Attention, Perception, & Psychophysics

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

SCHOLARONE™
Manuscripts

WMC AND ATTENTIONAL FILTERING   1

Visual selective attention is equally functional for individuals with low and high

working memory capacity: Evidence from accuracy and eye-movements

Jonathan T. Mall[1], Candice C. Morey[1,2], Michael Wolff[1], Franziska Lehnert[1]

1. University of Groningen, Experimental Psychology

2. University of Edinburgh, School of Philosophy, Psychology, and Language

Sciences

Word count (excluding references): 8,397; 53 references

Date submitted: 22 August 2013
Date Revision 1 resubmitted: 6 November 2013
Date Revision 2 submitted: 10 December 2013

WMC AND ATTENTIONAL FILTERING   2

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.

WMC AND ATTENTIONAL FILTERING   3

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

WMC AND ATTENTIONAL FILTERING   4

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

WMC AND ATTENTIONAL FILTERING   5

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

WMC AND ATTENTIONAL FILTERING   7

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

WMC AND ATTENTIONAL FILTERING   9

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

WMC AND ATTENTIONAL FILTERING   10

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.

WMC AND ATTENTIONAL FILTERING   11

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

WMC AND ATTENTIONAL FILTERING   12

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

WMC AND ATTENTIONAL FILTERING   15

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

WMC AND ATTENTIONAL FILTERING   16

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

WMC AND ATTENTIONAL FILTERING   17

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 ks 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 1.43×10^{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 $M_{Full-Set}$=0.96, $M_{Half-Set}$=0.95, whereas as set size 4, $M_{Full-Set}$=0.86, $M_{Half-Set}$=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

WMC AND ATTENTIONAL FILTERING   19

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.

WMC AND ATTENTIONAL FILTERING   21

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

WMC AND ATTENTIONAL FILTERING   22

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

WMC AND ATTENTIONAL FILTERING   23

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

WMC AND ATTENTIONAL FILTERING   25

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.

WMC AND ATTENTIONAL FILTERING   26

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

WMC AND ATTENTIONAL FILTERING   28

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.

<div align="center">INSERT FIGURE 5 HERE</div>

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

WMC AND ATTENTIONAL FILTERING   29

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.

<div align="center">INSERT FIGURE 6 HERE</div>

<div align="center">INSERT TABLE 4 HERE</div>

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

WMC AND ATTENTIONAL FILTERING   30

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.

WMC AND ATTENTIONAL FILTERING   31

        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

WMC AND ATTENTIONAL FILTERING   33

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.

WMC AND ATTENTIONAL FILTERING   35

    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.

WMC AND ATTENTIONAL FILTERING   36

　　　　　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.

WMC AND ATTENTIONAL FILTERING   37

References

Alloway, T. P. (2009). Working memory, but not IQ, predicts subsequent learning in

children with learning difficulties. *European Journal of Psychological

Assessment*, *25*, 92–98.

Awh, E., Matsukura, M., & Serences, J. T. (2003). Top-down control over biased

competition during covert spatial orienting. *Journal of Experimental

Psychology: Human Perception and Performance*, *29*, 52.

Awh, E., Sgarlata, A. M., & Kliestik, J. (2005). Resolving visual interference during

covert spatial orienting: online attentional control through static records of

prior visual experience. *Journal of Experimental Psychology: General*, *134*,

192-206.

Awh, E., & Vogel, E. K. (2008). The bouncer in the brain. *Nature Neuroscience*, *11*, 5–

6.

Beaman, C. P. (2004). The irrelevant sound phenomenon revisited: What role for

working memory capacity? *Journal of Experimental Psychology: Learning,

Memory, and Cognition*, *30*, 1106-1118.

Bleckley, M., Durso, F., Crutchfield, J., Engle, R., & Khanna, M. (2003). Individual

differences in working memory capacity predict visual attention allocation.

Psychonomic Bulletin & Review, *10*, 884–889.

Braver, T. S. (2012). The variable nature of cognitive control: a dual mechanisms

framework. *Trends in Cognitive Sciences*, *16*, 106–113.

WMC AND ATTENTIONAL FILTERING   38

Chuderski, A., Taraday, M., Nęcka, E., & Smoleń, T. (2012). Storage capacity explains

fluid intelligence but executive control does not. *Intelligence*, *40*, 278–295.

Colflesh, G. J. H., & Conway, A. R. A. (2007). Individual differences in working

memory capacity and divided attention in dichotic listening. *Psychonomic

Bulletin & Review*, *14*, 699–703.

Colom, R., Abad, F. J., Quiroga, M. Á., Shih, P. C., & Flores-Mendoza, C. (2008).

Working memory and intelligence are highly related constructs, but why?

Intelligence, *36*, 584–606.

Conway, A. R. A., Cowan, N., & Bunting, M. F. (2001). The cocktail party phenomenon

revisited: The importance of working memory capacity. *Psychonomic Bulletin

& Review*, *8*, 331-335.

Conway, A. R. A., Kane, M. J., Bunting, M. F., Hambrick, D., Wilhelm, O., & Engle, R. W.

(2005). Working memory span tasks: A methodological review and user's

guide. *Psychonomic Bulletin & Review*, *12*, 769-786.

Cowan, N., Elliott, E. M., Scott Saults, J., Morey, C. C., Mattox, S., Hismjatullina, A., &

Conway, A. R. A. (2005). On the capacity of attention: Its estimation and its

role in working memory and cognitive aptitudes. *Cognitive Psychology*, *51*,

42–100.

Cowan, N., Morey, C. C., AuBuchon, A. M., Zwilling, C. E., & Gilchrist, A. L. (2010).

Seven-year-olds allocate attention like adults unless working memory is

overloaded. *Developmental Science*, *13*, 120–133.

WMC AND ATTENTIONAL FILTERING   39

Elliott, E. M., & Cowan, N. (2005). Coherence of the irrelevant-sound effect:

Individual profiles of short-term memory and susceptibility to task-

irrelevant materials. *Memory & Cognition*, *33*, 664–675.

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working

memory capacity and what they tell us about controlled attention, general

fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P.

Shah (Eds.), *Models of working memory: Mechanisms of active maintenance*

and executive control (pp. 102-134). Cambridge, U.K.: Cambridge University

Press.

Ferreira, F., Apel, J., & Henderson, J. M. (2008). Taking a new look at looking at

nothing. *Trends in Cognitive Sciences*, *12*, 405–410.

Forster, S., & Lavie, N. (2011). Entirely irrelevant distractors can capture and

captivate attention. *Psychonomic Bulletin & Review*, *18*, 1064–1070.

Fukuda, K., & Vogel, E. K. (2009). Human variation in overriding attentional capture.

The Journal of Neuroscience, *29*, 8726–8733.

Gold, J. M., Fuller, R. L., Robinson, B. M., McMahon, R. P., Braun, E. L., & Luck, S. J.

(2006). Intact attentional control of working memory encoding in

schizophrenia. *Journal of Abnormal Psychology*, *115*, 658–673.

Huebner, G., & Gegenfurtner, K. (2010). Effects of viewing time, fixations, and

viewing strategies on visual memory for briefly presented natural objects.

Quarterly Journal of Experimental Psychology, *63*, 1398–1413.

Hughes, R. W., Hurlstone, M. J., Marsh, J. E., Vachon, F., & Jones, D. M. (2012).

Cognitive control of auditory distraction: Impact of task difficulty,

WMC AND ATTENTIONAL FILTERING   40

foreknowledge, and working memory capacity supports duplex-mechanism account. *Journal of Experimental Psychology: Human Perception and Performance*, *39*, 539-553.

Hutchison, K. A. (2007). Attentional control and the relatedness proportion effect in semantic priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 645.

Ishihara, S. (1966). *Tests for colour blindness*. Tokyo: Kanehara Shuppan.

Jarrold, C., & Towse, J. N. (2006). Individual differences in working memory. *Neuroscience*, *139*, 39–50.

Jeffreys, S. H. (1961). *The Theory of Probability* (3rd ed.). Oxford, U.K.: Oxford University Press.

Kane, M. J., Conway, A. R. A., Hambrick, D. Z., & Engle, R. W. (2007). Variation in working memory capacity as variation in executive attention and control. In A.R.A. Conway, C. Jarrold, M.J. Kane, A. Miyake, & J. Towse (Eds.) *Variation in working memory* (pp. 21–48). Oxford, U.K.: Oxford University Press.

Kane, M. J., Hambrick, D. Z., Tuholski, S. W., Wilhelm, O., Payne, T. W., & Engle, R. W. (2004). The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning. *Journal of Experimental Psychology: General*, *133*, 189–217.

Lavie, N., Hirst, A., De Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*, 339–354.

WMC AND ATTENTIONAL FILTERING   41

McNab, F., & Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access

to working memory. *Nature Neuroscience*, *11*, 103–107.

Morey, C. C., Cowan, N., Morey, R. D., & Rouder, J. N. (2011). Flexible attention

allocation to visual and auditory working memory tasks: Manipulating

reward induces a trade-off. *Attention, Perception, & Psychophysics*, *73*, 458–

472.

Morey, C. C., Elliott, E. M., Wiggers, J., Eaves, S. D., Shelton, J. T., & Mall, J. T. (2012).

Goal-neglect links Stroop interference with working memory capacity. *Acta

Psychologica*, *141*, 250–260.

Morey, R. D., Morey, C. C., Brisson, B., & Tremblay, S. (2012). A critical evaluation of c

as a measure of mnemonic resolution. *Journal of Experimental Psychology:

Human Perception and Performance, 38*, 1069-1072.

Morey, R.D., & Rouder, J. N. (2013). Package, *BayesFactor*, version 0.9.4.

http://bayesfactorpcl.r-forge.r-project.org/

Poole, B. J., & Kane, M. J. (2009). Working-memory capacity predicts the executive

control of visual search among distractors: The influences of sustained and

selective attention. *The Quarterly Journal of Experimental Psychology*, *62*,

1430–1454.

Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M. J.,

& Engle, R. W. (2012). Measuring working memory capacity with automated

complex span tasks. *European Journal of Psychological Assessment*, *28*, 164-

171.

WMC AND ATTENTIONAL FILTERING   42

Rouder, J. N., Morey, R. D., Morey, C. C., & Cowan, N. (2011). How to measure

     working memory capacity in the change detection paradigm. *Psychonomic*

     Bulletin & Review, *18*, 324–330.

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes

     factors for ANOVA designs. *Journal of Mathematical Psychology, 56*, 356–374.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime: User's guide*.

     Pittsburgh, PA: Psychology Software Tools, Incorporated.

Shao, N., Li, J., Shui, R., Zheng, X., Lu, J., & Shen, M. (2010). Saccades elicit obligatory

     allocation of visual working memory. *Memory & Cognition*, *38*, 629–640.

Shipstead, Z., & Engle, R. W. (2013). Interference within the focus of attention:

     working memory tasks reflect more than temporary maintenance. *Journal of*

     Experimental Psychology: Learning, Memory, & Cognition, *39*, 277–289.

Shipstead, Z., Redick, T., Hicks, K., & Engle, R. (2012). The scope and control of

     attention as separate aspects of working memory. *Memory*, *20*, 608–628.

Sörqvist, P. (2010). High working memory capacity attenuates the deviation effect

     but not the changing-state effect: Further support for the duplex-mechanism

     account of auditory distraction. *Memory & Cognition*, *38*, 651–658.

Sperling, G. (1960). The information available in brief visual presentation.

     Psychological Monographs, *74*, 1–29.

Tremblay, S., Saint-Aubin, J., & Jalbert, A. (2006). Rehearsal in serial memory for

     visual-spatial information: Evidence from eye movements. *Psychonomic*

     Bulletin & Review, *13*, 452–457.

WMC AND ATTENTIONAL FILTERING 43

Unsworth, N., Brewer, G. A., & Spillers, G. J. (2012). Variation in cognitive failures: An individual differences investigation of everyday attention and memory failures. *Journal of Memory and Language*, *67*, 1-16.

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory*, *17*, 635–654.

Unsworth, N., Schrock, J. C., & Engle, R. W. (2004). Working memory capacity and the antisaccade task: Individual differences in voluntary saccade control. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*, 1302-1321.

Unsworth, Nash, Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*, 498–505.

Van Lamsweerde, A. E., & Beck, M. R. (2012). Attention shifts or volatile representations: What causes binding deficits in visual working memory? *Visual Cognition*, *20*, 771–792.

Vogel, E. K., & Machizawa, M. G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature*, *428*, 748–751.

Vogel, Edward K., McCollough, A. W., & Machizawa, M. G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature*, *438*, 500–503.

Wetzels, R., & Wagenmakers, E.J. (2012). A default Bayesian hypothesis test for correlations and partial correlations. *Psychonomic Bulletin & Review*, *19*, 1057–1064.

WMC AND ATTENTIONAL FILTERING   44

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.

WMC AND ATTENTIONAL FILTERING   45

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

WMC AND ATTENTIONAL FILTERING   47

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.

WMC AND ATTENTIONAL FILTERING   48

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.

WMC AND ATTENTIONAL FILTERING   49

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.
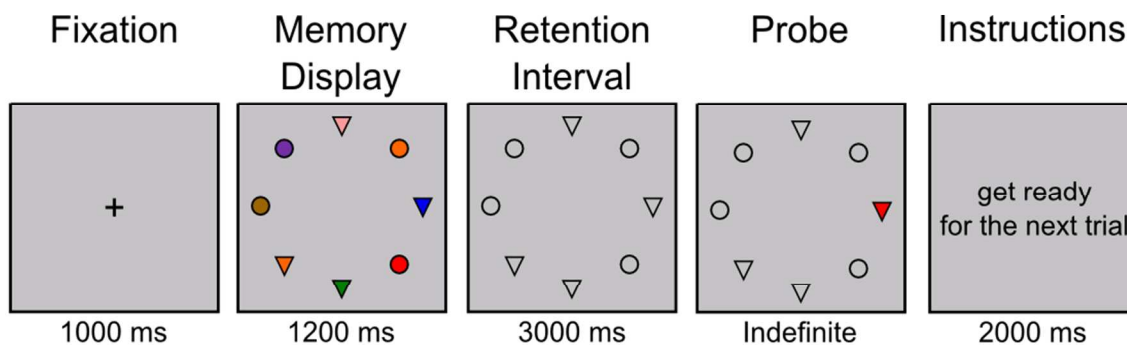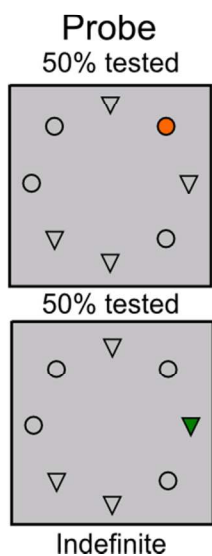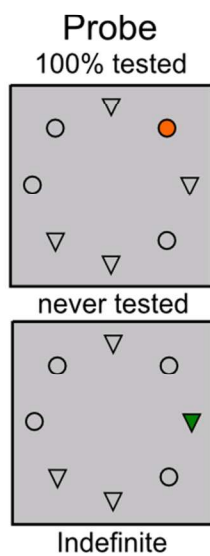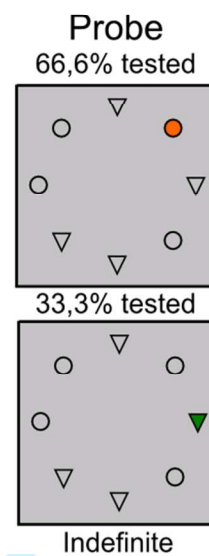
Figure 1. Schematic illustration of the visual task conditions and set-sizes. (A) Full-

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.

WMC AND ATTENTIONAL FILTERING
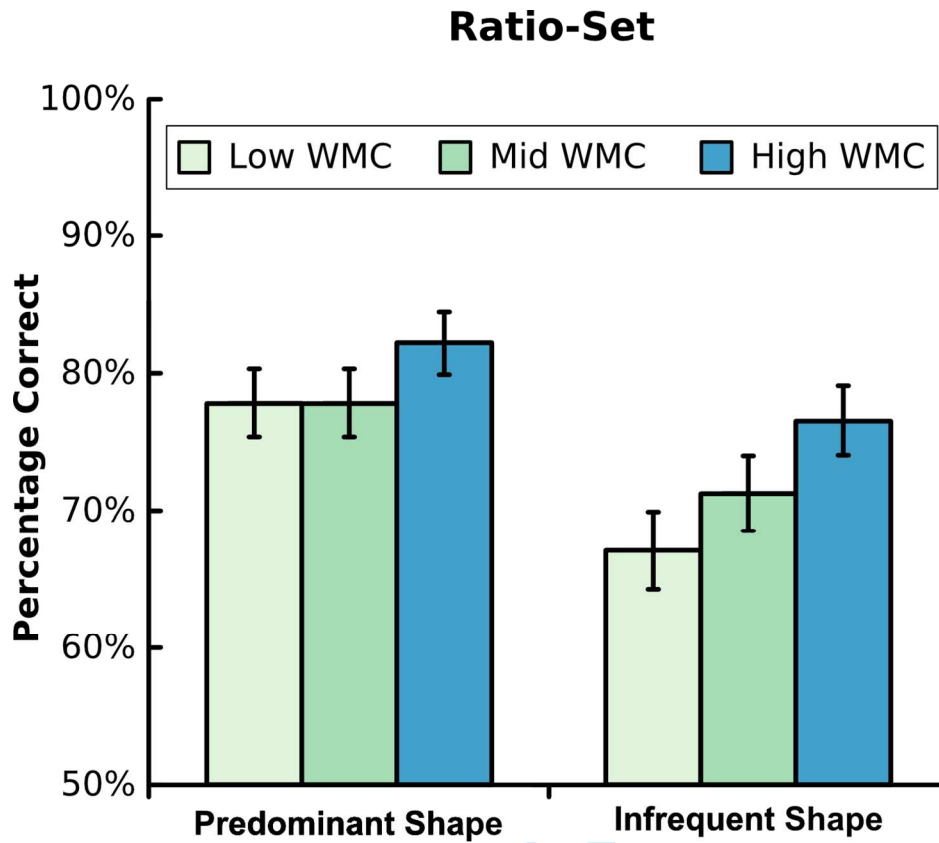
Ratio-Set

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.
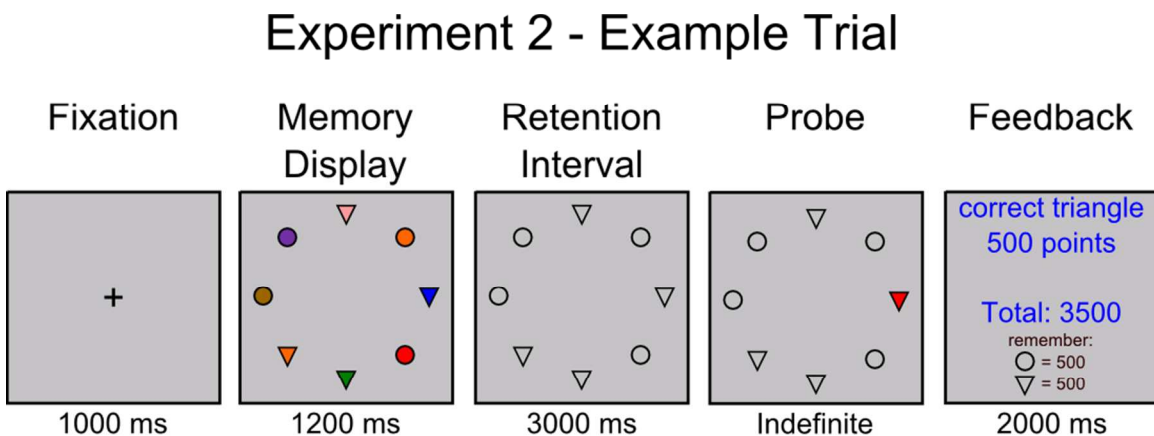
N=69.
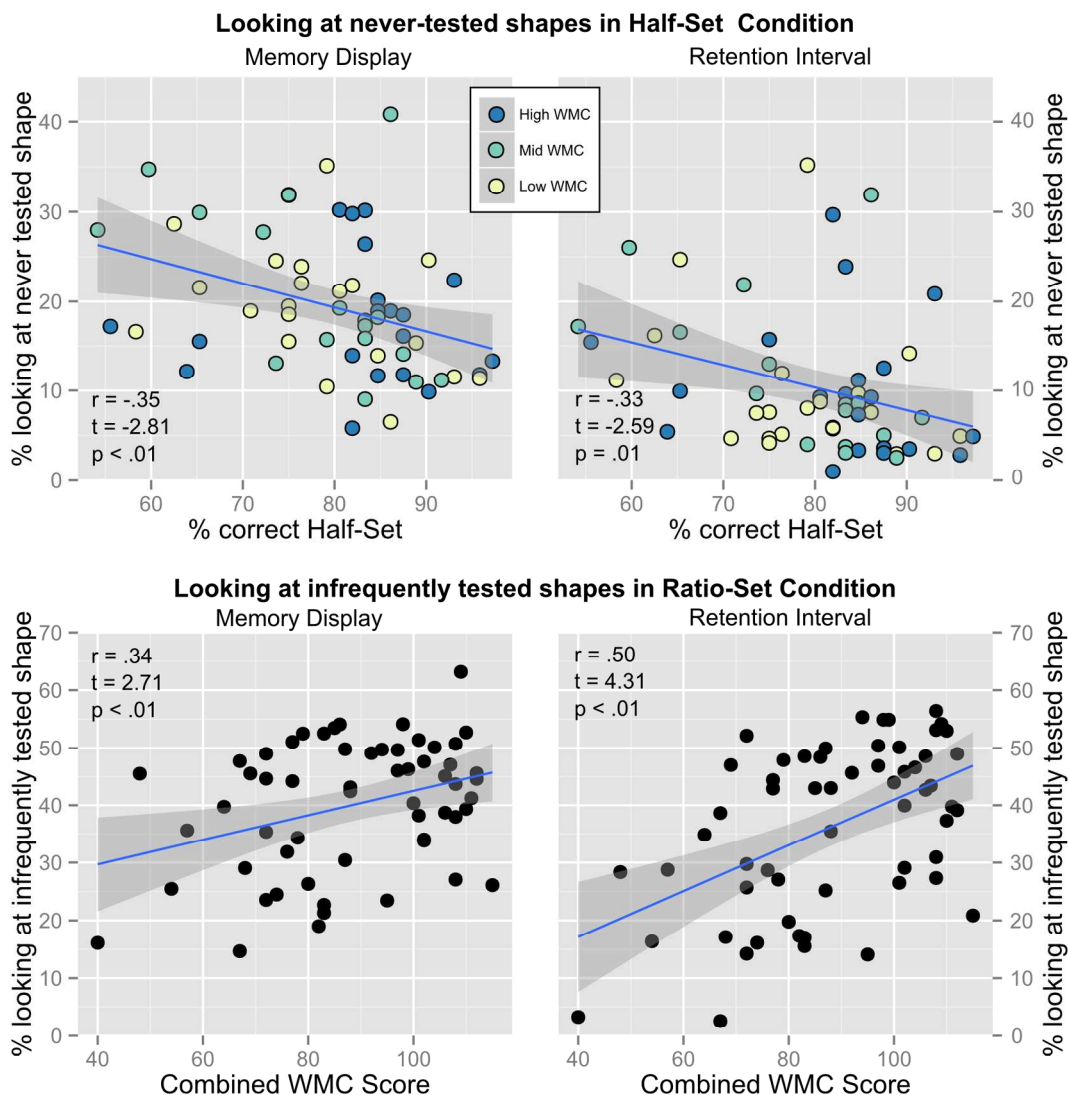
Figure 3. Correlation plots for set-size 8 trials, with best linear fit and t-based

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
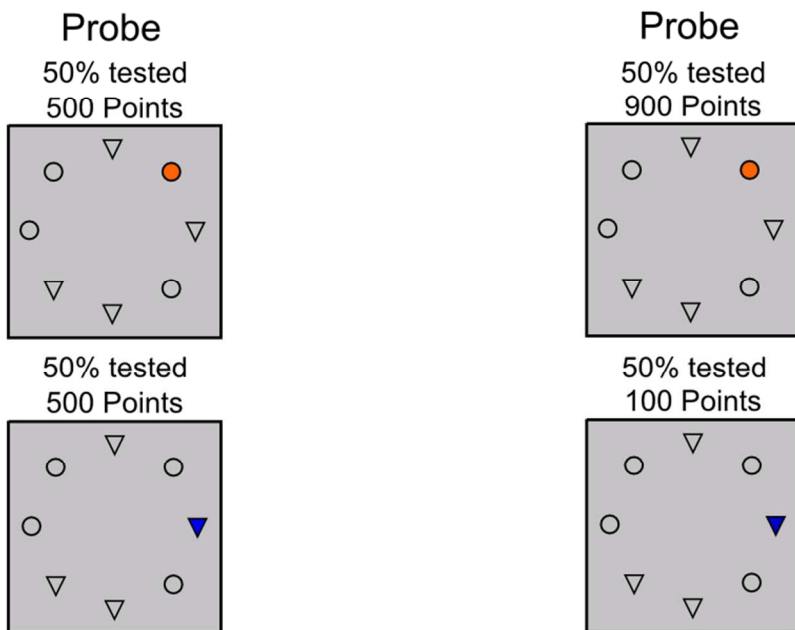
the Ratio-Set and WMC (Lower Panels). *N*=58.

WMC AND ATTENTIONAL FILTERING   53

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.
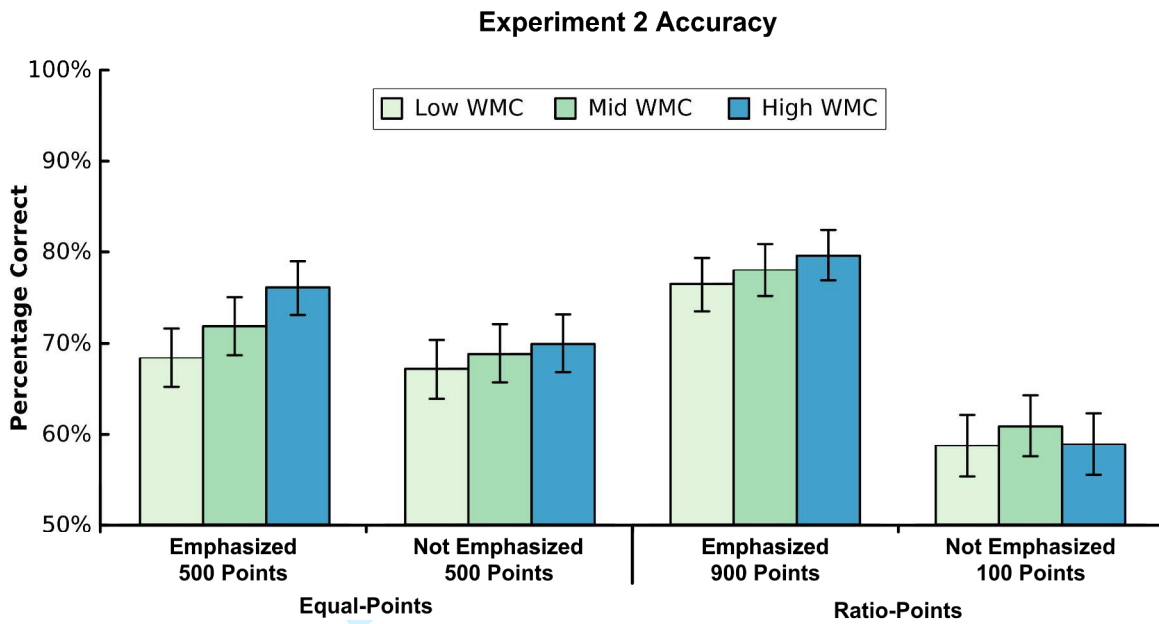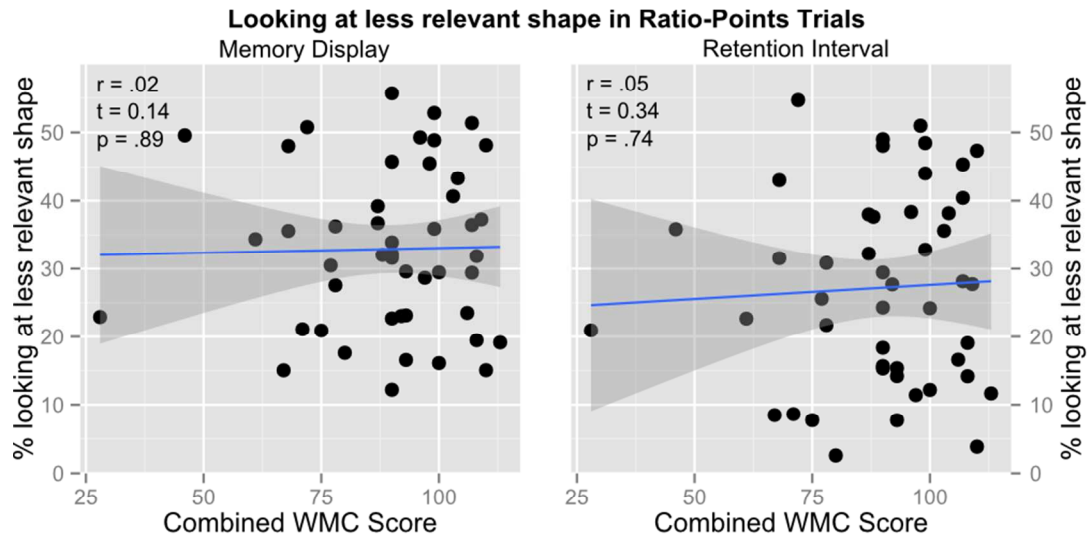
WMC AND ATTENTIONAL FILTERING 54

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

WMC AND ATTENTIONAL FILTERING   55

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.