibber, Anderson, Melmoth, Rees, & Morgan, 2009; Valyear, Culham, Sharif, Westwood, & Goodale, 2006) subserve perceptual and oculomotor responses (i.e., “vision/selection-for-perception” versus “vision/selection-for-action”). For example, several studies have demonstrated that when eye movements are centrally cued to a peripheral spatial location sensitivity to a perceptual probe is relatively enhanced at the saccadic landing site prior to movement onset (Kowler, Anderson, Dosher, & Blaser, 1995), arguing for a tight and obligatory coupling between eye movements and visuoperceptual attention.

While this phenomenon has been described for discriminations involving judgments of stimulus orientation (Castet, Jeanjean, Montagnini, Laugier, & Masson, 2006; Lee & Lee, 2008; Montagnini & Castet, 2007), the discrimination of a letter from its mirror-symmetric rotated counterpart (Baldauf & Deubel, 2008; Deubel, 2008; Deubel & Schneider, 1996; Schneider & Deubel, 2002) as well as alphanumeric character identification (Hoffman & Subramaniam, 1995; Kowler et al., 1995; Van der Stigchel & Theeuwes, 2005), a similar target-site benefit was not found for the detection of a briefly presented luminance increment (Remington, 1980), a fact that led the authors to conclude that the oculomotor system is relatively independent of visuoperceptual attention. However, it has since been shown that luminance...
of attentional resources (Pastukhov et al., 2009). This raises the possibility that Remington (1980) failed to find a link between visuoperceptual attention and saccadic eye movements as a result of using a non-spatial secondary task that was not attentionally demanding.

To test the theory that visuoperceptual judgments and oculomotor responses compete for common limited resources, and secondly, that spatial and non-spatial perceptual judgments make different claims on this resource, we employed a dual-task interference paradigm (Kowler et al., 1995; Pashler, 1994b; Pashler, Carrier, & Hoffman, 1993), in which observers performed eye movements and perceptual judgments in response to simultaneously presented visual information (Duncan, 1980). Two main perceptual tasks were undertaken: a perceptual extrapolation, which engages spatial processing mechanisms, and a non-spatial contrast discrimination, which does not require explicit encoding of stimulus position (see Figure 1A). If perceptual judgments and oculomotor responses compete for common attentional resources (Deubel et al., 1998; Schneider & Deubel, 2002) there should be a high degree of inter-task interference when observers attempt to concurrently undertake a perceptual extrapolation and saccadic eye movement. In addition, if spatial and non-spatial tasks make different claims on these resources, on the basis of previous studies we would expect interference between the non-spatial perceptual and eye movement tasks to be considerably reduced (Bonnel et al., 1992; Lee et al., 1997; Remington, 1980).

**Experiment 1**

In order to test for interference effects between eye movements and perceptual judgments it was first necessary to determine whether the two basic perceptual tasks were capacity limited. Consequently, we examined observers’ accuracy at performing perceptual extrapolations and contrast discriminations independently (single-task conditions: extrapolation, contrast discrimination) as well as concurrently with a second identical task (dual same task conditions: extrapolation/extrapolation, contrast/contrast) and concurrently with a different task (dual different task conditions: extrapolation/contrast) performed on two patches at different spatial locations. As an additional control condition observers performed a perceptual extrapolation and contrast discrimination on a single target patch (double report condition).

**Methods**

**Participants**

Four observers took part in Experiment 1 including one of the authors, two highly experienced observers (naive to the purpose of the experiment), and a naive observer with
no previous experience of psychological studies. In all experiments informed written consent was obtained in accordance with the Declaration of Helsinki, and ethical approval was obtained from the ethical committee of City University’s Optometry Department, reporting to the Senate Ethical Committee.

Stimuli

Stimuli were generated using MATLAB (The MathWorks, Natick, MA) with the Cambridge Research Systems toolbox (CRS) and were presented on a luminance calibrated Sony Trinitron monitor in conjunction with the Cambridge VSG graphics card. Images were presented at a spatial and temporal resolution of 800 × 600 pixels and 100 Hz, respectively, and viewed under ambient light conditions at a distance of 50 cm.

The perceptual targets and fixation patch were Gabor patches with identical spatial dimensions—random phase, σ = 0.8 degrees of visual angle (DVA) with a spatial frequency of 3 cycles per degree (cpd)—and were presented against a background gray display of 21.8 cd/m² (Figure 1A). The contrast of the fixation patch was set at 50% while the contrasts of the target patches were manipulated according to task requirements. The pointers subtended 3.3 DVA at the correct viewing distance and had proximal tips located at the centroid of the fixation patch. The two pointers were always oriented at +45° or −45° to the horizontal. However, in order to minimize the likelihood that observers used an internal standard to perform the task random angular jitter (±0–5°) was independently added to the basic orientation of both pointers on each trial. In addition, the entire stimulus (fixation patch, pointers, and targets) was randomly shifted in the vertical plane between −0.5 and +0.5 DVA. The centroids of both targets (Gabor patches) were presented iso-eccentrically from fixation and lay on the circumference of a theoretical circle with a radius of 13.7 DVA whose centroid coincided with that of the fixation patch. In order to remove extraneous luminance/contrast cues during contrast discrimination tasks the luminance of the pointers and contrast of the irrelevant Gabor patch were randomly jittered (±0–6%) in the appropriate task conditions.

Procedure

Two basic perceptual tasks were undertaken: a perceptual extrapolation/judgment of collinearity, in which observers judged a Gabor patch as being offset clockwise (CW) or anti-clockwise (ACW) relative to an axis defined by a pointer (with one tip rooted at fixation), and a contrast discrimination, in which observers judged whether a target patch was of higher or lower contrast than the patch presented at fixation (see Figure 1A). Trials began with the appearance of a Gabor patch at fixation, which remained onscreen throughout the trial. After 700 ms the entire stimulus ensemble was presented for 300 ms; this consisted of two Gabor patches and two pointers. [Note: both patches and pointers were always present, irrespective of whether the condition required judgments to be made on a single patch (single-task conditions) or on two patches (dual-task conditions). Consequently, a constant stimulus structure was maintained across all conditions.] The observer was then presented with a blank screen and an unlimited interval in which to make a single response (single-task conditions) or two responses (dual-task conditions).

In the single-task extrapolation condition judgments were made on a patch presented in the upper right quadrant (see Figure 1A). Conversely, in the single-task contrast condition, judgments were made on a target presented in the lower right quadrant. Dual-task performances were then related to these baseline measures of sensitivity. For example, in the dual different extrapolation condition, extrapolation acuity was measured for a target in the upper quadrant while observers simultaneously performed a contrast discrimination on a target presented in the lower right quadrant (see Table 1 for more details). As an additional control (double report) condition observers made extrapolation and contrast discrimination judgments on a single patch presented in the upper hemifield.

All stimulus levels (target offset relative to the point of collinearity and contrast difference between target and fixation patches) were controlled independently by a 2-down-1-up adaptive staircase. This converged on points of the underlying psychometric function for which CW/ACW responses were given 71% of the time. Hence, both the bias and threshold were actively tracked. Independently running increment and decrement staircases were interleaved (75 trials per staircase) so that a total of 150 trials were completed per block. Trials were blocked according to condition type (extrapolation: single, dual same, dual different and double report; contrast: single, dual same, dual different) and were presented in a pseudorandom order. (Note however that extrapolation and contrast dual different conditions are identical. See Table 1.) To minimize the likelihood of observers prioritizing one of the tasks, all multiple task conditions were performed twice,

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Table 1. Perceptual dual-task conditions. *These two conditions are in fact identical.
with the report orders reversed. In addition, participants were instructed to allocate equal attention to the two tasks and maintain fixation throughout. All blocks were repeated a minimum of 3 times by each observer.

Analysis

As observers’ responses showed large biases that varied seemingly idiosyncratically between experimental sessions (potentially confounding measures of observer sensitivity) data from each block were independently fit with 2-parameter Cumulative Gaussian psychometric functions using a method of maximum likelihood estimation (Wichmann & Hill, 2001a, 2001b). The point of subjective equality (relative to the orientation of the pointer) and slope of the underlying cumulative Gaussian distribution were taken as measures of bias and sensitivity, respectively. These were then averaged across blocks for each condition and each observer.

Results

In Figure 1B group mean extrapolation and contrast discrimination sensitivities (dual-task sensitivity divided by baseline single-task sensitivity) are shown for different dual-task combinations performed on distinct target patches: same (two extrapolations or contrast discriminations) and different (an extrapolation and a contrast discrimination). In addition, the white circle represents dual-task extrapolation performance when the second task is a contrast judgment made on the same patch (double report condition). As can be seen, when the two judgments were made on a single-patch at a single spatial location, extrapolation performance was indistinguishable from baseline \( t(3) = 0.29, P = 0.79 \) (single-sample \( t \)-test corrected for multiple comparisons). This is consistent with previous reports showing minimal/negligible interference when multiple judgments are made in response to a single spatial location or visual object (Duncan, 1980, 1984; Pashler, 1994a). However, as soon as spatial attention was divided across different locations and multiple judgments were made on distinct patches, performance fell below baseline. The magnitude of this effect was not equal across conditions. Thus, only the extrapolation-same and contrast-different condition performances were significantly different from baseline \( t(3) = 4.5, P = 0.05 \) and \( t(3) = 4.8, P = 0.04 \), respectively; all other \( t s < 2.8, Ps > 0.16 \) (single-sample \( t \)-tests corrected for multiple comparisons).

This pattern was confirmed by a repeated measures ANOVA with 2 factors, each at two levels (task type: extrapolation or contrast discrimination; task combination: same or different). Thus, there was no main effect of task type \( F(1,3) = 0.99, P = 0.39 \) (or task combination \( F(1,3) = 0.03, P = 0.87 \). However, there was a highly significant interaction between the two \( F(1,3) = 70.2, P = 0.004 \), reflecting the fact that performance on both tasks was significantly impaired when an extrapolation judgment was undertaken concurrently (extrapolation same and contrast different conditions).

Discussion

The results unambiguously demonstrate that both perceptual judgments (extrapolations and contrast discriminations) were susceptible to dual-task interference when performed in conjunction with a spatial extrapolation judgment. This finding adds credence to the theory that spatial tasks are particularly demanding on attentional resources (Pastukhov et al., 2009) and, further, supports the notion of a single integrated attentional resource (Lee, Itti et al., 1999; Lee, Koch et al., 1999; Pastukhov et al., 2009).

Experiment 2

Having shown that both perceptual tasks are susceptible to dual-task interference when performed concurrently with a perceptual extrapolation, we went on to determine whether perceptual extrapolations would similarly impair oculomotor responses made to simultaneously presented visuospatial stimuli. Given our original hypotheses, we predicted that mutual interference would be greater between concurrently performed perceptual extrapolations and target-oriented saccades than it would be between contrast discrimination judgments and eye movements.

Methods

Participants

Five observers took part in Experiment 2, including two of the authors, two highly experienced observers (naive to the purpose of the experiment), and one naive observer with no previous experience of psychological studies.

Stimuli

Stimuli were presented on a calibrated Protouch 17-inch TFT flat-screen display (928 × 799 pixels; 60 Hz) and eye movements were recorded using an ISCAN RK-464 eye tracker (60 Hz) with observers supported by a stabilizing chin rest. Stimulus dimensions were scaled to match Experiment 1. The only difference was that in Experiment 2 the upper patch was a solid black dot (radius of 0.4 DVA) instead of a Gaussian blob, and the upper pointer was not present (Figure 2). However, the position of the saccadic target was determined precisely the same.
way as the upper target in Experiment 1: it was presented at −45 degrees relative to fixation ±0–5° angular jitter. In addition, the luminance of the saccadic target and lower pointer were also jittered (±0–6%) to remove any possible cues to the contrast discrimination task.

**Procedure**

Observers completed 3 single-task conditions: a perceptual extrapolation, a contrast discrimination, and a saccade to a dot target. In addition, two dual-task conditions were included: saccade plus extrapolation, and saccade plus contrast discrimination, giving a total of five conditions. These were presented in blocks of 100 trials each. For all observers each condition/block was repeated 3 times.

Similar to Experiment 1 the structure of the stimulus was consistent across conditions. Thus, following a 700-ms fixation period, a single pointer and Gabor patch (perceptual target) were presented in the lower right quadrant for 300 ms, along with a single black dot (saccadic target), presented simultaneously in the upper right quadrant (Figure 2). All perceptual judgments were thus undertaken on the lower (perceptual) target, while saccades were directed toward a target in the upper right quadrant. The single perceptual task conditions were otherwise identical to Experiment 1: observers had to determine whether the Gabor patch was offset CW or ACW relative to the pointer axis (extrapolation), or else indicate whether the target was of a higher or lower contrast than the patch presented at fixation (contrast discrimination). In these conditions, observers were instructed to maintain fixation throughout; the saccadic target was irrelevant to the task but was maintained onscreen nonetheless. In the saccade only condition, which provided a measure of baseline oculomotor performance, observers were instructed to maintain fixation until stimulus onset, at which point they were to saccade to the upper (dot) target. Observers then maintained their gaze at this location until a short auditory beep indicated that they could move their eyes back toward the center of the screen in anticipation of the next trial (Figure 2).

In the dual-task conditions observers made a saccade to the target following stimulus onset and then had an unlimited response time—following the beep—to make a judgment about the perceptual target’s position or relative contrast. To minimize participants’ head/body movements following calibration of the eye tracker responses were indicated by a movement of the right index finger or thumb and recorded on the computer by the experimenter. In all conditions involving eye movements observers were instructed to saccade to the saccade target “as soon as the target appears” and given repeated reminders of this instruction every 50 trials.

Hence, priority should have been given to eye movement performance with emphasis on minimizing movement onset time.

**Analysis**

Two out of the 5 observers (HW and AT; the least practiced on eye movement/extrapolation tasks) exhibited a consistent drop in basic movement onset times across each of the 3 experimental sessions and a lack of inconsistent pattern of interference effects. To verify this pattern in the data quantitatively, for each individual we derived a practice effect index, which was calculated by taking the gradient of a line fit to a plot of movement onset time against practice session. A subsequent independent samples t-test using these indices confirmed that observers HW and AT exhibited a significantly greater practice effect than did the other observers ($t(3) = 3.32$, $P < 0.05$). Therefore, eye movement and psychophysical data for these two observers were only included from the last of three experimental sessions.

Basic eye movement data were analyzed using custom-written Matlab scripts with saccades defined as any displacements of gaze direction (initially computed independently for the horizontal and vertical axes) that exceeded a velocity threshold of 20 degrees per second, an amplitude threshold of one degree, and with the additional criterion that it must be followed by a minimum fixation period of 100 ms.
period of 50 ms. Data were temporally smoothed prior to analysis and individual trials corrupted by blinks or featuring multiple saccades were discarded. Saccade endpoints are defined in non-standard polar coordinate notation such that positive values represent a CW deviation from the zero azimuth. The radial/eccentricity coordinate ($r$) is expressed in degrees of visual angle (DVA) relative to fixation; the angular coordinate ($\theta$) is measured in degrees ($^\circ$). The constant error (an observer’s bias) and variable error (a measure of sensitivity) were defined as the mean and standard deviation of saccade endpoints in both the eccentricity and angular domains.

**Results**

In Figure 3, group data are presented in the form of attention operating characteristic (AOC) plots (Sperling & Melchner, 1978), which show how perceptual task and...
eye movement sensitivity are affected under dual-task conditions (Kowler et al., 1995). Although data are normally presented in this format when observer instructions are systematically varied to manipulate the proportion of attention dedicated to either task, even under single instruction conditions AOC plots provide a concise way of presenting a large amount of data. In addition, raw individual observer data are provided in a supplementary figure (Figure S1) so that inter-individual variation and absolute parameter levels can be noted.

For all observers and all tasks performance was normalized relative to the individual’s baseline performance, so that inter-observer differences in baseline performance were removed. Perceptual task performance (sensitivity) is plotted along the x-axis with various measures of saccadic performance plotted along the y-axis. These include: movement onset time (Figure 3A—lower values representing longer onset times), maximum movement velocity (Figure 3B—lower values representing slower velocities), and landing site variable error (accuracy) in the eccentricity (Figure 3C) and angular (Figure 3D) domains (lower values representing a greater spread of landing sites). In addition, landing site constant error (bias) was also calculated; however, this parameter is not presented in AOC format as biases are signed and may be strategic (i.e., functionally adapted; see supplementary Figure S1). While baseline (single-task) performance is represented by the outer data points the central data point represents dual-task performance. The cross denotes the point of independence and represents theoretical dual-task performance under conditions of zero interference. Error bars represent the standard error of the mean (SEM); where not visible they are smaller than the data points.

As can be seen from Figure 3, the middle (dual-task) data points are consistently shifted downward and toward the left in both the extrapolation and contrast discrimination conditions, reflecting negative interference effects. To see if these interference effects were significant a series of one-sampled t-tests was performed to determine whether eye movement performance levels were significantly different from 1 (baseline performance). For the extrapolation and saccade dual-task condition highly significant interference effects ($P < 0.01$) were found for movement onset times ($t(4) = 6.31, P = 0.003$) and constant errors in the angular domain ($t(4) = 5.04, P = 0.007$) but only approached significance ($P < 0.1$) for variable and constant errors in the eccentricity domains ($t(4) = 2.29, P = 0.084; t(4) = 2.42, P = 0.072$) as well as maximum movement velocity times ($t(4) = 2.15, P = 0.098$) once corrections for multiple comparisons were made (Bonferroni correction). However, there was no detectable interference effect with respect to variable errors in the angular domain ($t(4) = 1.81, P = 0.14$). In the contrast discrimination dual-task conditions none of the interference effects reached or even approached statistical significance (all $P > 0.1$).

Although all central data points were shifted downward and to the left of the point of independence there was clearly a trend for this shift to be greater in the extrapolation condition. To verify this quantitatively eye movement performance levels were compared for the extrapolation and contrast discrimination dual-task conditions using a series of one-tailed paired-samples t-tests. These show that movement onset was delayed to a greater extent by the simultaneous performance of a perceptual extrapolation than it was by a contrast discrimination ($t(4) = 2.94, P = 0.021$). In addition, maximum movement velocities were significantly lower in the extrapolation dual-task condition ($t(4) = 3.76, P = 0.01$) and the accuracy of the landing point in the eccentricity domain (i.e., the variable error) was significantly more impaired ($t(4) = 5.98, P = 0.002$). In contrast, landing site variable error (bias) in the angular domain did not differ significantly between task pairs ($t(4) = 0.46, P = 0.33$).

Raw data on landing site biases were compared for the extrapolation and contrast dual-task conditions. Saccadic landing site constant errors (biases) in the eccentricity domain were found to be more negative (i.e., saccades fell short of the target to a greater extent) in the extrapolation dual-task condition ($t(4) = 4, P = 0.02; two-tailed$); however, there were no differences between extrapolation and contrast dual-task conditions with respect to constant errors in the angular domain ($t(4) = 0.52, P = 0.77; two-tailed$). Thus, in conclusion, relative to the saccade + contrast condition, saccades made concurrently with a visuospatial perceptual judgment were delayed, slower, and less accurate in terms of the distance moved; in addition, they were biased such that the final landing position fell short of the target.

Finally, to check that the better eye movement performance in the saccade and contrast task pair was not achieved at a greater cost to perceptual task performance we also compared perceptual task performances in the two dual-task conditions using a one-tailed paired-samples t-test. This indicated that perceptual task sensitivity was in fact poorer in the extrapolation and saccade task pair than it was in the saccade and contrast task pair ($t(4) = 5.94, P = 0.002$). Further, dual-task extrapolation and contrast discrimination performances were significantly worse than baseline (single-task) performance ($t(4) = 7.25, P = 0.002$, $t(4) = 3.9, P = 0.018$, respectively). Thus, the elevated interference effect between concurrently performed saccades and a visuospatial perceptual task is bidirectional, impairing both eye movement and perceptual task performance alike.

**Discussion**

Perceptual extrapolations were found to incur a greater cost on eye movement performance than did contrast discrimination judgments. These findings are consistent with (1) perceptual judgments and oculomotor responses
relying on shared attentional mechanisms and (2) non-spatial perceptual tasks presenting a relatively low drain on these resources.

Experiment 3

Finally, given the prolonged movement onset time reported in the saccade + extrapolation task pairing we wondered whether the elevated interference reported might simply reflect a time-consuming extrapolation process. To assess this possibility we examined the processing time required to perform the basic perceptual judgments using a post-stimulus pattern mask. Observers performed single-task judgments (extrapolation and contrast discrimination) on post-masked images presented at varying stimulus durations. Pattern post-masks are thought to interrupt processing of a stimulus by flooding or diverting resources away from channels sensitive to the target (Reeves, 2007; Rolls, Tovee, & Panzeri, 1999). Although pilot data were gathered using several different mask types a “random lines” pattern mask provided the most robust masking effect (Figure 4).

Methods

Participants

Three observers took part in Experiment 3, including one of the authors, one highly experienced observer (naive to the purpose of the experiment), and a naive observer with no previous experience of psychological studies.

Stimuli

Stimulus contrast and structure was identical to that described in Experiment 1; however, the stimulus presentation time was manipulated in separate blocks. In addition, following offset of the stimulus a broadband “random lines” mask was presented onscreen for 300 ms (Figure 4). This was composed of 800 maximum contrast black and white contours of single pixel width: 400 of these were of a random orientation, position, and length, while a further 400 (of random length and orientation) projected radially outward from the location previously occupied by the centroid of the fixation patch.

Procedure

All observers made judgments at five stimulus presentation times (30, 50, 70, 100, and 300 ms) and performed 3 blocks of 150 trials per time point per task. Blocks were presented in a pseudo-random order, and the mask was presented for 300 ms. Following offset of the mask, observers indicated their response [target offset above or below (extrapolation task), contrast higher or lower (contrast discrimination task)] by button press.

Analysis

Data from the 30-ms stimulus presentation time were excluded from analysis as performance was at chance. For each observer and each task, all psychophysical data (from the remaining 4 time points) were fit with a 2-parameter power function using the method of maximum likelihood estimation (MLE). However, as observers exhibited large and seemingly idiosyncratic biases between

Figure 4. Trial sequence for Experiment 3. Observers performed single-task perceptual extrapolation and contrast discrimination judgments on post-masked stimuli over a range of stimulus presentation times.
experimental sessions at lower stimulus presentation times (i.e., even on identical tasks/conditions), all data were initially normalized with respect to biases before they were fit using the methods described above. In order to do this, data from each time point were independently fit with a two-parameter Gaussian distribution; the mean of this distribution was then subtracted from the stimulus levels (target offset for the extrapolation task and contrast for the contrast discrimination task), so that data were essentially bias free (Morgan, Giora, & Solomon, 2008).

Results

Individual extrapolation and contrast discrimination sensitivities are plotted as a function of stimulus duration following post-masking of the target stimulus (Figure 5). As can be seen, data are well fit by a series of power functions, suggesting that sensitivity increases as a function of increasing stimulus presentation time. However, critically, for all 3 observers the exponent term for the best fitting power function was consistently more positive for the contrast discrimination data than for the extrapolation data [MT: 0.66 vs. 0.35; NG: 0.78 vs. 0.32; JP: 0.5 vs. 0.46], suggesting that if anything, reducing the stimulus presentation time had a greater limiting effect on contrast discrimination performance. However, this difference was not significant in a paired-samples t-test ($t(2) = 2.2, P = 0.16$).

Discussion

These data clearly rule out the possibility that the differential interference pattern between the two perceptual tasks and saccadic eye movements described in Experiment 2 can be attributed to a sluggish extrapolation process.

Conclusions

This study was designed to test two main hypotheses: firstly, that visuospatial perceptual judgments and eye movements share common and limited resources (Kowler

Figure 5. Perceptual extrapolation and contrast discrimination data (single task/masked stimulus) were fit with a series of power functions (solid lines) using the method of maximum likelihood estimation (MLE); the exponent terms of the best fits are presented (in brackets). Data from individual time points were also independently fit with a series of cumulative Gaussians (using MLE). Sensitivity levels (1/threshold) thus derived are also presented; error bars represent 95% confidence limits. Stim(T)—stimulus presentation time (in milliseconds).
et al., 1995), and secondly, that a visuospatial perceptual task represents a greater drain on these resources than does a carefully matched non-spatial control task (Pastukhov et al., 2009). Both of these hypotheses were supported by the data: the results show that perceptual extrapolations share common limited resources both with a non-spatial perceptual task (Experiment 1) and a spatial oculomotor task (Experiment 2), and further, that there is significantly greater interference between the saccade and extrapolation task pair than there is between the saccade and contrast task pair (Experiment 2), a finding that cannot be attributed to a sluggish extrapolation process (Experiment 3). In fact, while there was a general trend toward reduced accuracy saccades in the saccade + contrast task pair (relative to baseline), none of these effects reached significance. While an alternative interpretation of the data may thus be that non-spatial perceptual judgments and eye movements depend on completely separate attentional resources this seems unlikely for several reasons. First, as mentioned above, while eye movement performance was not significantly impaired by concurrent contrast discrimination judgments there was a clear and consistent trend in this direction, which may have reached significance if a larger sample size had been used. Secondly, performing a concurrent saccade did significantly impair contrast discrimination performance. Finally, contrast discrimination performance was found to be susceptible to dual-task interference from a concurrent extrapolation judgment (Experiment 1), which in turn was shown to tap into the same resources as do target-directed saccades (Experiment 2). Therefore, the most parsimonious explanation of the data from Experiments 1–3 is that oculomotor responses and perceptual judgments rely on common resources that are heavily drawn upon by spatial tasks.

The finding that interference effects on saccadic eye movements are lower for a concurrently performed non-spatial perceptual task—rather than a spatial perceptual task—sheds some light on what may have been perceived as a discrepancy in the existing literature. Thus, while sensitivity for judgments of orientation (Castet et al., 2006; Lee & Lee, 2008; Montagnini & Castet, 2007), the discrimination of a letter from its mirror-symmetric rotated counterpart (Baldauf & Deubel, 2008; Deubel, 2008; Deuel & Schneider, 1996; Schneider & Deubel, 2002) as well as alphanumeric character identification (Hoffman & Subramaniam, 1995; Kowler et al., 1995; Van der Stigchel & Theeuwes, 2005) is known to be elevated at target site locations presaccadically, a similar effect was not found for the detection of a briefly presented luminance increment (Remington, 1980). While this led Remington et al. to conclude that the oculomotor system is relatively independent of visuoperceptual attention, the experiments reported here—which examine interference effects between spatial and non-spatial perceptual tasks and concurrently performed eye movements within a single carefully controlled study—instead suggest that oculomotor responses and visuoperceptual judgments do in fact rely on the same attentional mechanisms, its just that non-spatial tasks are relatively non-demanding. Our data are thus also consistent with previous demonstrations that “the discrimination of relative position places a particularly high demand on attention” (Pastukhov et al., 2009; see also Hess, Barnes, Dumoulin, & Dakin, 2003).

Thus, we have shown that the comparatively high cost on attentional resources of a spatial task is true even of carefully controlled spatial and non-spatial tasks matched for stimulus structure and task performance.

Given the purported role of the dorsal stream in spatial vision (Mishkin, Lewis, & Ungerleider, 1982) it also worthy of note that in a series of studies into the effects of performing saccades on basic psychophysical task performance Irwin and Brockmole (2004) have come to the conclusion that typical dorsal stream (e.g., visuospatial) tasks are suppressed during saccades, whereas ventral stream tasks are not. Thus, they report that horizontal eye movements interrupt the classification of an object’s direction of facing but not recognition of the object itself (Irwin & Brockmole, 2004). Similarly, numerical magnitude comparison (Irwin & Thomas, 2007), attentional shifts of scale (Brockmole, Carlson, & Irwin, 2002), and mental rotation (Irwin & Brockmole, 2000; all putatively dorsal stream tasks) are selectively suppressed during saccades, whereas parity judgments (Irwin & Thomas, 2007), identity priming (Irwin, Carlson-Radvansky, & Andrews, 1995), and word recognition/identification (Irwin, 1998) are unaffected. However, as task difficulty or observer performance was rarely verified, controlled, or equated in these tasks, the findings are difficult to interpret, and may instead simply be consistent with saccades showing greater (i.e., detectable) interference effects when coupled with perceptual tasks that are relatively difficult and/or those which are heavily spatial in nature, e.g., those involving judgments of object orientation, direction of facing, or rotation.

Several other converging lines of research highlight a close coupling between visuoperceptual and oculomotor space. Thus, there is evidence for a distortion of visual space around the time an eye movement is executed (perisaccadic mislocalization or compression; Cai, Pouget, Schlag-Rey, & Schlag, 1997; Honda, 1993; Kaiser & Lappe, 2004; Matin & Pearce, 1965; Ross, Morrone, & Burr, 1997; Schlag & Schlag-Rey, 1995) or when spatial information is retrieved from working memory following execution of a saccade (Bays & Husain, 2008). Further, when systematic saccade targeting errors are corrected over time in an adaptive manner (saccadic adaptation) perceptual judgments are similarly skewed (Collins et al., 2007), suggesting that a common map underlies both decision processes (Eckstein et al., 2007). Finally, saccades made in the presence of non-attended distracters exhibit systematic biases toward or away from the distracters (Ludwig, Gilchrist, & McSorley, 2005; McSorley, Haggard, & Walker, 2004, 2005, 2006; Nummenmaa &
Hietanen, 2006), suggesting that even unattended task-irrelevant stimuli gain partial access to a level of representation that encodes goal-directed saccadic targets (Doyle & Walker, 2002; McPeek, 2006).

In conclusion, the dual-task interference data reported provide strong evidence to suggest that visuospatial extrapolations and eye movements directed toward explicit targets compete for common limited resources. In addition, the results indicate that a non-spatial perceptual task (i.e., a contrast discrimination) is less demanding of these common resources, even when matched to the spatial task with respect to stimulus structure and task difficulty/observer performance. Future studies are needed however to begin to disentangle the nature of these interference effects—thus, it remains to be seen whether oculomotor and visuoperceptual spatial tasks compete for common representations of space as well as general attentional resources.

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