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Visual selective attention is equally functional for individuals with low and high working memory capacity: Evidence from accuracy and eye-movements

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Abstract

Selective attention and working memory capacity (WMC) are related constructs, but debate about the manner in which they are related remains active. One elegant explanation of variance in WMC is that the efficiency of filtering irrelevant information is the crucial determining factor, rather than differences in capacity per se. We examined this hypothesis by relating WMC (as measured by complex span tasks) to accuracy and eye movements during visual change detection tasks with different degrees of attentional filtering and allocation requirements. Our results did not indicate strong filtering differences between high and low WMC groups, and where differences were observed, they were counter to those predicted by the strongest attentional filtering hypothesis. Bayes factors indicated evidence favoring positive or null relationships between WMC and correct responses to unemphasized information as well as between WMC and the time spent looking at unemphasized information. These findings are consistent with the hypothesis that individual differences in storage capacity, not only filtering efficiency, underlie individual differences in working memory.

Abstract word count: 165

Keywords: attentional control, eye movements, working memory, visual short-term memory, individual differences

Visual selective attention is equally functional for individuals with low and high working memory capacity: Evidence from accuracy and eye-movements

Working memory capacity (WMC), the ability to concurrently store and process information, is strongly correlated with performance on a large range of cognitive tasks (Hutchison, 2007; Jarrold & Towse, 2006; Unsworth, Schrock, & Engle, 2004), scholastic achievements (Alloway, 2009), and common cognitive failures (Unsworth, Brewer, & Spillers, 2012). Several hypotheses have been put forward to explain these relationships. Some emphasize individual differences in attentional abilities (Engle, Kane, & Tuholski, 1999; Kane et al., 2004; Kane, Conway, Hambrick, & Engle, 2007) whereas others emphasize individual differences in storage capacity (Chuderski, Taraday, Nęcka, & Smoleń, 2012; Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Cowan et al., 2005). Both types of theory aim to explain individual differences in a number of key phenomena in selective attention.

A compelling illustration of relationships between individual differences in WMC and selective attention occurs in the cocktail party effect, or noticing one's own name in a nearby conversation while engaged in a different conversation. Conway, Cowan and Bunting (2001) had participants perform a dichotic listening task in which different streams of words were presented to each ear and the relevant stream had to be repeated aloud. Low WMC individuals were found to notice their own name in the irrelevant stream much more frequently than high WMC individuals, indicating a possible deficit in selective attention (Conway et al., 2001). When participants were asked instead to divide their attention between two streams and report immediately when they noticed their own name, high WMC individuals reported hearing their own name more often than low WMC individuals, demonstrating that high WMC affords the flexibility either to focus attention to the exclusion of irrelevant information or instead to effectively divide attention between two relevant sources (Colflesh & Conway, 2007). High WMC individuals thus seemed able to flexibly ignore irrelevant information or divide their attention between multiple sources of information, depending on what the situation called for.

However, relationships between effective selective attention and WMC are not always apparent in situations designed to evoke them, suggesting that boundary conditions for relationships between WMC and selective attention still need to be clarified. For instance, irrelevant speech effects, the decline in memory performance when listening to irrelevant auditory stimuli, do not show consistent relationships with WMC as one might expect. The association between irrelevant speech effects and WMC has often been found to be weak (Elliott & Cowan, 2005) or even absent under most circumstances (Beaman, 2004). In general, WMC has been found to strongly correlate with the deteriorating effect of unexpected, infrequent auditory distractors but not with continuous and predictable distractors (Hughes, Hurlstone, Marsh, Vachon, & Jones, 2012; Sörqvist, 2010).

However, with visual tasks, broader claims about relationships between selective attention and memory capacity have been made. Most notably, evidence suggests that low-WMC individuals store irrelevant along with relevant stimuli during a visual short-term memory task, and evidence for this has been found even in circumstances in which the same sorts of distractors were employed continuously across many trials. Vogel, McCollough, and Machizawa (2005) used a visual change detection paradigm including relevant and irrelevant items denoted by colors. Utilizing the amplitude of contra-lateral delay activity as a measure of memory storage (Vogel & Machizawa, 2004), Vogel et al. estimated how many items participants committed to memory during a visual change detection task. When both relevant and irrelevant items were briefly presented, participants with high working memory performance exhibited contra-lateral delay activity amplitudes similar to storing only the number of relevant items whereas participants with low memory performance seemed to store both relevant and irrelevant items. These and similar findings (e.g. McNab & Klingberg, 2008) have been interpreted to mean that low WMC individuals might not have a smaller storage capacity per se, but instead overload working memory with irrelevant information. Since the irrelevant information that low WMC individuals inevitably encode is not usually tested, they only seem to have lower storage capacity (Awh & Vogel, 2008).

Possibly, the same boundary conditions that limit relationships between attentional control and WMC as measured with auditory or verbal tasks would also apply to maintenance of visual images, but currently the evidence with visual memoranda and distractors is mixed. While some research suggests that individuals with low capacity consistently allow distractors to be encoded into working memory (McNab & Klingberg, 2008; Vogel et al., 2005), other findings suggest a more complex explanation is needed. Fukuda and Vogel (2009) presented a series of experiments in which participants were directed to search a visual array for a pre-cued item in order to report the location of a gap on the item. Sometimes, irrelevant probes were displayed after the offset of the array, and these could appear in the position of a target or a distractor item. Because the search arrays were presented very briefly, one would expect task performance to be sensitive to individual differences in attention. Fukuda and Vogel did observe that individual differences in WMC (as measured by a visual change detection task) strikingly correlated with various neural measures believed to index attentional capture or the encoding of information. However, despite observing significantly worse behavioral performance when irrelevant probes appeared in the same location as to-be-reported targets, the size of this effect did not correlate significantly with working memory capacity. Like the lack of a clear relationship between irrelevant sound effects and working memory capacity, these results suggest that it cannot be the case that low-WMC individuals are simply less able to voluntarily control attention than high-WMC individuals. Fukuda and Vogel (2009, 2011) thus conclude that low-WMC individuals are poorer at re-directing attention after involuntary attentional capture.

These patterns of relationships between various measures of attentional control and WMC indicate that relationships between working memory and selective attention are more complicated than once believed. New evidence using a wider variety of methods is essential for making further progress in understanding these relationships. Although several studies have previously investigated relationships between visual selective attention and WMC (e.g., McNab & Klingberg, 2008; Vogel et al., 2005), there are limitations to their interpretability. First, these studies typically relied on capacity estimates from a visual change detection task as the sole WMC indicator, while performance on the same task sometimes also generated the measure of attentional filtering efficiency. When correlations were observed between WMC and filtering efficiency, the correlations were striking, which is perhaps not surprising when both measures were derived from various aspects of performance on the same task. While Fukuda and Vogel (2009) generalized their findings across a broader range of tasks, their tasks still share many characteristics, particularly extremely brief presentation of visual materials. If similar relationships were uncovered between filtering efficiency during visual change detection and another typical measure of WMC, such as a complex WM span task (e.g., Shipstead, Redick, Hicks, & Engle, 2012; Unsworth et al., 2005), then interpretation of the meaning of the correlations would be stronger even if the correlations were somewhat weaker.

Second, though there seems to be an emerging consensus that low-capacity individuals are only especially susceptible to involuntary attentional capture (e.g. Fukuda & Vogel, 2009; Hughes et al., 2012; Sörqvist, 2010), this explanation does not entirely fit with the notion that low WMC individuals helplessly store irrelevant items during the visual change detection tasks. In these paradigms (e.g. Cowan et al., 2010; Gold et al., 2006; Vogel et al., 2005), participants were made aware of which items were most relevant and which were to-be-ignored, and these assignments were usually constant for a particular participant across an experimental session. The irrelevant items were typically distinguished from the relevant ones by some salient feature; for instance, relevant items might differ from distractors in color (McNab & Klingberg, 2008; Vogel et al., 2005). Those paradigms thus do not seem to fulfill the criteria that should be required to observe differences in filtering efficiency between low- and high-WMC individuals, because the distractors are consistent and predictable. Resisting capture with such stimuli seems more consistent with voluntary than involuntary attentional control. Though the relationships reported are undeniably strong, subsequent results (such as those of Fukuda & Vogel, 2009) suggest that original interpretations of the relationship ought to be tempered by new evidence.

Furthermore, in much of the research described above, there was no behavioral measure of memory for distractor stimuli. Assuming that the interpretation of the physiological indicators used by McNab and Klingberg (2008) and Vogel et al. (2005) is correct, individuals with low WMC should perform better on tests of distractors than individuals with high WMC. However, research with populations known to possess low WMC suggests otherwise. Cowan et al. (2010) compared WMC as measured with a visual probe recognition task in children and adults, including conditions that required attentional selection for optimal performance. Young children are known to have lower WMC than older children and adults (e.g., Cowan et al., 2005), yet even the youngest group of children in Cowan et al.'s sample were capable of following the attentional selection instructions, which indicated that they should focus more on remembering one particular category of colored shape. Cowan et al. concluded that even young children with smaller WMC could filter efficiently under conditions in which their storage capacity was not exceeded. Similarly, patients with schizophrenia, who demonstrate lower WMC than healthy controls, nonetheless show no clear difference in the ability to selectively attend to particular objects within a to-be-remembered visual array (Gold et al., 2006). These findings are potentially problematic for the assumption that low-WMC individuals seem to have low capacity *because* they store irrelevant as well as relevant items.

Finally, requiring maintenance across only a short retention interval should actually require little of the sustained attentional focus that some suggest should be necessary to detect WMC differences. For example, in a study by Poole and Kane (2009), participants searched a predetermined grid in which some locations were cued as likely to contain a target. Maintaining attentional focus on these cues was required over either short (300ms) or long (1500ms) delays. Low WMC individuals were slower when distractors were present, but only when the delay was long. Thus WMC was associated with the filtering of irrelevant information, but only when attentional focus needed to be maintained over some time. This suggests that over a period of time, low-WMC individuals are more likely to suffer an attentional lapse, not that they are deficient at orienting attention in response to a cue. However, previous visual change detection research usually measured retention over very brief intervals, often less than 1,000 ms (e.g., Fukuda & Vogel, 2009; Vogel et al., 2005). Durations so short may reflect sensory memory as well as working memory (Sperling, 1960).

To address these limitations, we designed experiments in which we examined populations of individuals ranging across a wide spectrum of scores on two popular complex working memory span tasks. In both experimental tasks, the object was to remember visual images over a retention interval long enough to exclude contribution from sensory memory, and the experimental designs enabled comparisons of recognition accuracy in conditions varying in attentional selection instructions (Experiment 1) and incentives (Experiment 2). To further explore the relationship between WMC and selective attention we recorded participants' eye movements, both during stimulus presentation and retention. Previous research using similar stimuli and timing has shown that fixations meaningfully affect behavioral performance (e.g., Huebner & Gegenfurtner, 2010; Shao, Li, Shiu, Zheng, Lu, & Shen, 2010; van Lamsweerde & Beck, 2012). Presumably, if individuals differ in their ability to selectively attend only the most relevant items in an array, we could discern this difference in gazes. If low-WMC individuals cannot selectively attend to task-relevant stimuli, they should fixate irrelevant distractors more often, for longer durations, and perhaps earlier during stimulus presentation than individuals with higher WMC. Because gaze information is also believed to reflect retrieval (Ferreira, Apel, & Henderson, 2008; Tremblay, Saint-Aubin, & Jalbert, 2006), we analyzed eye movements during the retention interval as well as during the stimulus display. Fixations during the stimulus presentation can be seen as reflecting selective attention or perceptually-driven attentional capture during encoding, but fixations during the retention interval (in which the stimulus colors were not available) are more likely to reflect selective attention toward mnemonic representations.

Experiment 1

Experiment 1 featured three conditions presented in separate blocks, depicted in Figure 1. (A) In Full-Set blocks, shapes from both categories were to be attended and both were tested equally often. Full-Set trials were used as a baseline measure of visual array task performance. (B) In Half-Set blocks, only one shape was tested and thus the other could be ignored with no cost to performance. Eye movements during Half-Set performance served as an estimation of filtering efficiency because selective attention towards the attended shape was required. (C) In Ratio-Set blocks, one shape was tested twice as often as the other shape. We considered both predominant and infrequent item performance within the Ratio-Set, with both accuracies and gaze fixations used to measure the strategic allocation of attention. Relationships between WMC and both gaze and accuracy dependent variables are important. If WMC is negatively correlated with the tendency to store irrelevant information, then low-WMC individuals should out-perform high-WMC individuals on recognition of infrequently tested items. We can only test this hypothesis using accuracy in the Ratio-Set, but can evaluate this hypothesis using gaze information in both the Ratio-Set and the Half-Set. If WMC reflects mainly attentional control abilities, WMC should negatively correlate with fixating irrelevant items in both the Half-Set and the Ratio-Set.

INSERT FIGURE 1 HERE

Method

Participants. Seventy-one students from the University of Groningen (43 women, 28 men, age 18-34, *M*=21.76, *SD*=2.60) participated as part of their course requirements or an honorarium of €14. One participant was excluded from all analyses due to probable color blindness, one due to a software malfunction, and an additional 11 participants were excluded from the dwell time analysis due to erroneous calibration of the eye-tracker in at least one experimental block. The study was approved by the local ethics committee and all participants gave written informed consent. All participants were fluent English speakers.

Working Memory Capacity screening. Participants were screened using two complex working memory span tasks in a 60-minute session at least two weeks prior to the main experimental session using computerized versions of the operation and symmetry span tasks (Unsworth, Redick, Heitz, Broadway, & Engle, 2009; Unsworth, Heitz, Schrock, & Engle, 2005). In operation span, participants were asked to remember serially presented consonants, while judging the accuracy of math equations. In symmetry span, participants were instructed to remember serially presented locations of red squares in a 4x4 matrix while judging whether block patterns were vertically symmetrical. All participants were required to respond correctly on at least 85% of the secondary task judgments (i.e., the math equations and symmetry judgments) to be eligible to take part in the visual recognition memory experiments. Performance was measured using the partial storage score (as recommended by (Conway et al., 2005)), the sum of items recalled in the correct serial position for a maximum score of 75 for operation and 42 for symmetry span.

We chose to analyze data based on a composite of two WMC tasks in order to increase the reliability of our predictor. Scores on these two tasks correlated significantly (*r*=0.52), and Chronbach's alphas were acceptable at 0.84 and 0.72 for operation and symmetry span, respectively.[1] We defined low-WMC as a composite score of less than 81 and high-WMC as a composite score above 99. These cut-offs were determined by calculating the lowest and highest 25% of a large sample (*N*=1014) of first year psychology students. We recruited high- and low-WMC individuals from these extreme quartiles plus individuals with scores in between (thus from the middle quartiles). Score distributions in our sample were comparable to established norms (see Redick et al., 2012, Tables 3 and 4). We provide descriptive statistics for each complex span task in Table 1.

INSERT TABLE 1 HERE

Apparatus and stimuli. The visual memory task was presented on a 48.26 cm CRT monitor, at a resolution of 1280 x 1024 and a refresh rate of 60Hz. Presentation was controlled using E-Prime (Schneider, Eschman, & Zuccolotto, 2002). Eye movements were measured at a rate of 1000 Hz using an SR Research EyeLink 1000 with 0.01° spatial resolution. Distance between monitor and chinrest was kept constant at 67 cm and the distance between chinrest and camera was always 50 cm. A Microsoft Sidewinder gamepad was used for response collection.

[1] Participants of Experiments 1 and 2 were included in this reliability analysis. The screening procedure was identical for both experiments.

All stimuli were presented against a grey background (HTML value: C0C0C0). Depending on condition and trial, two, four or eight colored triangles and circles with black outlines were randomly presented at eight fixed positions arranged in a circle around the center of the screen (Figure 1.). Per trial, half of the shapes were circles and the other half triangles. Memory and probe shapes were filled with one of nine colors: white (FFFFFF), red (FF0000), orange (FF6600), yellow (FFFF00), green (008000), blue (0000FF), purple (7030A0), brown (996600) or pink (FF9999). Colors were randomly selected within each shape category independently; a trial could thus have circles and triangles with the same color. During the retention interval, only the black outlines of the shapes were shown. The circular arrangement of invisible positions in which the shapes were presented subtended 7.51° and each stimulus' location was 3.76° from the center of the screen. Shapes were sized to fit inside an invisible rectangle which subtended 0.79° and this space served as the extent of the interest areas for analyzing eye fixations.

Procedure. After signing an informed consent form, an experimenter explained the task instructions. Each session began with a six-item color blindness screening (Ishihara, 1966) followed by six supervised practice trials with accuracy feedback. Before each experimental block, the eye tracker was manually calibrated to the right eye.

Figure 1 depicts the timing of events within a trial. Each trial began with a 1,000-ms fixation cross, followed by a 1,200-ms memory display of two, four or eight objects, then a 3,000-ms retention interval of the objects' outlines, and finally a probe display including the objects' outlines and one colored shape, which remained onscreen until a response was collected. Participants were asked to indicate via button press whether the color of the shape in the probe display was the same as or different from the shape at the same location on the memory display. The color of the shape changed on 50% of trials. After the response, a 2000-ms screen appeared with the text "get ready for the next trial". No accuracy feedback was given on experimental trials.

Each block featured one of three probe conditions (see Figure 1). Each participant was randomly assigned a predominant shape. In (A) Full-Set blocks, participants were informed that any shape could be tested. Full-Set trials featured two, four or eight shapes. In (B) Half-Set blocks, participants were informed that only the predominant shape would be tested and that the other shape should therefore be ignored. Half-Set trials featured four or eight shapes. In (C) Ratio-Set blocks, participants were informed that the predominant shape would be tested most frequently but the other shape would be tested occasionally. Participants were not informed about the exact percentages of predominant and other-shape tests (66.6% and 33.3% respectively). Ratio-Set trials featured four or eight shapes. To facilitate explanations of changes in the instructions with each block, all blocks were presented in the same order to each participant (Full-, Half-, Ratio-, Ratio-, Half- and Full-Set), with repeated blocks in reverse order to minimize influences of practice and fatigue on between-block differences. Between the third and fourth block participants took a mandatory break of 10 minutes; breaks were also allowed at the participant's discretion between each block. The complete session, including setup and debriefing, lasted 105 minutes.

Results

We employed Bayesian analysis of variance (Rouder, Morey, Speckman, & Province, 2012) to examine WMC group differences in accuracy. This software is freely available as the R package *BayesFactor* (version 0.9.2; Morey & Rouder, 2013). This technique allows for meaningful interpretation of null results, which is especially important here because the predicted negative relationships between WMC and accurate responding to infrequently tested shapes were not present. Furthermore, inference using Bayes factors is free from the interpretative difficulties associated with the criterion logic of *p*-values, namely that a "significant" value should be interpreted, regardless of effect size, while "non-significant" values can never support inference, regardless of how far from criterion the *p*-value may be. Mass dependence on this criterion-based logic has arguably cluttered the psychological literature with reports of effects that, because the accepted significance criterion was reached at least once, are considered to be true despite quite weak evidence provided by the data (see Wetzels and Wagenmakers (2012) for examples). Bayes factors instead convey the extent to which the evidence in the data favors an outcome, and readers may decide for themselves whether this level of evidence is persuasive. Bayes factors are intended to be interpreted subjectively, with individuals considering the values against their own prior expectations. Nevertheless, Jeffreys (1961) provided a rudimentary scale for assessing Bayes factors, in which values ranging from 4-10:1 provide “substantial” evidence, values of 10-30:1 provide “strong” evidence, with higher values continually increasing confidence. Importantly, Bayes factors can be calculated with respect to either the null or alternative hypothesis. Here, we always provide the Bayes factor favoring the hypothesis under discussion. We also provide outcomes from traditional correlational analyses in order to facilitate comparisons with previously published results.

Visual recognition accuracy. Proportions of correct responses, subjected to the arcsine square root transformation to ensure that assumptions of homogeneity were not violated, were computed as the dependent variable for ANOVAs. Though our design enables computation of Cowan’s *k* (Rouder, R. Morey, C. Morey, & Cowan, 2011), we chose to analyze proportions correct because the differing selective attention instructions in each block make it tricky to determine a fair, consistent way to specify set size and to compare *k*s between blocks. Proportion correct avoids this problem, and is an acceptable dependent measure in this design, where proportions of same and change trials were always equal and a more complex model was unnecessary (R. Morey, C. Morey, Brisson, & Tremblay, 2012). Descriptive statistics for all experimental conditions are given in Table 2. Inference on accuracies was carried out on the Full-Set and Half-Set, which we used to test the hypothesis that WMC groups differed in the costs of filtering irrelevant items. We then analyzed the Ratio-Set to compare recognition of infrequently tested shapes across WMC groups.

For a balanced test, we omitted the Full-Set trials with 8 to-be-remembered items, and compared Full-Set trials with 2 and 4 to-be-remembered items with Half-Set trials including 2 and 4 to-be-remembered items plus 2 or 4 irrelevant items, producing a three-way design with block (Full- or Half-Set) and set size (2 or 4) as within-participant factors and WMC (low, medium, and high) as a between-participants factor. Bayes factors were estimated for all combinations of these three main effects and their interactions, and calculated with 1,000,000 Monte Carlo simulations. The best-fitting model included main effects of block and set size, plus an interaction between block and set size, yielding a Bayes factor of $1.43\text{x}10^{64}$ (± 1.01% sampling error) in comparison to between-participants variance alone. Each effect can be separately quantified by comparing this best-fitting model with the best model excluding the relevant term, or alternatively, by comparing a model excluding the relevant term only from the model including all effects and interactions. Including main effects of block (Full-Set M=0.91, Half-Set M=0.87) and set size (Set Size 2 M=0.95, Set Size 4 M=0.83) were decisively favored, with the best model beating models excluding these terms by factors greater than 100,000. Inclusion of the block by set size interaction, which indicated that the cost of filtering increased with set size (at set size 2 $M_{Full\text{-}Set}$=0.96, $M_{Half\text{-}Set}$=0.95, whereas as set size 4, $M_{Full\text{-}Set}$=0.86, $M_{Half\text{-}Set}$=0.80), was favored by a factor of more than 38. An interaction between WMC and block, which could indicate that the cost of ignoring irrelevant items in the Half-Set differed based on WMC, was not in the best fitting model, and including it worsened model fit by a factor of more than 12. These results lend no weight to the notion that low-WMC individuals experience more difficulty ignoring irrelevant visual stimuli than high-WMC individuals.

Assuming the attentional filtering hypothesis, we also expected higher performance on infrequently tested items for low WMC individuals than for high WMC individuals. We therefore compared accuracy in the Ratio-Set with test likelihood (predominant (66.6%) or infrequent (33.3%)) and set size (4, 8) as within-participants variables and WMC (High, Middle and Low) as a between-participants variable. The model resulting in the highest Bayes factor included main effects for test likelihood (Predominant M=0.80, Infrequent M=0.71), set size (Set Size 4 M=0.85, Set Size 8 M=0.66), and WMC (high M=0.80, medium M=0.75, low M=0.72), producing a Bayes factor of 6.72×10^{40} (± 0.55% sampling error) against a model including only between-participant variability. Evidence in the data for the model excluding the interaction between test likelihood and WMC was greater than the model including this interaction by a factor of only 1.45; this is very weak evidence for or against including the interaction between test likelihood and WMC. However this value accounts only for the presence of the interaction, not its direction. Assuming that WMC actually measures individual differences in the ability to filter attention away from distractors (e.g. Vogel, et al., 2005), we would have expected to observe this interaction in the opposite direction. The interaction between test likelihood and WMC is plotted in Figure 2, showing that 1) high WMC individuals out-performed low WMC individuals on both the predominant and the infrequently-tested shape, and 2) the difference between accuracy on the predominant and infrequently-tested shapes was, if anything, smaller for the high

WMC than the low WMC individuals. Consistently with this outcome, WMC and accuracy on the infrequently tested shapes correlated strongly and positively (r=0.41, p<.01). Bayes factors analyses indicated that this relationship was favored over the null by a factor of more than 37. Note that this strong positive relationship runs counter to the hypothesis that lower-WMC individuals helplessly store irrelevant information.

INSERT TABLE 2 HERE

INSERT FIGURE 2 HERE

Dwell time. Before analyzing eye movement data, we computed descriptive statistics of several gaze variables. These statistics (see Appendix A) are intended to provide information about the global looking behavior of participants broken down by WMC. These values suggest that the looking data acquired in each group of subjects was comparable; we uncovered no systematic differences between groups in the number or the duration of fixations acquired. We also tested the essential assumption that directly fixating an item improved performance when the fixated item was eventually probed. Accuracy was better when an item was fixated during stimulus presentation (M=0.90, SD=0.06) than not (M=0.76, SD=0.08), and also better when the previous location of an item was fixated during the retention interval (M=0.88, SD=0.06) than not (M=0.75, SD=0.08). Evidence favored an effect of fixating over only between-participant variance with Bayes factors exceeding 100,000. This outcome enables analyses of preferential looking behavior in the Half- and Ratio-Set blocks.

To examine the preference to look at particular shapes, we computed relative proportion of dwell time per trial toward the positions containing each kind of shape, excluding fixations on anything but shape positions. Proportions were computed separately for the memory display and retention interval. To test whether the ability to filter distractors increased visual recognition performance, we correlated the proportion of time gazing toward never-tested shapes with performance in the Half-Set block in set-size 8 trials (Figure 3, upper panels). The highest set-size was chosen to ensure that the total number of to-be-attended items was near or above capacity for all participants and thus that filtering requirements were maximal. Result patterns were similar when analyses were conducted collapsed across set-sizes (see Table 3).

INSERT FIGURE 3 HERE

INSERT TABLE 3 HERE

In the Half-Set blocks, irrelevant stimuli were never tested and therefore could be completely ignored with no cost to performance. Consistently with the notion that filtering irrelevant in favor of relevant information increases visual change detection performance, looking less at never-tested shapes correlated with visual recognition memory performance during the memory display (see Table 3 and Figure 3, upper left panel). This is logically consistent with the results of Vogel et al. (2005): participants whose eye movements indicated a tendency to restrict looking at the irrelevant information tended to perform better. Bayes factor analysis indicated that this evidence favors some relationship between looking at the never-tested items and performance by factors of at least 4; the Bayes factor that the evidence favors specifically negative relationships was about 12 for the stimulus period and about 8 for the retention period.

However, the chaotic distribution of WMC groups (denoted by color) in the upper panels of Figure 3 suggests that WMC as measured by complex span tasks and tendency to ignore the irrelevant shapes were unrelated. Indeed, for set size 8, correlations between looking at never-tested shapes during the Half-Set blocks and WMC in both the memory display and retention interval were non-significant (r=.07 and r=.13, respectively). With all set sizes, these correlations were somewhat more positive (though still nonsignificant). Bayes factors against a negative correlation between WMC and looking at the irrelevant shapes exceeded 5. Together with the reported null interactions between WMC and changes in accuracy between the Full- and Half-Set blocks, this evidence lends no support to the hypothesis that individuals with low WMC attend more to irrelevant stimuli than those with high WMC.

To corroborate our behavioral finding that high-WMC individuals remembered infrequently tested shapes in the Ratio-Set blocks better than low WMC individuals, we correlated the proportion of looking directed toward infrequently tested shapes in displays with 8 items with WMC (Figure 3, lower panels; for correlations including set sizes 4 and 8, see Table 3). In line with the notion that high WMC individuals tried to encode more information regardless of its test likelihood, looking at infrequently tested shapes correlated positively with WMC in both the memory display and retention interval. Bayes factor analyses showed that for this relationship during the memory display, evidence tentatively favored the positive relationship (*BF*=5.22), while the Bayes factor on the data from the retention interval strongly favored the relationship by a factor of more than 300. This strong positive relationship, coupled with the evidence that selective looking behavior enhanced recognition performance, refutes the hypothesis that individuals with low WMC haphazardly attend to less important information under these predictable task circumstances.

Discussion

Contrary to the notion that WMC measures the ability to selectively focus attention by ignoring irrelevant information, we observed that individuals with low WMC spent less time looking at less relevant items in a visual memory display, responded less accurately to probes of infrequently-tested items than high-WMC participants, and showed no evidence of greater filtering costs compared to high-WMC participants. Low WMC individuals were clearly *more* prone to ignore the infrequently tested shapes during the Ratio-Set block than the high WMC individuals, and also were not more liable to fixate on the never-tested shapes during the Half-Set block. Accuracy in the Ratio-Set was best explained by a model that excluded an interaction between WMC and test likelihood, but even if we assume that this interaction should be considered, it occurred in the opposite direction from what the strongest attentional filtering hypothesis predicts.

Analyses also showed that performance in the Half-Set was higher when filtering was more efficient during the memory display, conceptually replicating findings of Vogel et al. (2005), but that WMC was not negatively correlated with looking at irrelevant distractors. In the Ratio-Set, where some shapes were infrequently tested, WMC decisively predicted looking at infrequently tested shapes, with high-capacity individuals attending more toward the infrequently tested shapes, and WMC correlated positively with proportion correct on infrequently tested shapes. Though we can reproduce the finding that accuracy in the visual array task correlates with filtering efficiency in the same visual array task (e.g., Vogel et al., 2005), an independent measure of WMC did not show the same relationship. This undermines the argument that WMC primarily indexes individual differences in the ability to divert attention away from irrelevant stimuli. Our results instead tend to support the idea that individuals with high WMC 1) can flexibly allocate their storage capacity (e.g., Colflesh & Conway, 2007), and 2) that extra capacity might spill-over to extraneous stimuli, perhaps particularly when perceptual load is low (Lavie, Hirst, De Fockert, & Viding, 2004).

Our results, like those of Colflesh and Conway (2007), seem to suggest that high-WMC individuals can strategically divide their attention to optimize performance, while also showing that low-WMC individuals can adequately ignore less relevant information. However, our task instructions might not have sufficiently motivated high-WMC individuals to strategically allocate attention to the predominant shapes. Possibly, high-WMC individuals believed they could remember all the stimuli in the Ratio-Set blocks and thereby optimize performance. We did not give accuracy feedback in this experiment, so the high-WMC individuals may not have realized that they were not performing near ceiling on the predominant shape probes; perhaps they did not have sufficient information to motivate a strategy of ignoring the infrequently-tested shapes. To consider this possibility, we carried out Experiment 2, in which we used rewards to motivate individuals to focus attention towards one shape (cf. Morey, Cowan, Morey, & Rouder, 2011). The incentive was a reduction of total experiment time when individuals responded correctly. We reasoned that high WMC individuals would be motivated to use any attentional control advantage to perform optimally on this task, which with the consistently high set sizes we chose, would entail selectively attending the high-reward shapes. Carrying out Experiment 2 also provided the opportunity to replicate the somewhat unexpected findings of Experiment 1, namely that low WMC individuals selectively attend at least as effectively as high-capacity individuals in a visual change detection task.

Experiment 2

Method

Participants. Fifty-eight students from the University of Groningen (39 women, 19 men, age 18-25, *M*=19.64, *SD*=1.33) participated as part of their course requirements. Four participants were excluded from all analyses due to possible color blindness (i.e., 2 or more mistakes on the 6-item Ishihara test), one participant was excluded due to a software malfunction, and another because of self-reported use of medicine that could affect cognitive functions. An additional 5 participants were excluded from the dwell time analyses due to poor calibration of the eye-tracker.

As in Experiment 1, all participants undertook a working memory screening in a separate session prior to the experimental session. Descriptive statistics for complex span task performance are provided in Table 1, and as in Experiment 1, indicate that the range and distributions of performances of our sample were consistent with those of much larger samples (e.g., Redick et al., 2012).

Apparatus, Stimuli and Design, and Procedure. The stimulus materials were the same as in Experiment 1. We added accuracy feedback for each trial in order to reinforce our reward instructions (e.g. 'Correct Circle, you get 900 points'). Correct answers earned participants points on each trial. During each block of trials, when a participant accumulated 32000 points, the current block ended. Thus the faster participants accumulated points, the sooner the experimental session ended for them.

Each block featured one of two within-participants probe conditions (Figure 4). As in Experiment 1, the shapes participants were directed to attend were counterbalanced between-participants. All trials featured eight shapes and each shape type (circle or triangle) was tested 50% of the time. In (A) Equal-Points blocks, participants were informed that correct answers for any shape would earn them 500 points. In (B) Ratio-Points blocks, participants were informed that the emphasized shape would earn them 900 points and the other shape 100 points.

INSERT FIGURE 4 HERE

Blocks were alternated and the beginning block was counterbalanced between participants (Full-, Ratio-, Full-, Ratio-Points, or Ratio-, Full-, Ratio-, Full-Points). Between the second and third block, participants took a mandatory break of

10 minutes; breaks were also allowed at the participant's discretion between each block. The experiment, including setup and debriefing, lasted on average 94 minutes (72-147 minutes, *SD*=13.72).

Results and Discussion

Visual recognition accuracy. Proportion of correct responses was computed on the minimum number of trials needed to reach the point threshold in any block (i.e., the first 64 trials per block for each participant). To test whether WMC was related to the ability to disregard the less relevant shape in favor of the relevant shape we included block type (Ratio-Points, Equal–Points) and shape emphasis (otherwise predominant/900 Points, otherwise less relevant/ 100 Points) as within-participants factors and WMC (High, Middle and Low) as a between-participants variable. In the Equal-Points block, we expected participants to perform similarly on tests of both shapes, but in the Ratio-Points blocks, according to a strong controlled attention account of WMC, high-capacity individuals should benefit more than low-capacity individuals from the disproportionate rewards because they will be better able to allocate attention flexibly to optimize reward; this relationship would be reflected by a 3-way interaction in which the difference between accuracy with 900 and 100 points is greater for the high WMC individuals, while no groups differ much on the two tested shapes in the Equal-Points block.

Bayes factors were estimated (with 1,000,000 Monte Carlo samples) for models including of each combination of the three possible main effects and their interactions. The model resulting in the highest Bayes factor included main effects for block type, shape emphasis, and an interaction between block type and shape emphasis, producing a Bayes factor of 7.05×10^{15} (± 1.06% sampling error) against a model including only between-participant variance. Mean performance by WMC, block type, and shape emphasis is given in Figure 5. The second best model additionally included a main effect for WMC and evidence for the best model, without WMC, was preferred by factor of about 4. The means shown in Figure 5 do not hint at any interaction between WMC and the other factors. The best model, which did not include the 3-way interaction that would indicate superior filtering in high-WMC participants, was favored over the model including this interaction by factor of about 900. This is consistent with Figure 5, which clearly suggests that all WMC groups performed much better on the high-reward than the low-reward shapes. A two-way interaction between WMC and block type might also be considered good evidence of an effect of capacity on filtering, if it indicated that WMC effects were larger in the Ratio-Points than the Equal-Points blocks. Figure 5 does not suggest this, and the Bayes Factor against including this interaction was approximately 25.

INSERT FIGURE 5 HERE

Dwell time. To test whether the ability to filter unemphasized shapes was associated with WMC, we correlated the percentage of gazes (out of the total time spent looking at any kind of shape) directed at unemphasized shapes during the Ratio-Points blocks with WMC scores (Figure 6). As in Experiment 1, performance improved for items that were directly fixated (M=0.78, SD=0.08 for the stimulus period; M=0.80, SD=0.08 for the retention period) compared with items that were never fixated (M=0.67, SD=0.05 and M=0.64, SD=0.06 for stimulus and retention periods respectively; Bayes factors favoring an effect of fixating exceeded 100,000). Descriptive statistics summarizing global looking behavior can be found in Appendix B. Consistently with the notion that participants did not differ in their ability to filter unemphasized in favor of emphasized information, looking at unemphasized shapes did not correlate with WMC during the memory display (r=.02, p=.89) or the retention interval (r=.05, p=.75). Bayes factors that the relationship was negative (as predicted) favored the null by factors of approximately 4 for both the stimulus and the retention periods. WMC did not correlate with any other performance or filtering measure in this experiment (Table 4). Thus in contrast to the view that efficient filtering abilities are confined to high WMC individuals (e.g. Conway, Cowan, & Bunting, 2001; Vogel, et al., 2005) we observed no obvious differences in strategically allocating attention across the spectrum of WMC scores, despite designing a task that should theoretically have provoked differences if one assumes that low capacity individuals cannot control attention effectively.

INSERT FIGURE 6 HERE

INSERT TABLE 4 HERE

General Discussion

The relationship between WMC and higher cognitive functions has previously been explained by positing differences in attentional abilities or differences in storage capacity. Both explanations can be applied to the effects of visual distractors on visual memory performance. If WMC is virtually a measure of attentional control, low WMC individuals should be unable to filter irrelevant information as efficiently as high WMC individuals, as observed by Vogel et al. (2005). But if storage capacity underlies WMC differences, less elegant, more complex outcomes and interpretations become necessary: high WMC individuals may show superior filtering efficiency, or they might encode both relevant and less relevant information, perhaps in an attempt to improve performance, or simply to avoid any cost that filtering might incur.

We chose to address this using eye-tracking during a visual change detection task, comparing conditions of varying attentional filtering requirements. We used performance on complex working memory span tests collected in a prior experimental session to predict eye movements in these conditions. In Experiment 1, we operationalized attentional filtering by manipulating the proportion of trials per block that tested particular shapes. Participants were always made aware of these proportions, but were not explicitly instructed to try to remember only frequently-tested shapes. In Experiment 2, we instead manipulated the size of the reward given for correct responses to each type of shape, which we expected would make choosing to selectively attend a more attractive strategy. Both behavior and eye movement data were considered as potentially providing evidence for assessing attentional filtering hypotheses, and we analyzed eye movements during both stimulus presentation, which presumably reflect attentional filtering during encoding, and retention, which must reflect attention toward mnemonic representations.

Consistently with the evidence of Vogel et al. (2005), ignoring irrelevant information during stimulus encoding in visual change detection was related to visual change detection accuracy. Participants who looked less at irrelevant information performed better on tests of relevant information. However, we did not observe the same relationship between WMC as measured by complex span and looking behavior during this visual memory task. Contrary to the notion that WMC is primarily a measure of filtering efficiency, the ability to ignore irrelevant information was not confined to high WMC individuals. We observed compelling evidence via Bayes factor analyses that individuals with low WMC did not store items haphazardly, but selectively attended at least as well as high WMC individuals, during both stimulus presentation and during the retention periods. Reasoning that high WMC individuals might not have realized that they could have improved their performance by selectively attending the emphasized shapes, we carried out a second experiment using rewards to convey emphasis and providing accuracy feedback. However, we found that individuals across the spectrum of WMC scores responded similarly to the reward scheme we imposed, in both their accuracy and looking behavior. Bayes factor analyses allowed for the quantification of the lack of differences between individuals with high, medium, and low WMC, and produced extremely strong evidence in support of the null hypothesis that individuals across the spectrum behaved similarly when considering visual change detection accuracy, supported by modest evidence in the gaze data.

It has been shown previously that individuals with high WMC can use their resources to either focus (Conway et al., 2001) or efficiently divide their attention

(Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Colflesh & Conway, 2007). Because of this, many possible outcomes for individuals with high WMC can be explained by the hypothesis that their control of attention is superior. The importance of our findings for further theorizing about relationships between attention and WMC therefore lies in the performance of the low-capacity individuals. While it is acknowledged that high-capacity individuals may control their performance flexibly, individuals with low WMC are expected to be far less capable of this, despite evidence suggesting that individuals from populations with low WMC (e.g., young children or schizophrenic patients: Cowan et al., 2010; Gold et al., 2006) can ignore distracting information as well as higher-capacity populations, as well as mounting evidence that WMC does not universally correlate with efficient selective attention in healthy young adults (e.g., Beaman, 2004; Poole & Kane, 2009). In our sample, WMC scores were positively related to the tendency to attend less relevant information in Experiment 1, where individuals were not explicitly instructed to attend to one type of information over another. However, in Experiment 2, in which we introduced a stronger incentive to focus on a particular set of shapes, WMC was not at all predictive of the tendency to look at and encode less relevant information. Thus low-capacity individuals were no more likely to attend to unemphasized information than high WMC individuals, and in Experiment 1 where strategic allocation was not rewarded, they were substantially less likely to look at and encode irrelevant information than high WMC individuals. We think this is best explained by positing that differences in storage capacity, possibly in addition to qualified differences in attentional control, underlie WMC scores. While low WMC individuals seemed to preserve their limited storage capacity for more relevant information irrespective of incentives, high WMC individuals seemed to flexibly alter their strategy depending on the perceived benefit of engaging in filtering.

Previous evidence for the claim that low-capacity individuals cannot efficiently filter attention has likely been inflated because measures of filtering efficiency and capacity were derived from aspects of performance on the same task (e.g., McNab & Klingberg, 2008; Vogel et al., 2005). To measure WMC, we instead used a combined score of two popular complex working memory span tasks, for which standards of performance based on very large samples are available (Reddick et al., 2012). We think this design is more appropriate for making generalizations to broader theoretical constructs. First, our combined WMC scores included two complex span tasks, one arguably more reliant on verbal processes (i.e., operation span) and one arguably more reliant on visual processes (i.e., symmetry span); with a predictor score composed of these tasks, any relationship we observed could not be attributed only to domain-specific processes. Second, these complex span tasks require participants to maintain information in the face of interference over a period of several seconds; in many of the instances we cited, this ability is presumed to be lacking in low WMC individuals (e.g., Poole & Kane, 2009).

Alternative theories, such as the perceptual load hypothesis of Lavie et al. (2004), predict instead that when there is sufficient capacity (such as when perceptual load is low or WMC is high), distractors will be encoded. That previous studies have supported both the perceptual load hypothesis (e.g. Forster & Lavie,

2011) and the attentional filtering hypothesis (Vogel et al., 2005; McNab & Klingberg, 2008) suggest that boundary conditions for explaining relationships between WMC and attention are not yet sufficiently understood. One factor to be considered is the predictability of the distracting information. In our task, the irrelevant or unemphasized shapes were constant for each participant. Studies of auditory distraction (Hughes et al., 2012; Sörqvist, 2010) have previously shown that WMC does not correlate with effects of such predictable distractors. In the dichotic listening studies of Conway et al. (2001) and Colflesh and Conway (2007), the occurrence of the participants' name could be considered an unpredictable distractor, occurring as it did within a changing stream of irrelevant information, which can plausibly account for the difference in the behavior of low-WMC participants in their studies and ours. Differences may also be expected in selective attention toward auditory and visual stimuli, because due to fine control of eye movements, in some contexts encountering distracting visual stimuli can be more completely avoided than processing auditory stimuli. The notion that predictability of visual distractors can decrease their ability to affect performance (Awh, Matsukura, & Serences, 2003; Awh, Sgarlata, & Kliestik, 2005) has been broached, and our results likewise suggest that low-capacity individuals can cope with these kinds of distractors. It seems that for expected WMC differences in conflict resolution to emerge (Braver, 2012), distractors must be salient and unexpected (e.g. Fukuda & Vogel, 2009; Sörqvist, 2010), which contradicts the notion that low WMC individuals helplessly store irrelevant during predictable visual change detection tasks.

The relationships we observed between visual change detection performance and complex WM span were generally consistent in magnitude with those previously published (e.g. Cowan et al., 2005; Shipstead et al., 2012; Shipstead & Engle, 2013). An exception was performance in the Half-Set trials of Experiment 1. Several aspects of our task, particularly the length of the stimulus presentation and the organization of stimuli in constant locations, differed from the standard administration, and may have affected the relationships we observed. Despite these modifications, complex span correlated with visual change detection of infrequently tested shapes of the Ratio-Set of Experiment 1, showing that relationships between complex span and visual change detection can be robust to procedural modifications. The robust positive relationship between storing unemphasized shapes and WMC in Experiment 1 is consistent with the idea that in our paradigm, storing these “extra” items really distinguished high and low-capacity individuals. This suggests that as it is typically administered, visual change detection correlates with complex span because it effectively measures WM storage capacity (Cowan et al., 2005), while in our administration, this relationship was most apparent in performance toward the less relevant shapes, which were most likely to be attended and stored by the participants with the highest WMC. Indeed, if this account is correct, one would not expect to have observed as much variance in our Half-Set block, where participants were discouraged from attempting to maintain more than the small amount of items that would potentially be tested, and maintaining any irrelevant items would not have boosted visual change detection performance.

In conclusion, by showing that low WMC individuals are at least as capable as high-capacity individuals of selectively attending based on test likelihood or reward, we cast considerable doubt on the hypothesis that WMC differences emerge because low-capacity individuals cannot prevent themselves from attending irrelevant or unimportant stimuli. This research will help theorists determine appropriate boundary conditions to set upon theoretical relationships between attention and working memory capacity, which is crucial to enabling prediction of how distraction and WMC are truly related.

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Appendix A: Descriptive fixation statistics by trial period and WMC group, Experiment 1

Stimulus Period

	Mean (SD)	Average Range
High WMC (*N*=21)		
Count	4.69 (0.61)	1.81 - 7.48
Duration	323 (53)	4 - 1125
Medium WMC (*N*=17)		
Count	5.03 (0.59)	1.88 – 8.00
Duration	304 (57)	3 – 1084
Low WMC (*N*=20)		
Count	4.98 (0.58)	1.50 – 7.95
Duration	301 (31)	3 – 1111

Retention Period

High WMC (*N*=21)		
Count	6.61 (1.22)	1.62-12.14
Duration	864 (174)	4 – 2956
Medium WMC (*N*=17)		
Count	7.50 (1.22)	1.88-13.47
Duration	753 (149)	3 – 2897
Low WMC (*N*=20)		
Count	7.77 (1.58)	1.90-14.15
Duration	766 (141)	4 – 2925

Note. Count refers to the count of the total number of recorded fixations in a trial, averaged by subject, regardless of whether the fixation landed on a valid interest area. Duration refers to the average time in milliseconds for fixations towards valid interest areas, which included stimulus objects and the center of the screen.

Appendix B: Descriptive fixation statistics by trial period and WMC group, Experiment 2

Stimulus Period

	Mean (SD)	Average Range
High WMC (*N*=14)		
Count	5.03 (0.76)	2.07-7.21
Duration	315 (64)	4-1119
Medium WMC (*N*=20)		
Count	5.09 (0.73)	1.95-7.60
Duration	302 (76)	5-1132
Low WMC (*N*=13)		
Count	5.31 (0.81)	2.23-7.69
Duration	282 (70)	5-1078

Retention Period

High WMC (*N*=14)		
Count	7.13 (1.58)	2.29-11.36
Duration	688 (142)	6-2870
Medium WMC (*N*=20)		
Count	7.16 (1.70)	2.30-11.70
Duration	705 (143)	5-2835
Low WMC (*N*=13)		
Count	7.58 (1.44)	2.85-12.15
Duration	668 (134)	5-2728

Note. Count refers to the count of the total number of recorded fixations in a trial, averaged by subject, regardless of whether the fixation landed on a valid interest area. Duration refers to the average time in milliseconds for fixations towards stimuli.

Table 1
Descriptive statistics for complex WM span tasks, by experiment

	Mean	SD	Skew	Kurtosis
Experiment 1 (*N*=69)				
Operation Span	58.49	12.43	-0.95	1.02
Symmetry Span	29.66	7.21	-0.55	-0.44
Experiment 2 (*N*=52)				
Operation Span	58.25	12.87	-1.25	1.58
Symmetry Span	30.40	7.29	-0.57	-0.64

Table 2

Average proportion correct (and standard deviation) per block type, test likelihood and set size

	Full-Set			Half-Set		Ratio-Set	
	8	4	2	8	4	8	4
High WMC (N=22)	.70(.08)	.89(.09)	.97(.03)	.83(.10)	.96(.05)	.72(.09)	.90(.08)
Mid WMC (N=23)	.67(.08)	.85(.07)	.96(.04)	.80(.10)	.94(.05)	.68(.07)	.86(.08)
Low WMC (N=24)	.65(.08)	.83(.10)	.95(.06)	.78(.11)	.94(.07)	.67(.09)	.83(.11)

Note. Here, set size indicates the total number of items presented in each condition.

Table 3

Pearson 2-tailed correlations between relative dwell times on irrelevant or infrequently tested shapes collapsed across set sizes, proportion correct (PC) per block type and WMC

Measure	1	2	3	4	5	6	7	8
Half-Set dwell percentage on irrelevant shape								
1. Memory Display								
2. Retention Interval	.74**							
Ratio-Set dwell percentage on 33.3% tested shape								
3. Memory Display	.45**	.32*						
4. Retention Interval	.46**	.41**	.91**					
Performance Measures								
5. Full Set PC	-.27*	-.24	-.14	-.06				
6. Half-Set PC	-.45**	-.36**	-.22	-.17	.84**			
7. Ratio-Set PC Predominant	-.39*	-.28*	-.46**	-.36**	.82**	.79**		
8. Ratio-Set PC Infrequent	-.02	.01	.35**	.40**	.65**	.55**	.50**	
9. WMC	.15	.20	.34**	.53**	.24	.17	.15	.41**

Note. * p <.05, ** p < .01. N=58 for values involving gaze data, N=69 for correlations between accuracy measures.

Table 4

Pearson 2-tailed correlations between relative dwell times on the unemphasized, 100-point shapes, accuracy measures and WMC.

Measure	1	2	3	4	5
Ratio-Point dwell percentage on 100-Points shape					
1. Memory Display					
2. Retention Interval	.91**				
Performance Measures					
3. Equal-Points PC	.10	-.02			
4. Ratio-Points PC 900 Points	-.58**	-.64**	.33*		
5. Ratio -Points PC 100 Points	.69**	.69**	.24	-.43**	
6. WMC	.02	.05	.08	-.06	.06

Notes. PC = proportion correct. * = *p*<.05. ** = *p*< .01. *N*=47.

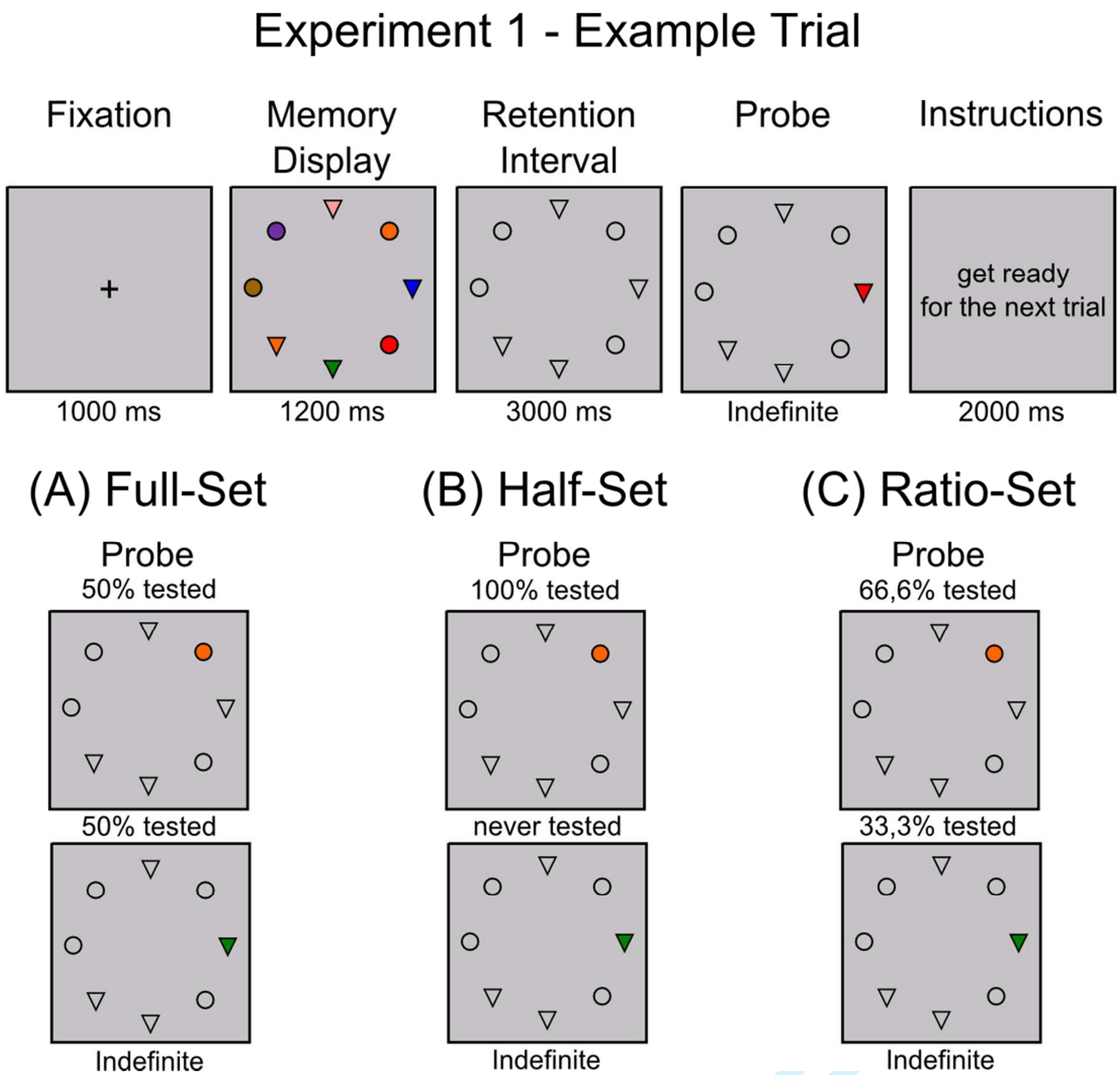

Figure 1. Schematic illustration of the visual task conditions and set-sizes. (A) Full-Set, all shapes are tested (B) Half-Set, one shape is always tested (C) Ratio-Set, one shape is tested 66,6% and the other 33,3% of the time. For this schematic, the predominant shape is a circle; which shape was predominant varied by participant. Changes occurred to 50% of probes in each block.

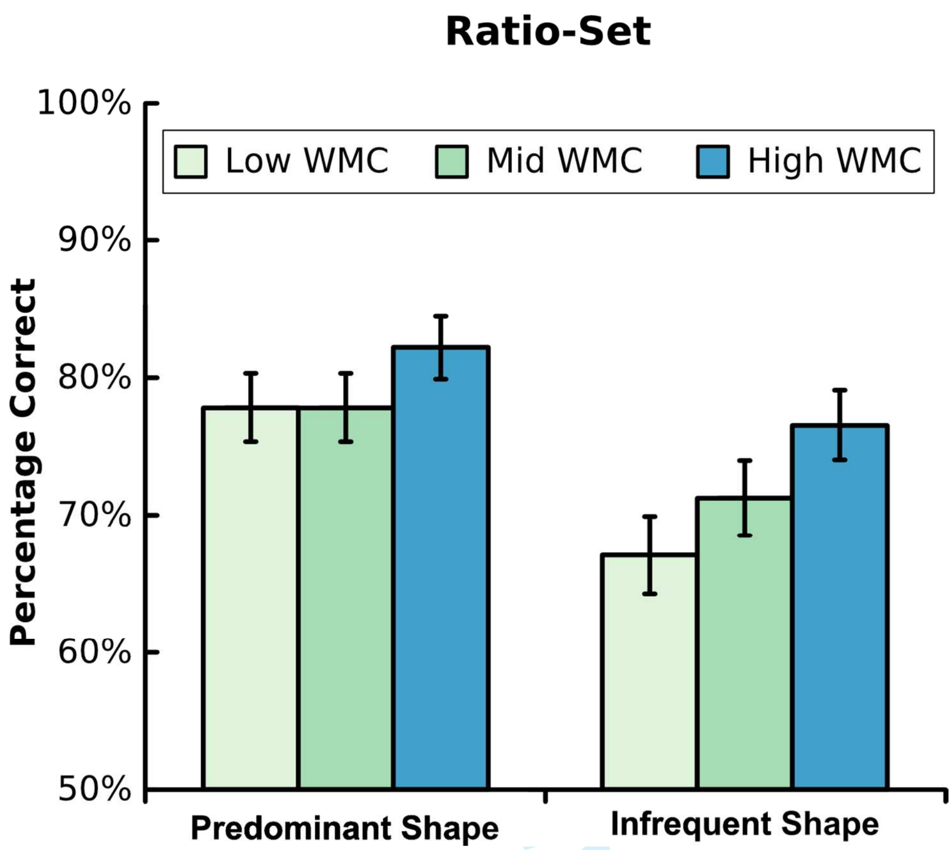

Figure 2. Average percentage correct across set-sizes in the Ratio-Set for predominant and infrequent shapes. Error bars depict standard errors of the mean. *N*=69.

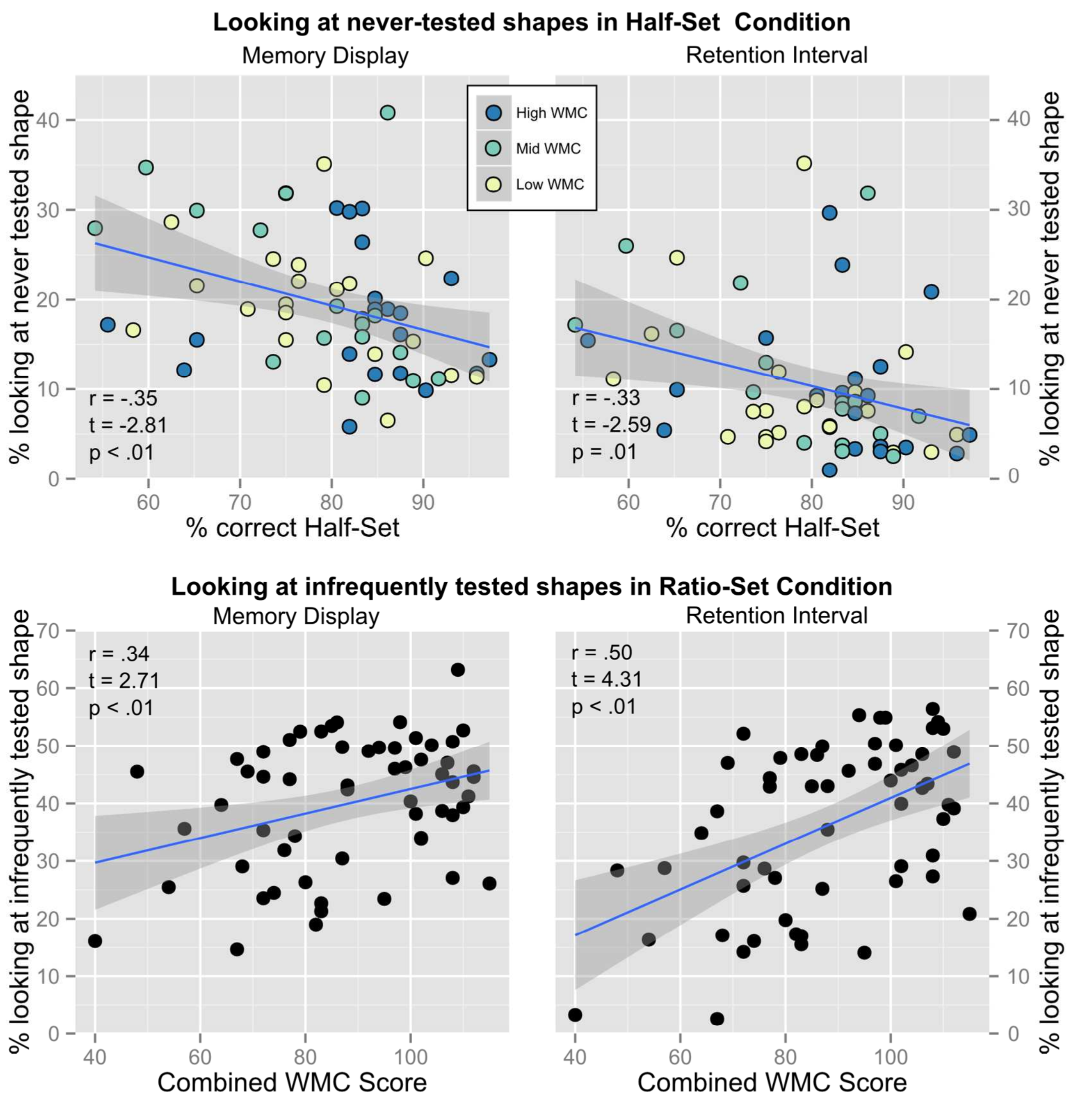

Figure 3. Correlation plots for set-size 8 trials, with best linear fit and t-based confidence interval estimation, between performance in the Half-Set and looking at the never-tested shape (Upper Panels) and looking at infrequently tested shape in the Ratio-Set and WMC (Lower Panels). *N*=58.

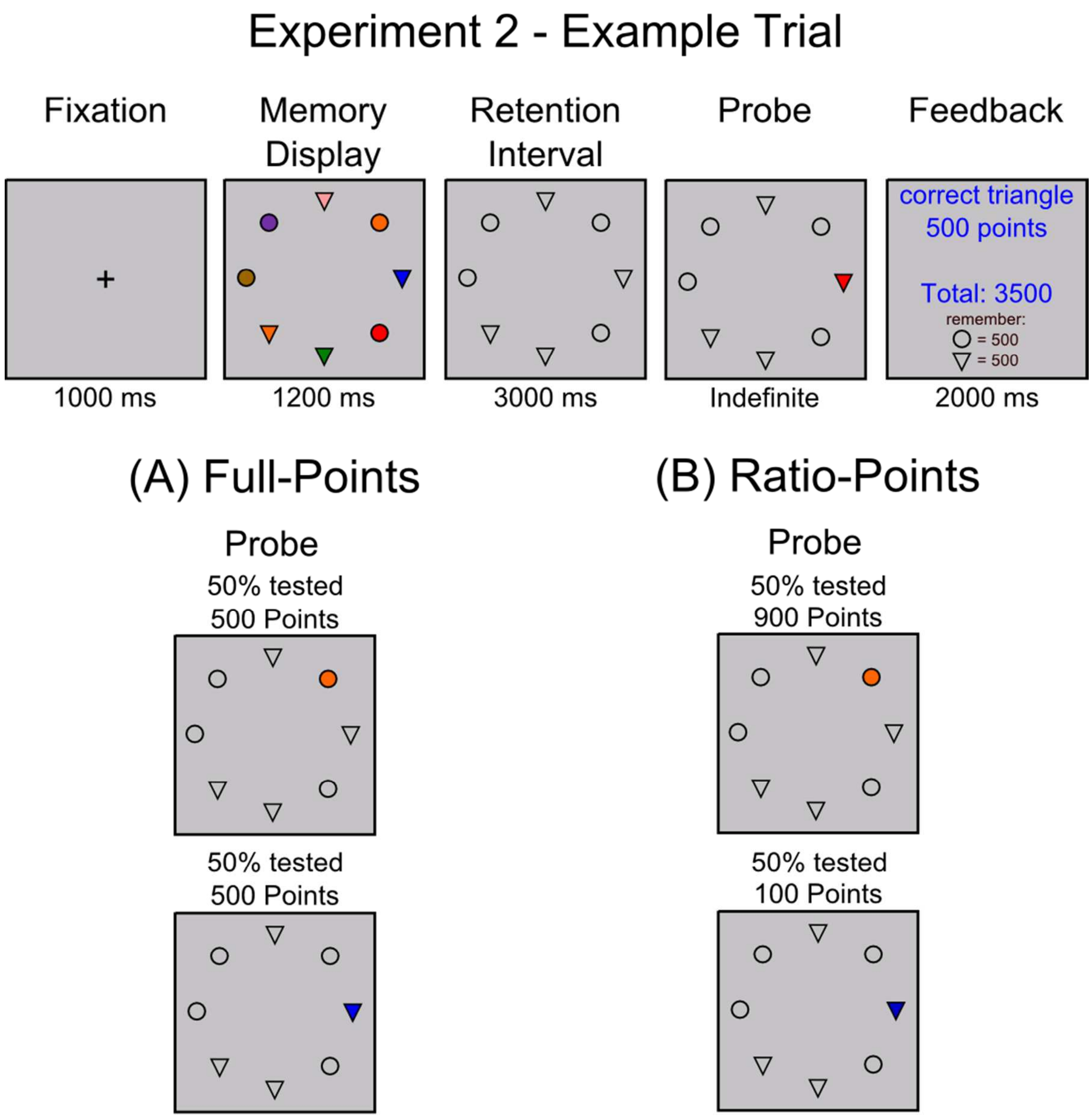

Figure 4. Schematic illustration of Experiment 2 conditions. (A) Full-Points, each correct shape awards 500 points (B) Ratio-Points, one shape awards 900 and the other 100 points. For this schematic, the predominant shape is a circle; which shape was predominant varied by participant. Changes occurred to 50% of probes in each block.

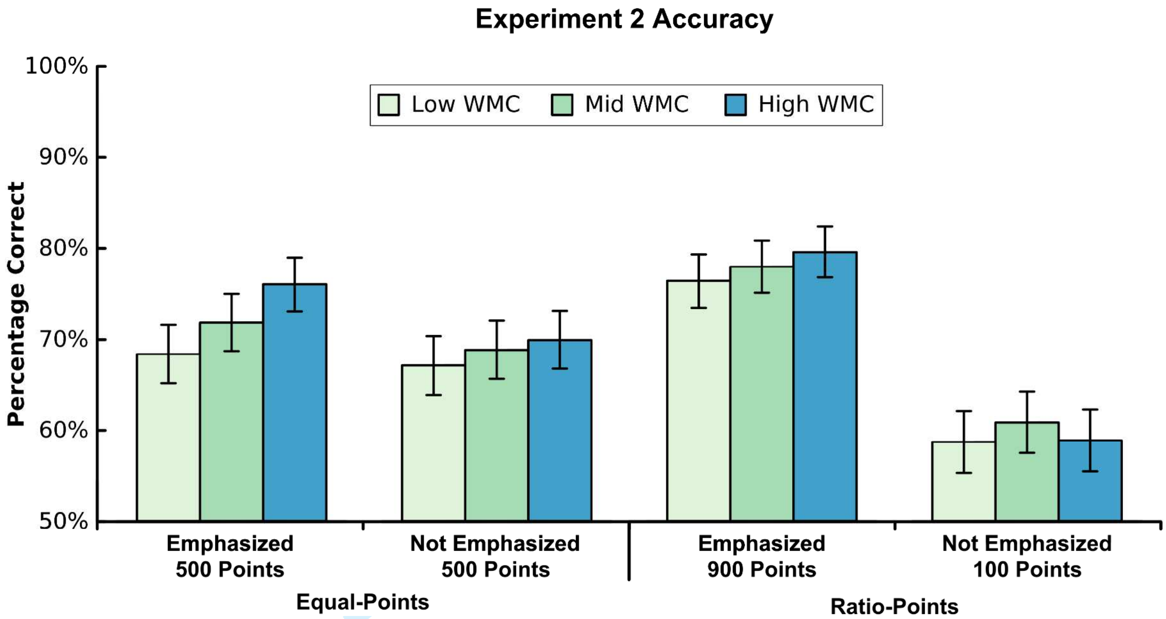

Figure 5. Average percentage correct per block type and shape emphasis. Error Bars depict standard errors of the mean. *N*=52.

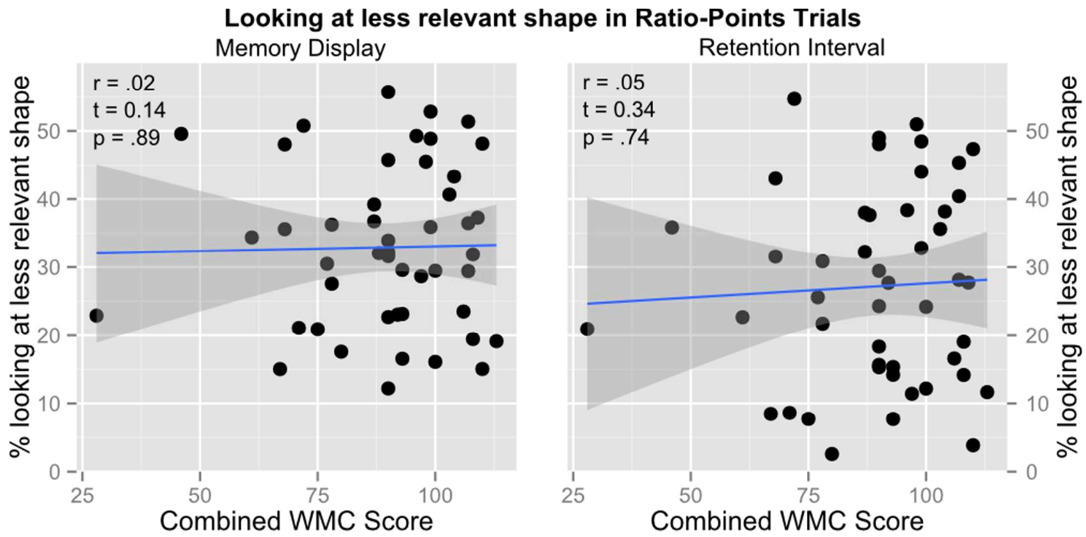

Figure 6. Correlations between percentage of time fixating on unemphasized shapes and WMC, with best linear fit and t-based confidence interval estimation, for Ratio-Points trials. N=47.