

The effects of array structure and secondary cognitive task demand on processes of visual search.

Dr Steven William Savage, CPsychol,

Schepens Eye Research Institute, Massachusetts Eye and Ear, Harvard Medical School

20 Staniford Street, 02114 Boston MA, USA. +1 (617) 912-2527,

Steven_Savage@meei.harvard.edu

Dr Douglas D Potter

University of Dundee, Scotland

Professor Benjamin W Tatler

University of Aberdeen, Scotland

Word Count 8813

The effects of array structure and secondary cognitive task demand on processes of visual search.

Many aspects of our everyday behaviour require that we search for objects.

However, in real situations search is often conducted while internal and external factors compete for our attention resources.

Cognitive distraction interferes with our ability to search for targets, increasing search times. Here we consider whether effects of cognitive distraction interfere differentially with three distinct phases of search: initiating search, overtly scanning through items in the display, and verifying that the object is indeed the target of search once it has been fixated.

Furthermore, we consider whether strategic components of visual search that emerge when searching items organized into structured arrays are susceptible to cognitive distraction or not. We used Gilchrist & Harvey's (2006) structured and unstructured visual search paradigm with the addition of Savage, Potter & Tatler's (2013) secondary puzzle task.

Cognitive load influenced two phases of search: 1) scanning times and 2) verification times. Under high load, fixation durations were longer and re-fixations of distracters were more common. In terms of scanning strategy, we replicated Gilchrist & Harvey's (2006) findings of more systematic search for structured arrays than unstructured ones. We also found an effect of cognitive load on this aspect of search but only in structured arrays. Our findings suggest that our eyes, by default, produce an autonomous scanning pattern that is modulated but not completely eliminated by secondary cognitive load.

Keywords: Visual search; Cognitive Control and Automaticity; Eye movements and visual attention

Introduction

How is search disrupted by cognitive distraction? Visual search is at the heart of our visual behaviour: each eye movement we make involves a search of peripheral vision to identify the target of the next saccade, and search for an object in a cluttered scene can take several saccades until the object is correctly located and scrutinised by central

vision. While our understanding of visual search in simple arrays and complex scenes is relatively well developed, the conditions under which we search in the lab are often unlike those under which we search in real situations. In particular, when we search in real situations, search is rarely the sole task we are engaged in. Rather search is conducted in situations where internal and external factors compete for our attention resources. Real environments are visually cluttered (unstructured), dynamic and noisy. However, there are also situations where the arrangement of objects in the environment provides structure for our search, for example looking for a specific cereal in a supermarket or your car in a crowded parking lot. Furthermore, we are often preoccupied, thinking about other things. This preoccupation can come from within the task we are engaged in: when searching for a particular object we are likely doing so as part of a larger behavioural goal and the processes of monitoring progress and planning the next steps of the task are themselves cognitively demanding. Preoccupation can also come from distracting secondary tasks such as contemplating previous conversations, rehearsing a shopping list, or listening to the radio. In some real world scenarios such cognitive preoccupation can have a profound effect on our ability to complete attentionally demanding real-world tasks (such as driving). Given the attentional demands of search, which are both low-level and high-level, it is likely that our ability to search effectively might be at risk from cognitive distraction.

Previous work has shown that distraction by secondary tasks can make search slower (Oh & Kim, 2004; Woodman & Luck, 2004), with participants being slower to initiate search, spending longer overtly scanning the items in the display and being slower to verify that the target has been found once it is looked at (Solman, Cheyne & Smilek, 2011). These previous studies have used working memory paradigms based upon memory for recently seen visual displays. However, little is known about the

impact of cognitive load coming from less visual sources, such as preoccupation with a previous conversation, upon search. Furthermore, whether secondary cognitive load impacts strategic elements of search is as yet unknown. Here we extend current understanding by studying the effect of cognitive load arising from a non-visual source of preoccupation and by considering whether systematic aspects of search are disrupted by such distraction.

How we search for targets amongst distractors has been studied extensively and much is understood about the underlying mechanisms when searching arrays of targets presented on computer monitors (see Wolfe, 1998). It is clear that search is guided by both low-level visual information and higher-level strategies (Wolfe, 2007). The low-level component is often operationalized as arising from an internal priority map of the scene constructed by combining low-level featural descriptions of the scene (e.g., Treisman, 1988; Treisman & Gelade, 1980; Itti and Koch, 2000; Wolfe, 2003). However, when attempting to extend these models to account for search behavior in more complex scenes, it is clear that purely low-level accounts of attention selection are very limited (see Tatler, Hayhoe, Land and Ballard, 2011 for a review) because they fail to account for the influence of high-level factors such as strategy and task demands, on search behavior in complex scenes (Buswell, 1935; Yarbus, 1967). More recently Adeli, Vitu and Zelinsky (2017) have proposed a model which includes high-level processes but core principles of superior colliculus organization. Their MASC (model of attention in the superior colliculus) is capable of predicting fixation locations of individuals when performing categorical and exemplar search tasks. The predictive success of this model relies on the incorporation of saliency and target maps (for prioritizing areas to be fixated based on low level features contrasts and higher level target goals respectively) coupled with the constraints associated with the basic organizing brain principles in the

oculomotor system. This demonstrates the importance of considering low level, task specific as well as organizing brain principles when trying to understand the relationship between the visual world and overt visual attention.

In simple search arrays of targets and distractors on a screen, there appear to be clear strategic components to search that arise not from the visual features of the items in the display but from the structure of the array of items. Gilchrist and Harvey (2006) showed that search behavior differed when searching structured (that is, regularly arranged) arrays of items from that when searching unstructured arrays. When searching structured arrays, with items arranged in clearly identifiable rows and columns (see Figure 1, left), searchers made more horizontal and vertical eye movements than when searching arrays that were less structured (as in Figure 1, right). However, while disrupting the display structure led to a reduction in this horizontal/vertical bias, it did not eliminate it.

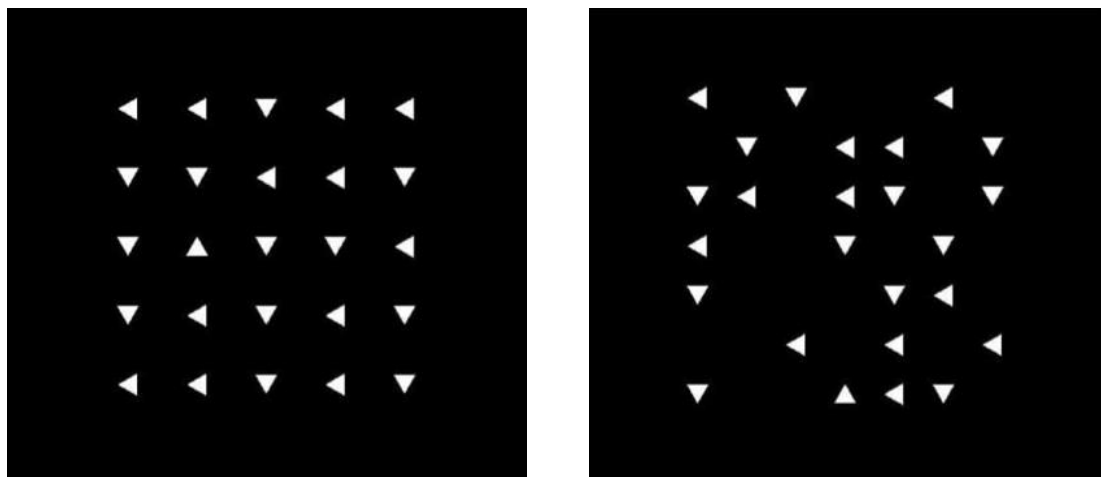


Figure 1, Example displays of both structured (left panel) and unstructured (right panel) search arrays.

The presence of a preference to make more horizontal and vertical saccades irrespective

of display structure suggests a systematic component to visual search. Strategic search has been found in other types of search arrays (e.g., Hooge and Erkelens, 1999) and even when viewing natural scenes, where horizontal and vertical saccades dominate (Tatler and Vincent, 2009). Gilchrist and Harvey (2006) interpreted this systematic component of search, as evidence for a strategic component of visual search behaviour that greatly reduces the need to remember items that have been viewed previously. In a study conducted by Amor and colleagues (2016) the authors found that subjects had a clear preference towards a reading like pattern of eye movements during visual search. Such a preference, it is argued, eliminates the need to remember the location of previously inspected items. Likewise during mindless reading and z-string reading tasks it has been found that we move our eyes across letter strings in the same way regardless of the cognitive demands of the visual information (Rayner & Fischer, 1996; Nuthmann et al., 2007; Luke & Henderson, 2013). Moreover, Vitu et al. (1995) tested both a letter search task and a z-reading task, and found that the eye-movement behaviour was similar regardless of the linguistic content or the type of task. Although these studies have demonstrated similarities in eye movement behaviour when looking at words and z-strings, it should be stated that we cannot be certain that eye movements in mindless reading are not affected by cognitive task demand.

It is not yet clear whether search strategies such as the systematic scanning identified by Gilchrist and Harvey (2006) and others is affected by distraction stemming from a secondary cognitive task. If systematic scanning were a result of higher-level processes or strategies, one would expect a reduction of this systematic component when secondary cognitive task demand is high. Conversely if systematic scanning requires no effortful top-down control but is a process employed to free up resources and guide visual search when secondary cognitive task demand is high, one might

expect an increase in this systematic component. Another alternative would be that the preference to make reading like eye movements (many horizontal and vertical interspersed with a few oblique saccades) is automatic due to decades of reading and is not affected at all by the addition of a cognitive task.

Previous research has found that working memory resources play an important role in visual search processes. These are thought to be in terms of maintaining a template of the search target in working memory throughout search (e.g., Shiffrin & Schneider 1977; Wolfe, 1994, 2012), and deploying attention (Bundesen, 1990, Desimone & Duncan, 1995; Miller & Cohen, 2001). This is supported by previous reports that secondary visual working memory load slows search (Oh & Kim, 2004; Oliviers, Meijer & Theeuwes, 2006; Woodman & Luck, 2004; Woodman et al., 2001) increases disruption by distractors (Lavie, 2005) and increases the rate of re-fixating previously-fixated items (Solman, Cheyne & Smilek, 2011).

In the present study, we considered the effect of cognitive distraction on oculomotor behaviour when searching for a target within structured and unstructured search arrays (like those in Gilchrist and Harvey, 2006; see Figure 1). This allowed us not only to consider what aspects of search are disrupted by secondary cognitive load, but also whether the systematic scanning identified by Gilchrist and Harvey (2006) is susceptible to cognitive distraction. We considered the effects of preoccupation with a lateral thinking puzzle on 1) the initiation of search (first saccade latency); 2) overt visual scanning of the array; and 3) verification and response selection once the target has been fixated. We considered whether cognitive load arising from a non-visual secondary task would produce the same prolonging of all three phases of search that was found by Solman, Cheyne and Smilek (2011) using a secondary visual working memory task. Given the lack of effect of array structure on search times in Gilchrist and

Harvey's (2006) study, we did not expect to find differences in response times between structured and unstructured arrays, but it is not known whether the strategic component of search afforded by structured arrays might protect search from the detrimental effects of cognitive distraction.

During scanning, we considered not only the time spent searching for the target but also whether array structure and cognitive distraction influenced oculomotor indicators of on-going decision processes (the durations of individual fixations and the tendency to return to items fixated earlier in the search).

Fixation durations can be thought of as reflecting the time it takes to evaluate a decision to move the eyes, based on the relative merit of prolonging fixation at the current location compared to the expected benefit of moving the eyes to a new location (Tatler, Brockmole & Carpenter, 2017). These decision processes are likely to involve a complex interaction of factors related to extraction and evaluation of information in central and peripheral vision, along with influences of oculomotor factors, such as the amplitude of the outgoing saccade and the change in direction between the incoming and outgoing saccades (Tatler & Vincent, 2008; Tatler et al., 2017), and landing position on a word or object (Henderson, 1993; Pajak & Nuthmann, 2013; van der Linden & Vitu, 2017; Vitu et al., 2001). There is evidence that low-level visual information influences fixation durations, with longer fixations when the luminance (Loftus, 1985) or contrast (Loftus et al., 1992) of fixated items is reduced (Van Diepen et al., 1995). Higher-level interpretation of visual information also influences fixation duration. Fixations are longer when objects are difficult to recognise (De Graef, Christiaens, & d'Ydewalle 1990) or semantically inconsistent with the scene background (see Spotorno & Tatler, 2017, for a discussion of this literature). In reading studies, fixation durations on infrequent words are longer than frequent words (Rayner,

1998). Preoccupation with a secondary cognitive task may influence the underlying decision process by impairing the extraction and evaluation of information in central and/or peripheral vision, or by changing the threshold for accepting that there is sufficient evidence to move the eyes to a new location. We might, therefore, expect cognitive distraction to lengthen fixation durations. However, Solman, Cheyne and Smilek (2011) found no influence of a secondary visual working memory task on fixation durations during search. Given previous findings (Gilchrist and Harvey, 2006) we do not expect to find any direct effect of array structure on fixation durations, but it is not clear whether any effects of distraction on fixation duration might be modulated by array structure.

How frequently a previously-inspected item is re-fixated during search has been thought to reflect the level of processing which has gone into each item of the display: more re-fixations reflecting more frequent incomplete processing or less memory for previously fixated items (Gilchrist and Harvey, 2000, Peterson et al, 2001). If high-level executive functions such as working memory are required to keep in mind previously processed distractor locations then one should expect an increase in re-fixations within the high compared to the low cognitive load condition; indeed Solman, Cheyne and Smilek (2011) found higher rates of re-fixation when distracted by a secondary visual working memory task. We extend this previous work by also considering the structure of the search array on re-fixation rates. The systematic scanning afforded by structured search arrays should reduce the likelihood that items are re-fixated in structured arrays compared to unstructured arrays. Furthermore, if re-fixations reflect memory failures then cognitive distraction might be expected to have an effect on re-fixation rate within unstructured but not structured arrays.

Methods

Design

In this 2 x 2 within subjects design the independent variables were cognitive load, which was either high or low (puzzle = high; easy question = low), and search array structure which was either structured or unstructured.

Participants

Fifteen participants (7 male and 8 female, age range 17- 33) were recruited in and around the University of Dundee by means of the Universities Research Participation System “SONA”. Informed consent was obtained from all subjects prior to the start of testing. All testing was carried out in the Research Wing of the School of Psychology at the University of Dundee. Participation lasted no longer than 45 minutes and subjects were compensated with course credit or chocolate for their participation. The study followed the tenets of the Declaration of Helsinki and was approved by the institutional review board at the University of Dundee

Materials

Participants sat at a table with their heads supported by a chinrest 85 cm away from a 19” CRT-Monitor on which the visual stimuli were displayed with a resolution of 1024x768 pixels. Experiment Builder software by SR Research was used to program the presentation of the audio and visual stimuli. We modified Gilchrist & Harvey’s (2006) visual search paradigm to include a secondary cognitive task. In all conditions the target in the primary visual search task was a white upward facing triangle and distractor items consisted of white downward and rightward facing triangles. The display size always consisted of 25 items (1x1° visual angle), with 12 of each type of distractor. In the case

when the target was not present it was replaced by one of the distractor types (randomly selected). In the structured condition, 25 items were placed randomly onto the junctions of an invisible 5x5 grid resulting in no free placeholders and thus a spatially structured array (e.g., Figure 1, left). In the unstructured condition the same 25 items were placed randomly onto the junctions of a 7x7 grid, leaving 24 randomly selected blank locations in each trial resulting in a spatially unstructured search array (e.g., Figure 1, right). Across both conditions the overall display size was kept constant (12x12° visual angle) resulting in structured and unstructured search arrays, which subtend the same visual space. We made use of the same lateral thinking puzzles to increase secondary cognitive task demand as Savage, Potter & Tatler (2013) with the addition of simple undemanding questions instead of no audio in the control condition. These questions and riddles were presented via a set of Logitech loudspeakers at a comfortable and constant volume, which was regulated individually for each participant.

Procedure

A white fixation disc was presented at the beginning of each block of visual search trials in order to check for any spatial offset in the calculated eye position. A drift correction was performed at the beginning of each block of trials. If the spatial offset was too large to perform the drift correction, we repeated our calibration procedure before continuing. Participants were either presented with a puzzle (high-load i.e. “*What can pass through water without getting wet?*”) or an easy question (low-load i.e. “*What city are you in?*”) directly prior to the start of each (1-minute) block of 14 search trials. We chose the time of one minute after having examined puzzle-solving times of five pilot participants for a variety of riddles. We found that these participants were not able to solve any of the selected puzzles within 1 minute. Trials of high/low secondary cognitive task demand were presented randomly but interleaved within each array structure condition. The

structured and unstructured search arrays were presented in blocks, which were counterbalanced for presentation order across all participants. In the primary visual search task, participants were required to make a target present/absent response using the one of two button boxes provided. For a target present decision subjects were required to press the button box in their right hand and for target absent choices the button box in their left hand.

At the end of each 1-minute block there was a brief intermission in which participants were asked to indicate whether they knew the riddle and whether they had managed to solve the riddle and to state their answer. This information was relevant only for high load questions. All together participants completed 320 structured (160 high load & 160 low load) and 320 unstructured (160 high load & 160 low load) search trials.

Eye Movement recording

Eye movements were recorded using a tower mounted SR Research EyeLink1000 eye-tracker, sampling at 1000 Hz. Each participant completed three brief eye dominance tests prior to the start of testing so that the experimenter was able to track the subject's dominant eye (see Appendix 2 for description of eye dominance tests). A 9-point calibration procedure was used to calibrate the tracker and repeated to validate tracker accuracy. If the validation procedure showed an average error in excess of 0.5° or a maximum error in excess of 1° , the calibration procedure was repeated. Single-point calibration checks were performed at the beginning of each block of trials. Saccades were identified using the standard SR Research algorithm, which detects saccades when eye position deviates by more than 0.1° , with a minimum velocity of 30 deg s^{-1} and a minimum acceleration of 8000 deg s^{-1} , maintained for at least 4 ms. Data were exported

via custom-made Matlab routines for subsequent analysis of saccade, fixation and blink events.

Data Analysis

Dependent variables were: (1) overall response performance (correctly identifying the presence or absence of the target); (2) response time (from array appearance to manual button press indicating the target presence); (3) fixation duration; (4) re-fixation rate; (5) distribution of saccade directions; and in the cases that a target was present: (6) search initiation time (first saccade latency); (7) scanning time (from the end of the first saccade to the start of the first fixation on the target); and (8) verification time (from the start of the first fixation on the target to the manual response by the participant).

In all statistical analyses, data were excluded if the first saccade latency was very short (< 100 ms: 757 trials, 9.0% of trials), or if the log-transformed first saccade latency was more than 3 standard deviations from the mean (51 trials, 0.6% of trials). These initial transformations were made in order to avoid trials in which the participant anticipated the appearance of the search array or were unusually slow to respond, implying disengagement from the task. Trials were also excluded from the high load condition if participants indicated that they already knew the puzzle (1587 trials, 18.9% of trials), as in these cases the puzzle was unlikely to preoccupy the participant during the search task and as such our load manipulation would have failed in these cases.. Blinks were also removed from the recorded data. After these exclusions, data from 5995 trials were available for subsequent analyses. Further exclusions were made specific to certain models below in order to ensure that suitable data were included in each model to reflect the measure under test.

To determine the impact of secondary cognitive task demand and array structure on

behavioural and oculomotor measures, data were analysed by means of Linear Mixed Models (LMMs) for continuous variables and GLMMs for binary variables using the *lme4* package (version 1.1-7; Bates et al., 2014) in the R statistical programming environment (R Development Core Team, 2007). LMMs and GLMMs are particularly well suited to datasets such as those collected in this study because (1) they can combine continuous and categorical factors within the same model, (2) they allow a simultaneous estimation of between-subjects and between-item variance and (3) they are more robust than ANOVAs when a design is not fully balanced as a result of data exclusions for example (Kliegl et al 2012). Categorical predictors in models (array structure, cognitive load, target presence) were sum coded. This produces effects for each predictor that are equivalent to main effects in ANOVAs. We explored any significant interactions using follow-up models to test the relevant simple effects within the interaction. We did this by creating a variable with one level per cell in the significant interaction and coding this variable to test the simple effects of interest¹. Subjects and items (sound clips) were entered as random effects for all models. For the random effects structure we attempted to include random slopes and intercepts for all

¹ Dummy (or treatment) coded variables would remove the need to produce simple-effect-coded variables to express significant interactions, but for 3 (or more)-way interactive models would require repeating the models with different reference levels for the categorical predictors in order to test for any 2-way interactions in the model. Thus, whether interactions are found or not, the data must be retested over models with different reference levels. In contrast, in our approach data are only retested if a significant interaction is found. Thus, given the fact that many of our models include three categorical predictors, we prefer to use our approach of deviation-coded categorical predictors, with simple effects models to follow up where necessary.

fixed effects and their interactions in order to produce a maximal random effects structure (Barr et al., 2013). However, maximal structure models often fail to converge. When these models did not converge, we first removed the computation of correlation parameters within the random effects structures. If further simplification was required for convergence, we began by simplifying the item (sound clip) term first. To this effect, we first removed the interactions, starting with the highest order interactions. When it became necessary to remove random slopes for individual fixed effects we removed the slope for array structure before that for cognitive load. In the sections that follow the results are reported for the most complex random effects structure for which the LMM converged. A full list of model structures can be found in Appendix 4. In practice, the full random effects structure models only converged for our models of search initiation time and scanning time. In all other cases a reduced structure was required, and in most cases no random slopes were included for the items (audio clip) term. For LMMs, *p*-values for fixed effects were calculated using the *lmerTest* library (Kuznetsova, Bruun Brockhoff, & Haubo Bojesen, 2016). Graphics were created using the *ggplot2* package (Wickham, 2009).

Because the load manipulation was provided in the form of a question or puzzle at the start of a block of 14 trials, it is possible that any effects of high load might change over the course of the block. In order to test for this possibility, we ran initial models for each of our analyses with trial number and cognitive load as variables to test for any interaction between these two predictors that might suggest a changing effect of load over time. For these models we ran intercept-only models as these are the least conservative form of LMM and thus would be the most likely to find any interactions between load and trial number. Because these initial models served only to check that effects did not vary over trials, they are reported in Appendix 3 rather than the main

body of text below unless they indicated an effect of trial number that needed to be accounted for in the main models for each variable. In the sections that follow, no interaction between trial number and cognitive load were found for Accuracy, Response Time, Search Initiation Time, Scanning Time, Verification Time and Re-fixation Rate, suggesting that the influence of (high) cognitive load did not change over the course of each block of trials for these measures. We did find an interaction between trial number and Cognitive Load for fixation duration, and so we tested whether this influenced any effects of our experimental variables (see Results).

Results

Overall behavioural measures of search

Table 1 summarises response accuracy (correct classifications of target present and target absent trials) and response times for the eight conditions of target presence, array layout, and cognitive load.

Accuracy

A GLLM (Model 1) showed that participants were more accurate when the target was absent than when it was present, $\beta= 1.83$, $SE= 0.13$, $z = 14.0$, $p < .001$, and were less accurate when contemplating a puzzle than when contemplating a question, $\beta= 0.61$, $SE= 0.16$, $z = 3.91$, $p < .001$. These effects were qualified by a significant interaction between target presence and load, $\beta= 0.39$, $SE= 0.13$, $z = 2.95$, $p = .003$. There was also a significant interaction between target presence and array structure, $\beta= 0.28$, $SE= 0.13$, $z = 2.14$, $p = .033$. No other effects in the model were significant.

To explore the significant interaction between target presence and load we ran a

follow-up model coded for simple effects of load (Model 1.1). This model showed that performance was worse following a puzzle than a question when the target was absent, $\beta= 1.99$, $SE= 0.54$, $z = 3.67$, $p < .001$, and also when the target was present, $\beta= 0.45$, $SE= 0.19$, $z = 2.30$, $p = .021$. The drop in performance under high cognitive load was greater (but more variable) when the target was present (low load: $M = 0.827$, $SE = 0.009$ correct; high load: $M = 0.763$, $SE = 0.013$ correct), than when it was absent (low load: $M = .997$, $SE = 0.001$ correct; high load: $M = 0.981$, $SE = 0.004$ correct) .

To explore the interaction between target presence and array structure we ran a follow-up model coded for simple effects of structure (Model 1.2). Performance was better for structured arrays than unstructured arrays when the target was present, $\beta= 0.31$, $SE= 0.11$, $z = 2.71$, $p = .007$. There was no effect of array structure when the target was absent.

Response Times

Response times were log-transformed and outliers more than three standard deviations from the mean log-transformed response time were excluded, leaving 5994 trials for analysis. Participants responded sooner when the target was present than when it was absent, $\beta= 0.13$, $SE= 0.003$, $t = 44.8$, $p < .001$, and later when contemplating a puzzle than when contemplating a question, $\beta= 0.07$, $SE= 0.02$, $t = 3.92$, $p = .001$ (Model 2). These effects were qualified by a significant interaction between target presence and cognitive load, $\beta= 0.02$, $SE= 0.003$, $t = 5.38$, $p < .001$. Participants were overall slower when searching an unstructured array than when searching a structured array, $\beta= 0.03$, $SE= 0.004$, $t = 8.33$, $p < .001$. No other effects in the model were significant.

A follow up model of the simple effects of cognitive load in the interaction between target presence and cognitive load (Model 2.1) showed that responses were

significantly slower under conditions of high cognitive load than under low cognitive load both when the target was absent, $\beta= 0.10$, $SE= 0.009$, $t = 11.2$, $p < .001$, and when it was present, $\beta= 0.16$, $SE= 0.009$, $t = 18.1$, $p < .00$. The increase in RT under high cognitive load was slightly greater when the target was absent (low load: $M = 3414$ ms, $SE = 32$ ms; high load: $M = 4388$ ms, $SE = 59$ ms) than when it was present (low load: $M = 2029$ ms, $SE = 32$ ms; high load: $M = 2966$ ms, $SE = 58$ ms).

Table 1, Average Accuracy and Response Times along with appropriate standard errors in parentheses between target present and absent trials, for structured and unstructured arrays split by Low Load (LL) and High Load (HL) conditions.

	Target Present				Target Absent			
	Structured		Unstructured		Structured		Unstructured	
	LL	HL	LL	HL	LL	HL	LL	HL
Accuracy [proportion correct]	.847 (.012)	.800 (.018)	.807 (.013)	.731 (.018)	.997 (.002)	.971 (.007)	.998 (.001)	.990 (.004)
Response Time [ms]	1878 (42)	2792 (82)	2189 (48)	3118 (81)	3245 (46)	4171 (85)	3580 (45)	4578 (80)

Searching for a present target

When a target was present in the display we considered whether cognitive load and array structure influenced the duration of each of three phases of search: initiation, overt scanning, and target verification (see Malcolm & Henderson, 2010). As for the analyses of accuracy and response time above, in the analyses that follow we removed trials in

which search initiation was unusually fast (first saccade latency < 100 ms) or long (first saccade latency more than 3 standard deviations from the log-transformed mean).

Furthermore, we only considered trials in which the participant correctly responded that a target was present.

Search initiation

For search initiation we excluded trials in which the first saccade was less than 1 degree. This is because we wanted to ensure that we were analysing the time to initiate overt search of the array rather than any microsaccadic responses to the display, or any potential errors by the saccade detection algorithm. Search initiation time was log-transformed for the model that follows and 2166 trials were available for this analysis after the exclusions explained above.

The time to first initiate overt search of search array (i.e. the latency of the first saccade after array onset) was not influenced by cognitive load, array structure or the interaction between these factors (Model 3). There was a trend toward longer time to initiate search when contemplating a puzzle than when contemplating a question, but this failed to reach significance, $\beta= 0.07$, $SE= 0.03$, $t = 1.95$, $p = .073$.

Scanning time

As for the above analyses we removed trials with an unusually short or long initiation time, or a recorded first saccade amplitude of less than 1 degree. A first analysis of scanning was to consider how frequently the target was reached in a single saccade (that is there was no scanning of other locations in the array). We identified these cases by employing a minimum scanning time of 100 ms. For the 127 trials identified in this way, we found that single saccade searches were less common under high cognitive

load than low cognitive load when searching structured arrays, $\chi^2 = 6.54, p = .011$ (26 vs 48 trials), and when searching unstructured arrays, $\chi^2 = 8.32, p = .003$ (16 vs 37 trials). Conversely there was no effect of array structure either under low cognitive load, $\chi^2 = 2.38, p = .123$ (structured = 26, unstructured = 16 trials), or high cognitive load, $\chi^2 = 1.42, p = .233$ (structured = 48, unstructured = 37 trials). For the analyses that follow, we excluded these trials in which the target was reached within a single saccade. This is because, while single-saccade searches were relevant for understanding search initiation (analyses above) and verification (analyses below), these instances do not provide insights into the process of scanning an array of items. Data were log-transformed and outliers more than three standard deviations from the mean log-transformed scanning time were excluded. After all exclusions 1307 trials were available for this analysis.

Scanning time was longer when participants were contemplating a puzzle than when they were contemplating a simple question, $\beta = 0.04, SE = 0.02, t = 2.41, p = .029$. There was no effect of array structure nor any interaction.

Verification time

In addition to removing trials with unusually short or long initiation time, we also removed any trial for which the log-transformed verification time was more than three standard deviations from the mean log-transformed verification time, leaving 1537 trials for analysis. Since verification time is the summed fixation duration on the target item, it was important to consider possible confounds on this measure arising from indirect effects of the experimental manipulations on factors that mediate fixation duration. In particular, the landing position on a word or object influences both the chance that an immediate re-fixation is made (O'Regan, Lévy-Schoen, Pynte & Brugailière, 1984; van der Linden & Vitu, 2017) and the duration of the fixation (Henderson, 1993; Pajak &

Nuthmann, 2013; van der Linden & Vitu, 2017; Vitu et al., 2001). Landing closer to the center of a word or object is associated with a decreased likelihood of making an immediate re-fixation and longer fixation durations. Thus any influence of our manipulations of cognitive load and array structure on landing positions on items in the display could influence our measured verification time in a manner that is due to spatial targeting rather than influences of these manipulations on the underlying processes of target verification. We addressed this issue in two ways. First we ran a model (Model 5) to determine whether our manipulations of cognitive load and array structure significantly influenced the landing position of the first saccade on the search target (expressed as the distance between the centre of vision and the centre of the target). Second, we included landing position as an additional fixed effect in our model of verification time (Model 6).

The landing position of the first saccade on the target item was not influenced by cognitive load, array structure or the interaction between these factors (Model 5). The LMM to predict verification time (Model 6), showed no influence of saccade landing position (linear or quadratic) or interaction between this factor and any other factor or interaction in the model. Thus landing position on the target did not influence verification time. Participants were faster to correctly indicate target presence when contemplating a question than when contemplating a puzzle, $\beta= 0.10$, $SE= 0.03$, $t = 3.21$, $p = .006$. Verification times were also longer for targets within unstructured arrays than for targets within structured arrays, $\beta= 0.03$, $SE= 0.02$, $t = 2.20$, $p = .040$.

Table 2, Average Search initiation times (milliseconds), Scanning times (milliseconds) and Verification times (milliseconds) along with appropriate standard errors in parentheses between target present and absent trials, for structured and unstructured arrays split by Low Load (LL) and High Load (HL) conditions.

	Target Present			
	Structured		Unstructured	
	LL	HL	LL	HL
Search	248	262	241	247
initiation [ms]	<i>(3.1)</i>	<i>(5.1)</i>	<i>(2.8)</i>	<i>(4.0)</i>
Scanning time	1105	1428	1366	1677
[ms]	<i>(44)</i>	<i>(97)</i>	<i>(60)</i>	<i>(100)</i>
Verification	357	935	513	806
time [ms]	<i>(13)</i>	<i>(73)</i>	<i>(25)</i>	<i>(54)</i>

Indicators of decision processes and strategic scanning

Fixation durations reflect the time taken to evaluate a decision to move the eyes to a new location in the scene based on a combination of factors including information extraction and evaluation in central and peripheral vision (Tatler et al., 2017). Re-fixations of previously-fixated objects can indicate either unfinished processing of the object (as has been suggested in reading research, Rayner, 1998) or can indicate low use of memory during search (Peterson et al., 2001). Saccade directions provide an indicator of the presence of strategic approaches to search behaviour (Gilchrist and Harvey, 2006). For fixation duration and re-fixation rate, we considered only fixations (and re-fixations) of distractors during search. Table 2 summarises fixation durations and re-fixation rate for the eight conditions of target presence, array layout, and cognitive load.

Fixation duration

In keeping with previous analyses, we excluded trials with first saccade latencies that were unusually short or long (using the same criteria as above). We excluded fixations that fell outside of the display area or were preceded by a saccade with an amplitude less than 0.5 degrees. On trials in which the target was present, we also excluded fixations that were made on the target or after the target had been fixated. Fixation durations were log-transformed and outliers more than three standard deviations from the mean log-transformed fixation duration were excluded, leaving 45,663 fixations for analysis.

An initial LMM (Model 7)² was run to consider whether fixation durations differed when fixating items in the search array to spaces between or around the items in the array. Fixation durations were longer on items ($M = 219$ ms, $SD = 84$ ms) than on background spaces ($M = 210$ ms, $SD = 81$ ms), $\beta = 0.01$, $SE = 0.003$, $t = 3.89$, $p < .001$.

For the analyses that follow we considered only fixation falling on items and included landing position (distance from the centre of the item) as a fixed effect in our model of fixation duration (Model 8), in order to account for possible effects of landing position on fixation duration (Henderson, 1993; Pajak & Nuthmann, 2013; van der

² A model to test for effects of trial number showed a significant interaction between trial number and cognitive load for fixation duration (see Appendix 3). We therefore, ran a version of Model 7 that included trial number as an additional Fixed effect that interacted with the other fixed effects in Model 7. The inclusion of trial number did not change the pattern of significant and non-significant effects reported for Model 7 and did not improve the overall fit of the model and so here we report the results of Model 7, which for simplicity does not include trial number as a fixed effect.

Linden & Vitu, 2017; Vitu et al., 2001). There was a quadratic effect of landing position, $\beta = -0.38$, $SE = 0.17$, $t = 2.23$, $p = .026$, with fixation duration initially increasing and then decreasing with distance from the centre of the item. Landing position did not interact with any other factors in the model. Fixation durations were longer when contemplating a puzzle, than when contemplating a question, $\beta = 0.01$, $SE = 0.001$, $t = 11.08$, $p < .001$, and longer when searching unstructured arrays than when searching structured arrays, $\beta = 0.005$, $SE = 0.001$, $t = 4.22$, $p < .001$. Furthermore, there was an interaction between cognitive load and array structure, $\beta = 0.003$, $SE = 0.001$, $t = 3.03$, $p = .004$. A follow-up model (Model 8.1) showed that fixation durations were longer under high load than under low load in structured arrays, $\beta = 0.03$, $SE = 0.004$, $t = 9.10$, $p < .001$, and unstructured arrays, $\beta = 0.02$, $SE = 0.003$, $t = 6.38$, $p < .001$. The increase in fixation duration under high cognitive load was greater when searching structured arrays (low load: $M = 208$ ms, $SE = 0.9$ ms; high load: $M = 225$ ms, $SE = 1.3$ ms) than when searching unstructured arrays (low load: $M = 216$ ms, $SE = 0.8$ ms; high load: $M = 228$ ms, $SE = 1.1$ ms).

Re-fixations

The opportunity for re-fixating an object will be greater when search takes longer. Given these findings above we would expect more re-fixations of objects when the target is absent, when contemplating a puzzle, or when searching an unstructured array, simply because search takes longer in these situations. To account for this possibility, the re-fixation data were scaled by search time in order to provide the rate of re-fixations (number of re-fixations per second of search). We only considered re-fixations of distractors rather than the target object. Furthermore, only re-fixations occurring prior to any fixation of the target in target-present trials were included as re-fixations of distractors after the target has been located may reflect different underlying processing

(likely to serve a purpose of target verification) than re-fixations of distractors prior to fixating the target. A total of 5995 trials were available for this analysis.

Re-fixation rate was higher when the target was absent than when it was present, $\beta= 0.03$, $SE= 0.006$, $t = 4.28$, $p < .001$, and higher when the array was unstructured than when it was structured, $\beta= 0.08$, $SE= 0.006$, $t = 12.0$, $p < .001$. Re-fixation rate was also higher under high cognitive load than under low cognitive load, $\beta= 0.02$, $SE= 0.006$, $t = 2.56$, $p = .014$. No other effects or interactions were significant.

Table 3, Average Fixation durations (milliseconds) and average re-fixation rates (re-fixations per second) along with their appropriate standard errors between target present and absent trials, for structured and unstructured arrays split by Low Load (LL) and High Load (HL) conditions.

	Target Present				Target Absent			
	Structured		Unstructured		Structured		Unstructured	
	LL	HL	LL	HL	LL	HL	LL	HL
Fixation duration [ms]	210 (1.7)	227 (2.5)	215 (1.4)	227 (1.7)	208 (1.1)	224 (1.6)	216 (1.0)	229 (1.3)
Re-fixation rate [1/s]	.233 (.015)	.258 (.021)	.370 (.018)	.394 (.021)	.256 (.011)	.313 (.015)	.437 (.016)	.457 (.019)

Saccade directions

To consider whether our experimental manipulations influence the directions in which saccades are launched, we calculated the probability distributions of saccade endpoints relative to the starting location of each saccade. We calculated these probability distributions by adding a Gaussian with full width at half maximum of 2

degrees of visual angle at the endpoint of each saccade. This creates plots that convey the direction and amplitude of each saccade (as in Tatler & Vincent, 2009). We created these probability distributions for each of the cells in our design and then compared simple effects of cognitive load and array structure using Kolmogorov-Smirnov tests to test whether the probability distributions differed.

Figure 2 shows that in all conditions, the common tendency to make saccades preferentially along horizontal and vertical directions is present (Tatler & Vincent, 2008, 2009). However, modulation of this between conditions is also evident. We found a simple effect of load when searching structured arrays, $D = 0.037$, $p = .002$, but no effect of load when searching unstructured arrays, $D = 0.021$, $p = .422$. Figure 2, rightmost column illustrates these simple effects by plotting the difference between high and low cognitive load conditions. For the significant effect of load in structured arrays this appears to arise from high load decreasing the probability of saccading upwards or to the right, and slightly increasing the downwards and obliquely downwards. We also found significant simple effects of array structure in both the low cognitive load condition, $D = 0.072$, $p < .001$, and the high cognitive load condition, $D = 0.053$, $p < .001$. In both cases (Figure 2, bottom row) this arises from the structured array being associated with more horizontal and vertical saccades, and fewer oblique saccades than the unstructured array, as would be expected.

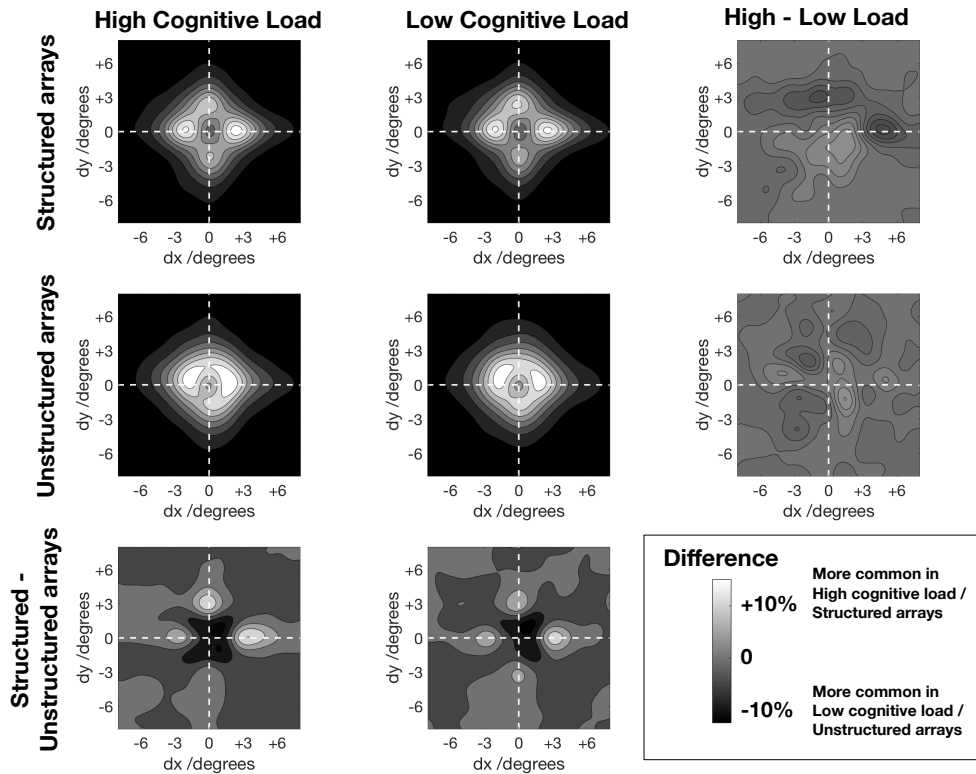


Figure 2. Saccade endpoints relative to launch site for each of the four conditions in our experiment, together with plots of the differences between these conditions, showing the simple effects of cognitive load and array structure. For the difference plots, intensities are scaled to the possible range of differences between the probability densities that make up the differences. All four difference plots are plotted with the same range of intensities to allow the relative magnitudes of these differences to be visualised. A 10% difference reflects a difference that is 10% of the maximum possible difference. In the plots of the simple effects of load (rightmost column), brighter greys show saccade landing positions more common in the high load condition and dark greys show saccade landing positions more common in the low load condition. For plots of the simple effects of structure (bottom row), brighter greys show saccade landing positions more common when searching structured arrays and dark greys show saccade landing positions more common when searching unstructured arrays.

Discussion

In the current experiment we considered the consequences of contemplating a previously heard puzzle on behavioural and oculomotor measures within a visual search task. Our aims were to 1) determine the extent to which systematic components (Gilchrist & Harvey, 2006) of visual search were affected by secondary cognitive task demand and 2) examine the effects of load and structure on the three phases of visual search (prior to, during and following search). Not only does this work provide insights into how search is affected by cognitive distraction, but it also provides insights into whether previously observed decrements in real world tasks such as driving hazard perception performance (Savage, Potter & Tatler, 2013) may, to some extent, be related to cognitive task demand interfering with the basic processes of visual search.

Behavioural consequences of load and structure

Array structure influenced search accuracy, with participants more frequently detecting the target when it was present in structured arrays than in unstructured arrays; array structure did not influence response accuracy when the target was absent (but this may be due to ceiling effects in this situation). Array structure also influenced response times, with longer response times when searching unstructured arrays than when searching structured arrays, and this was the case both when the target was present and when it was absent. These findings for accuracy and response times are unlike those reported by Gilchrist and Harvey (2006), who found no effect of array structure on accuracy or response time. It is not clear why these differences might have arisen.

Cognitive load also influenced both the accuracy and response times for search. High cognitive load resulted in fewer correct responses both when the target was present and when it was absent. The detrimental effect of load on accuracy was larger when the target was present than when it was absent (but performance in the target absent trials was close to ceiling irrespective of load). Response times were faster under low cognitive load than under high cognitive load for both target present and absent trials, but the difference (about 300 ms in both types of trial) was proportionately larger in target present trials than in target absent trials.

Previous research has demonstrated that additional secondary cognitive load increased response times in visual search tasks (Oh & Kim, 2004; Woodman & Luck, 2004; Woodman et al., 2001). Depending on the nature of secondary memory task and the primary search stimuli, cognitive load has in some cases been shown to influence the slope of the RT x set size function (Oh & Kim, 2004; Woodman & Luck, 2004). However other work (Woodman et al., 2001) has suggested that although secondary cognitive task demand led to a general increase in search times, it did not influence the efficiency of the search itself (i.e. the slope of the search function was not affected). Although some authors argue that visual search is thought to require working memory resources (Bundesen, 1990; Duncan & Humphreys, 1989) these results have been taken to indicate that the cost to response times under load was caused by interference with processes either prior to (e.g., residual encoding processes) or following (e.g., response generation) the search itself. As the current study tracked participants' eye movements while they searched, we were able to determine which processes of search itself were influenced by secondary cognitive load.

Phases of search

The three phases of search were differentially effected by array structure and load. Array structure was associated only with a change in verification time, with longer verification time when the target was located within an unstructured array than when it was located within a structured array; search initiation and scanning time were not influenced by array structure. Longer verification times can reflect differences in object recognition due to difficulties in segmenting the object from its surrounding, or differences in the decision criterion for accepting the item as the target, or a combination of these factors (see Gordon, 2004). Thus an unstructured array of objects appears to influence either how easy it is to segment the target from the distractors, the decision threshold for accepting that the target has been found, or both.

We found that high cognitive load was associated with longer overt scanning and longer verification times between fixating the target and manually responding that the target had been found. These findings are broadly consistent with previous work by Solman, Cheyne & Smilek (2011) which demonstrated that a concurrent memory task affects all stages of search (pre, during and post search). Here we extend this previous result by showing that a similar pattern of effects can be found when cognitive load is increased by a non-visual secondary task (contemplating a lateral thinking puzzle) as has previously been found when cognitive load is increased by a visual working memory task (remembering the colours or positions of items). It is not clear why Solman et al. found an effect on search initiation but we did not. However, it should be noted that our data showed a numerical difference in the expected direction and this difference approached significance. Similarly to Solman, Cheyne & Smilek (2011) we further considered whether secondary load influenced eye movement measures that indicate depth of processing and strategy during search.

Decision processes and strategic scanning

Fixation Durations

Fixation durations were significantly longer in the high compared to the low cognitive load condition, suggesting that our finding of increased scanning times when distracted may arise in part due to prolongation of individual fixations during search. This result is in contrast to previous work by Solman, Cheyne and Smilek (2011) who found no difference in fixation durations associated with the introduction of a secondary working memory task. The discrepancy between our findings and this previous study may arise from differential effects of visual (their work) and non-visual (our work) working memory tasks on this aspect of search, or from differences in the sensitivity of our linear mixed modelling compared to traditional ANOVA models of data. Fixation durations have been suggested to reflect the timing of underlying decision processes, which at least in part involve the extraction and evaluation of information in central and peripheral vision in order to weigh the relative merits of prolonging the current fixation or moving to a new location (Tatler et al., 2017). Therefore in the current experiment, longer fixation durations in the high cognitive load condition may suggest a cross-modal interference with visual processing thus resulting in more time being needed to extract the necessary information in central and peripheral vision. Alternatively, high cognitive load may interfere with other aspects of the decision processes that underlie deciding when and where to move the eyes with each saccade, requiring longer to gather and evaluate sufficient evidence to decide to move the eyes during each fixation, either by slowing the rate of evidence accumulation or by increasing thresholds for saccadic decisions (Tatler et al., 2017). Given the internal source of the distraction generated in the present study, interference at this decisional stage rather than

perceptual processing of the display seems more likely. The effect of array structure might arise from the fact that items in the display are on average further away from the current fixation than in the structured array. If the fixation duration reflects the time required to extract and evaluate information both in central and peripheral vision to assess potential targets for the next fixation (Tatler, et al., 2017) and evaluating information further into peripheral vision requires longer (as found in Tatler, et al., 2017), we would expect on average slightly longer fixations in unstructured arrays. Thus our finding is consistent with this decision-based explanation of fixation durations.

Re-fixations

As Shore and Klein (2000) have demonstrated, memory processes can have an effect on visual search at a variety of levels. One issue that remains to be determined is the extent to which memory mechanisms are necessary to prevent re-fixating previously inspected items. Previous research has argued a range of positions including that memory plays no role (Horowitz & Wolfe, 1998), a limited role (Gilchrist & Harvey, 2000) and even an extensive role (Peterson et al., 2001) in preventing re-fixations.

Unsurprisingly, re-fixation rates were higher when the target was absent as compared to when it was present. In agreement with Solman, Cheyne and Smilek (2011), we found a higher rate of re-fixations in the high load condition, suggesting that secondary cognitive load interferes with our ability to effectively ‘tag’ previously-visited locations and avoid re-fixating them, whether that distraction comes from visual or non-visual working memory load. While we found, as might be expected, an influence of array structure on re-fixation rate, with higher re-fixation rates when the array was unstructured than when it was structured, the lack of interaction between

array structure and cognitive load suggests that the effect of load was the same whether the structure of the array supported efficient search or not. That is, a more ordered display did not protect against detrimental effects of cognitive distraction, nor did a less ordered display increase susceptibility to this.

The effects of load and structure on systematic component of visual search

The disruption of the display structure resulted in a modulation of systematic scanning. In highly regular grids the distribution of saccade directions was different from that in irregular grids. This difference was evidenced by a reduction in vertical and horizontal saccades in the unstructured arrays. Although the structure of the array affected the overall distribution of saccade directions, participants still exhibited a systematic element in visual scanning, in that they made more horizontal and vertical than oblique saccades. Replicating previous research, this current study confirmed that the disruption of the regular grid-like structure altered this strategic element within saccade distributions but did not eliminate it (Gilchrist & Harvey, 2006). This suggests that systematic scanning of visual scenes does not necessarily rely on strictly regular displays. Work by Tatler & Vincent (2009) has shown that when viewing complex scenes, horizontal and vertical saccade directions are more common than oblique saccades. Most natural scenes contain a complex spatial structure (Marr, 1982), which most likely shapes systematic scanning. Furthermore subjects systematically search around circular displays, which indicates that systematic scanning is not unique to regular grid-like displays (Hooge, & Erkelens, 1999) but can be influenced strongly by the structure of the array.

The strategic component of visual search as described by Gilchrist and Harvey (2006) was affected by secondary cognitive task demand but only in structured arrays.

This difference was caused by subjects making fewer upward and rightward saccades in the high load condition in favour of making more downward and obliquely downward saccades. It should however be noted that far and away the most common direction for saccades was still horizontal and vertical in the high load condition. This indicates that cognitive load did modulate the systematic component of eye movements but did not eliminate it completely. The fact that load did disrupt ordered scanning of structured arrays might suggest that this systematic tendency to scan horizontally and vertically is at least partly under the control of resources vulnerable to increased cognitive load. As we know that increasing cognitive load increases working memory load (e.g., Corbetta Patel & Shulman, 2008), it is tempting to suggest that the systematic scanning might fall partly under the control of working memory resources. However, the relatively modest extent of the effect of cognitive load on this aspect of viewing and the fact that such modulation was not found when searching unstructured arrays suggests that these systematic tendencies to produce eye movements in particular direction are largely protected from changes in cognitive load, suggesting that they rely on resources other than working memory.

When reading we make predominately horizontal eye movements along the line of text and oblique saccades when jumping to the next line (Rayner, 1998). As reading is a skill acquired very early on in development it could be argued that this preference (or strategy) has been rehearsed so often that it becomes automatic and is applied to any grid like array when searching for items. The fact that saccade directions were mainly influenced by the structure with very little modulation from cognitive load suggests that the manner in which we search is predominately affected by the distribution of information in the scene rather than higher-level cognitive functions. This finding is consistent with work on mindless reading (Reichle, Reineberg & Schooler, 2010) and z-

string reading (Vitu et al., 1995). Results from the z-string task conducted by Vitu and colleagues (1995) have shown that global characteristics of eye movements when scanning real sentences were similar to when all letters in the text were replaced with the letter “z”. The fact that subjects made similar eye movements in the absence of any linguistic information supports the argument that predetermined oculomotor scanning strategies are a crucial determinant of eye movements in reading. Results from our own study have demonstrated that these predetermined oculomotor scanning strategies may not be unique to the task of reading but are applicable to other visually guided tasks. An alternative explanation however could be that eye movements follow a systematic pattern as a result of low-level visuo-motor principles (see Vitu, 2008).

Conclusions

This study replicates and extends previous studies of the effects of array structure and secondary cognitive load on search behaviour. We extend previous findings that secondary cognitive load from a visual working memory task prolongs search initiation, overt scanning and target verification stages of search by showing that this is also the case for a non-visual working memory task. We replicated structural effects on saccade directions found by Harvey and Gilchrist (2006). Furthermore we showed that the effects of the array structure and cognitive load are separable from one another in terms of their effects on the systematic component of visual search. Our findings suggest that although cognitive load did modulate the systematic component of visual search, it did not eliminate it completely.

References

Adeli, H., Vitu, F., & Zelinsky, G. J. (2016). A model of the superior colliculus predicts fixation locations during scene viewing and visual search. *Journal of Neuroscience*, 0825-16.

- Amor, T. A., Reis, S. D., Campos, D., Herrmann, H. J., & Andrade Jr, J. S. (2016). Persistence in eye movement during visual search. *Scientific reports*, 6, 20815.
- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of memory and language*, 68(3), 255-278.
- Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H. & Rcpp, L. (2014). Package 'lme4'. *R Foundation for Statistical Computing, Vienna*.
- Bundesen, C. (1990). A theory of visual attention. *Psychological review*, 97(4), 523.
- Buswell, G. T. (1935). *How people look at pictures*, 136-141. Chicago: University of Chicago Press.
- Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron*, 58(3), 306-324.
- Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual review of neuroscience*, 18(1), 193-222.
- De Graef, P., Christiaens, D., & d'Ydewalle, G. (1990). Perceptual effects of scene context on object identification. *Psychological research*, 52(4), 317-329.
- Droll, J. A., Hayhoe, M. M., Triesch, J., & Sullivan, B. T. (2005). Task demands control acquisition and storage of visual information. *Journal of Experimental Psychology: Human Perception and Performance*, 31(6), 1416.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological review*, 96(3), 433.
- Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8(2), 97-120.
- Gilchrist, I. D., & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology*, 10(19), 1209-1212.
- Gilchrist, I. D., & Harvey, M. (2006). Evidence for a systematic component within scan paths in visual search. *Visual Cognition*, 14(4-8), 704-715.

- Gordon, R. D. (2004). Attentional allocation during the perception of scenes. *Journal of Experimental Psychology: Human Perception and Performance*, 30(4), 760.
- Hayhoe, M. M., Shrivastava, A., Mruczek, R., & Pelz, J. B. (2003). Visual memory and motor planning in a natural task. *Journal of vision*, 3(1), 6.
- Henderson, J. M. (1993). Eye movement control during visual object processing: effects of initial fixation position and semantic constraint. *Canadian Journal of Experimental Psychology/Revue canadienne de psychologie expérimentale*, 47(1), 79.
- Henderson, J. M., & Hollingworth, A. (1998). Eye movements during scene viewing: An overview. *Eye guidance in reading and scene perception*, 11, 269-293.
- Hooge, I. T. C., & Erkelens, C. J. (1999). Peripheral vision and oculomotor control during visual search. *Vision research*, 39(8), 1567-1575.
- Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature*, 394(6693), 575-577.
- Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision research*, 40(10), 1489-1506.
- Kliegl, R., Dambacher, M., Dimigen, O., Jacobs, A. M., & Sommer, W. (2012). Eye movements and brain electric potentials during reading. *Psychological research*, 76(2), 145-158.
- Kuznetsova, A., Brockhoff, B. P., & Bojesen, C. R. H. (2016). lmerTest: Tests in Linear Mixed Effects Models (R package version 2.0–33).
- Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, 9(2), 75–82.
- Loftus, G. R. (1985). Picture perception: Effects of luminance on available information and information-extraction rate. *Journal of Experimental Psychology: General*, 114(3), 342.
- Loftus, G. R., Kaufman, L., Nishimoto, T., & Ruthruff, E. (1992). Effects of visual degradation on eye-fixation duration, perceptual processing, and long-term visual memory. In *Eye Movements and Visual Cognition* (pp. 203-226). Springer New York.

- Luke, S. G., & Henderson, J. M. (2013). Oculomotor and cognitive control of eye movements in reading: evidence from mindless reading. *Attention, Perception, & Psychophysics*, 75(6), 1230-1242.
- Pajak, M., & Nuthmann, A. (2013). Object-based saccadic selection during scene perception: Evidence from viewing position effects. *Journal of vision*, 13(5), 2-2.
- Marr, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. New York: Freeman.
- Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience*, 24(1), 167-202.
- Oh, S. H., & Kim, M. S. (2004). The role of spatial working memory in visual search efficiency. *Psychonomic Bulletin & Review*, 11(2), 275-281.
- Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, 32(5), 1243.
- Olivers, C. N., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in cognitive sciences*, 15(7), 327-334.
- Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual search has memory. *Psychological Science*, 12(4), 287-292.
- Pomplun, M., Reingold, E.M., Shen, J. (2001). Investigating the visual span in comparative search: the effects of task difficulty and divided attention. *Cognition*, 81, B57-B67.
- Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, 124(3), 372.
- Rayner, K., & Fischer, M. H. (1996). Mindless reading revisited: Eye movements during reading and scanning are different. *Perception & psychophysics*, 58(5), 734-747.
- Rayner, K., Pollatsek, A., Drieghe, D., Slattery, T. J., & Reichle, E. D. (2007). Tracking the mind during reading via eye movements: Comments on Kliegl, Nuthmann, and Engbert (2006).

- Reichle, E. D., Reineberg, A. E., & Schooler, J. W. (2010). Eye movements during mindless reading. *Psychological Science*, *21*(9), 1300-1310.
- Reimer, B. (2009). Impact of cognitive task complexity on drivers' visual tunneling. *Transportation Research Record*, *2138*, 13–19. doi:10.3141/2138-03.
- Reimer, B., Mehler, B., Wang, Y., & Coughlin, J. F. (2012). A field study on the impact of variations in short-term memory demands on drivers' visual attention and driving performance across three age groups. *Human Factors*, *54*(3), 454-468.
- Savage, S. W., Potter, D. D., & Tatler, B. W. (2013). Does preoccupation impair hazard perception? A simultaneous EEG and Eye Tracking study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *17*, 52–62. doi:10.1016/j.trf.2012.10.002.
- Spotorno, S., & Tatler, B. W. (2017). The elephant in the room: Inconsistency in scene viewing and representation. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(10), 1717.
- Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological review*, *84*(2), 127.
- Shore, D. I., & Klein, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision*, *14*, 59–75.
- Solman, G. J., Cheyne, J. A., & Smilek, D. (2011). Memory load affects visual search processes without influencing search efficiency. *Vision research*, *51*(10), 1185-1191.
- Tatler, B. W., & Vincent, B. T. (2008). Systematic tendencies in scene viewing. *Journal of Eye Movement Research*, *2*(2).
- Tatler, B. W., & Vincent, B. T. (2009). The prominence of behavioural biases in eye guidance. *Visual Cognition*, *17*, 1029–1054.
- Tatler, B. W., Hayhoe, M. M., Land, M. F., & Ballard, D. H. (2011). Eye guidance in natural vision: Reinterpreting salience. *Journal of vision*, *11*(5), 5-5.
- Tatler, B. W., Brockmole, J. R., & Carpenter, R. H. S. (2017). LATEST: A model of saccadic decisions in space and time. *Psychological Review*, *124*(3), 267-300.
- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97-136.

- Treisman, A. (1988). Features and objects: The 14th Bartlett Memorial Lecture. *Quarterly Journal of Experimental Psychology*, 40A, 201-237.
- van der Linden, L., & Vitu, F. (2017). On the optimal viewing position for object processing. *Attention, Perception, & Psychophysics*, 78(2), 602-617.
- Van Diepen, P. M., De Graef, P., & d'Ydewalle, G. (1995). Chronometry of foveal information extraction during scene perception. *Studies in visual information processing*, 6, 349-362.
- Vitu, F., O'Regan, J. K., Inhoff, A. W., & Topolski, R. (1995). Mindless reading: Eye-movement characteristics are similar in scanning letter strings and reading texts. *Perception & Psychophysics*, 57(3), 352-364.
- Vitu, F., McConkie, G. W., Kerr, P., & O'Regan, J. K. (2001). Fixation location effects on fixation durations during reading: An inverted optimal viewing position effect. *Vision Research*, 41(25-26), 3513-3533.
- Vitu, F. (2008). About the global effect and the critical role of retinal eccentricity: Implications for eye movements in reading. *Journal of Eye Movement Research*, 2(3).
- Wickham, H. (2009). *Ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York.
- Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, 1, 202-238.
- Wolfe, J.M. (1998) Visual Memory: What do you know about what you saw? *Current Biology*, 8: R303-R304
- Wolfe, J. M. (2003). Moving towards solutions to some enduring controversies in visual search. *Trends in Cognitive Sciences*, 7(2): 70-76
- Wolfe, J. M. (2007). Guided Search 4.0: Current Progress with a model of visual search. In W. Gray (Ed.), *Integrated Models of Cognitive Systems* (pp. 99-119). New York: Oxford.
- Wolfe, J. M. (2012). Saved by a log: How do humans perform hybrid visual and memory search? *Psychological Science*, 23(7). 698-703
- Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, 12, 219-224

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review*, *11*, 269–274.

Yarbus, A. L. (1967). Eye movements during perception of complex objects. In *Eye movements and vision* , 171-211. Springer US.

Appendix 1

Example Puzzle and easy questions used for cognitive load manipulation

Puzzle task questions (high load):

- 1) What English word has three consecutive double letters? - Bookkeeper
- 2) What's black when you get it, red when you use it, and white when you're all through with it? – Charcoal
- 3) What always runs but never walks, often murmurs, never talks, has a bed but never sleeps, has a mouth but never eats? – A river
- 4) The person who makes it, sells it. The person who buys it never uses it and the person who uses it doesn't know they are. What is it? – A coffin
- 5) What has to be broken before it can be used? – An egg
- 6) What has only two words, but thousands of letters? – Post office
- 7) The more you take, the more you leave behind. What are they? – Footsteps
- 8) When one does not know what it is, then it is something; but when one knows what it is, then it is nothing. – A riddle
- 9) What is it that everybody does at the same time? – Grow older
- 10) A girl who was just learning to drive went down a one-way street in the wrong direction, but didn't break the law. How come? – She was walking
- 11) A prisoner is told "If you tell a lie we will hang you; if you tell the truth we will shoot you." What can he say to save himself? - You will hang me. If they hang him, then the statement was true and they could only hang him for telling a lie. If they shoot him, then it makes the statement a lie and they were only to shoot him for telling the truth. An alternate solution is to say, "You will not shoot me," leading to the same quandary for the killers.
- 12) How far can a dog run into the forest? Halfway – afterwards he's running out
- 13) Name three consecutive days without using the words Wednesday, Friday, or Sunday. – Yesterday, today, Tomorrow
- 14) If you were to spell out the numbers, how far would you have to go before encountering the letter 'A'? One thousand (or one hundred AND one)
- 15) A clock loses exactly ten minutes every hour. If the clock is set correctly at noon, what is the correct time when the clock reads 3:00pm? A clock loses exactly ten

minutes every hour. If the clock is set correctly at noon, what is the correct time when the clock reads 3:00pm?

- 16) Two days ago Lilly was 7 years old. Next year she will turn 10. How can this be?
- Her birthday is on December 31st. Today is January 1st so she was 7 two days ago, now she's 8. She will turn 9 this year and next year she'll turn 10.
- 17) What is round as a dishpan and no matter the size, all the water in the ocean can't fill it up? – A sieve
- 18) What is it that you will break every time you name it? - Silence
- 19) What grows in winter, dies in summer, and grows roots upward? - An icicle
- 20) What turns everything around, but does not move? - A Mirror
- 21) What has a tongue, cannot walk, but gets around a lot? – A Shoe
- 22) What runs around a house but doesn't move? - A fence
- 23) What gets whiter the dirtier it gets? – Chalkboard
- 24) What can you catch but not throw? A Cold
- 25) What sits in a corner while traveling all around the world? A stamp
- 26) What needs an answer, but doesn't ask a question? A telephone
- 27) What travels around the world all year without using a single drop of petrol? –
The moon
- 28) What kind of running means walking? Running out of petrol
- 29) A man drove 200 miles without noticing that he had a flat tire. How can this be? -
His spare tyre was flat

Easy Questions (low load):

- 1) What is the capital of France? – Paris
- 2) What is eight divided by four? – 2
- 3) How many wheels are there on a car? - 4
- 4) How many wheels are there on a motorbike? -2
- 5) How many letters are there in the word sky? 3
- 6) What is the capital of England? - London
- 7) What is ten plus five? - 15
- 8) Who is the current prime minister of England? – Cameron
- 9) Who is the current president of the United States? - Obama
- 10) What is the Capital of Scotland? – Edinburgh
- 11) What is capital of Germany? - Berlin

- 12) What is the largest number on a regular die? - Six
- 13) What language is spoken in Poland? - Polish
- 14) Where can you find the Eiffel Tower? - Paris
- 15) What is four multiplied by five? – 20
- 16) What is twenty minus ten? - 10
- 17) At what temperature does water freeze? 0°C
- 18) In what town can you find the Tower Bridge? - London
- 19) Which University do you study at? – University of Dundee
- 20) What is half of twenty? - 10
- 21) At what temperature does water boil and turn into steam? 100°C
- 22) How many letters are there in the word “Door”? - Four
- 23) Where can you find the white house? Washington DC
- 24) What is the opposite of white? Black
- 25) What is your favourite colour? .
- 26) How many legs does a cat have? - Four
- 27) How many horns does a bull have? – Two
- 28) What do you study?
- 29) What is the chemical formula for Oxygen – O₂
- 30) What is 100 – 50? - 50
- 31) What is the opposite of happy? - Sad
- 32) What is the typical colour for a fire engine? - Red
- 33) What is the highest mountain in the world? – Mt Everest
- 34) Linda reads ten pages of her book every day. How many pages does she read in a week - 70
- 35) What is 10 + 10
- 36) How many sides are there on a triangle? - Three
- 37) What is 100 – 10? - 90
- 38) What is 200 – 100? - 100
- 39) What is 10 * 10? - 100**

Appendix 2: Description of Eye Dominance Tests

- 1) “Hand triangle” method
 - a. “Fully extend your arms out in front of you and form a small triangular opening between your thumbs”
 - b. “Choose a small object in the room (typically a thumb tack on the opposing wall) and position the small opening made with your hands in such a way that you can see it with both eyes open.”
 - c. “Close your left eye. Do you still see the object?”
 - d. “Close your right eye”. Do you still see the object?”
 - e. The dominant eye is the eye with which the subject was able to still see the object through the small triangular opening in his hands.
- 2) “The thumb” method
 - a. Fully extend one of your arms and cover the object you just used for test 1 with your thumb so that the object disappears when viewed with both eyes
 - b. Alternately close one eye after the other.
 - c. The eye that keeps your thumb directly in front of the object while the other eye is closed is considered the dominant eye.
- 3) “The photographer” method
 - a. “Imagine you are taking a photograph through a camera”
 - b. “Hold the camera to your face and look through the viewfinder with one eye”
 - c. The eye that subjects automatically use to look through the “viewfinder” is considered their dominant eye

Appendix 3: Effects of trial number within blocks

Models to check for variation in cognitive load effect over trials, within each block.

Here we report whether there was an effect of trial number and crucially whether the effect of trial number interacted with cognitive load. Any such interaction might imply a variation in the effect of the cognitive load manipulation as the block progresses. We do not report whether there was a main effect of cognitive load, because this is explored in the main models in the manuscript. While trial number did have an effect on some variables (RT, Scanning time and refixation rate) there was only an interaction between trial number and cognitive load for fixation duration. We therefore re-ran the LMM for fixation duration reported in the main text with trial number as an additional fixed effect (in interaction with the other fixed effects). This inclusion did not change the pattern of significant fixed effects and did not improve the fit of the model (tested by comparing models using `anova()` in R).

Table A1. Effects of trial number for each experimental variable in the manuscript.

Variable	Fixed effects	β	<i>SE</i>	<i>t / z</i>
Accuracy	Trial Number	0.015	0.011	1.42
	Cognitive load X trial number	0.018	0.011	1.69
RT	Trial Number	-0.002	0.001	-2.12*
	Cognitive load X trial number	-0.001	0.001	-1.60
Search initiation	Trial Number	<-0.001	0.001	-0.63
	Cognitive load X trial number	0.001	0.001	-0.81
Scanning time	Trial Number	-0.015	0.007	-2.05*

	Cognitive load X trial number	-0.008	0.007	-1.10
Verification time	Trial Number	-0.005	0.002	-2.09
	Cognitive load X trial number	<-0.001	0.002	-0.09
Fixation duration	Trial Number	<-0.001	<0.001	-0.46
	Cognitive load X trial number	-0.001	<0.001	-3.01**
Refixation rate	Trial Number	-0.003	0.002	-2.15*
	Cognitive load X trial number	0.001	0.002	0.79

* p < .05, ** p < .01, *** p < .001.

Appendix 4: Model structures

Model 1: Accuracy

$Accuracy \sim Target\ Presence * Cognitive\ Load * Array\ Structure + (1 + Cognitive\ Load + Array\ Structure || Subject) + (1 | Audio\ Clip)$

Model 1.1: Simple effects of load on accuracy in target present and absent trials

$Accuracy \sim Target\ Presence\ by\ Cognitive\ Load * Array\ Structure + (1 + Cognitive\ Load + Array\ Structure || Subject) + (1 | Audio\ Clip)$

Where *Target Presence by Cognitive Load* is a four-level factor describing this interaction, contrast coded for simple effects of cognitive load.

Model 1.2: Simple effects of array structure on accuracy in target present and absent trials

$Accuracy \sim Target\ Presence\ by\ Array\ Structure * Cognitive\ Load + (1 + Cognitive\ Load + Array\ Structure || Subject) + (1 | Audio\ Clip)$

Where *Target Presence by Array Structure* is a four-level factor describing this interaction, contrast coded for simple effects of array structure.

Model 2: Response Time

$\log_{10}(RT) \sim Target\ Presence * Cognitive\ Load * Array\ Structure + (1 + Cognitive\ Load || Subject) + (1 | Audio\ Clip)$

Model 2.1: Simple effects of load on accuracy in target present and absent trials

$\text{Log}_{10}(\text{RT}) \sim \text{Target Presence by Cognitive Load} * \text{Array Structure} + (1|\text{Subject}) + (1|\text{Audio Clip})$

Where *Target Presence by Cognitive Load* is a four-level factor describing this interaction, contrast coded for simple effects of cognitive load.

Model 3: Search initiation (first saccade latency)

$\text{Log}_{10}(\text{First saccade latency}) \sim \text{Cognitive Load} * \text{Array Structure} + (1 + \text{Cognitive Load} * \text{Array Structure}|\text{Subject}) + (1 + \text{Array Structure}|\text{Audio Clip})$

Model 4: Scanning time

$\text{Log}_{10}(\text{scanning time}) \sim \text{Cognitive Load} * \text{Array Structure} + (1 + \text{Cognitive Load} * \text{Array Structure}|\text{Subject}) + (1 + \text{Array Structure}|\text{Audio Clip})$

Model 5: Initial landing position on target (distance from target centre)

$\text{Saccade landing position} \sim \text{Cognitive Load} * \text{Array Structure} + (1|\text{Subject}) + (1|\text{Audio Clip})$

Model 6: Verification time

$\text{Log}_{10}(\text{verification time}) \sim \text{poly}(\text{Saccade landing position}, 2) * \text{Cognitive Load} * \text{Array Structure} + (1|\text{Subject}) + (1|\text{Audio Clip})$

Model 7: Fixation durations on and between items

$\text{Log}_{10}(\text{fixation duration}) \sim \text{On or off item} + (1|\text{Subject}) + (1|\text{Audio Clip})$

Model 8: Fixation duration

$\text{Log}_{10}(\text{fixation duration}) \sim \text{poly}(\text{Saccade landing position}, 2) * \text{Target Presence} * \text{Cognitive Load} * \text{Array Structure} + (1|\text{Subject}) + (1|\text{Audio Clip})$

Model 8.1: Simple effects of cognitive load on fixation duration in structured and unstructured arrays

$\text{Log}_{10}(\text{fixation duration}) \sim \text{poly}(\text{Saccade landing position}, 2) * \text{Target Presence} * \text{Cognitive Load by Array Structure} + (1|\text{Subject}) + (1|\text{Audio Clip})$

Where *Cognitive Load by Array Structure* is a four-level factor describing this interaction, contrast coded for simple effects of cognitive load.

Model 9: Refixation rate

$\text{Refixation rate} \sim \text{Target Presence} * \text{Cognitive Load} * \text{Array Structure} + (1|\text{Subject}) + (1|\text{Audio Clip})$