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ORIGINAL ARTICLE

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Abstract Working memory and attention are closely related constructs. Models of working memory often incorporate an attention component, and some even equate working memory and attentional control. Although some attention-related processes, including inhibitory control of response conflict and interference resolution, are strongly associated with working memory, for other aspects of attention the link is less clear. We examined the association between working-memory performance and attentional breadth, the ability to spread attention spatially. If the link between attention and working memory is broader than inhibitory and interference resolution processes, then working-memory performance might also be associated with other attentional abilities, including attentional breadth. We tested 123 participants on a variety of working-memory and attentional-breadth measures, finding a strong correlation between performances on these two types of tasks. This finding demonstrates that the link between working memory and attention extends beyond inhibitory processes.

Introduction

Most models of working memory include attention as a central component (Baddeley, 2003; Cowan et al., 2005; Miyake & Shah, 1999; Oberauer, 2002), and some even treat attention and working memory as equivalent constructs (e.g., Cowan, 2005; Engle, 2002). Working-memory capacity is tightly linked to performance in especially those attention tasks that require inhibitory control: People with higher working-memory capacity are faster and more accurate on an anti-saccade task (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), perform better on a Stroop task (Kane & Engle, 2003; Long & Prat, 2002), and are less disrupted by distractors during dichotic listening (Conway, Cowan, & Bunting, 2001). In addition to links with attentional tasks that require inhibitory control, working-memory capacity is also associated with higher-order cognitive abilities that do not seem to depend heavily on interference resolution or response inhibition, including language comprehension (Daneman & Carpenter, 1980), bridge playing (Clarkson-Smith & Hartley, 1990), reasoning (Kyllonen & Christal, 1990), and computer-language learning (Shute, 1991). Thus, working-memory measures might be most strongly associated with attentional processes that require interference resolution and response inhibition, but they might also tap other aspects of cognitive control (Kane, Poole, Tuholski, & Engle, 2006).

The controlled-attention view of working-memory capacity suggests that a general attentional capability beyond inhibitory processes underlies working-memory performance (Kane et al., 2001). Yet, working-memory capacity does not predict performance in all attention-related tasks. For example, working memory did not predict performance on visual-search tasks that require attentional, but not inhibitory control (Kane et al., 2006). Working memory is, however, linked to visual-search tasks that incorporate habitual responses or tasks in which people must overcome distraction from irrelevant items (Poole &

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Kane, 2009; Sobel, Gerrie, Poole, & Kane, 2007). Such findings provide a challenge to models that equate working memory and attention (Cowan, 2005; Engle, 2002).

Even if working-memory capacity is not related to all demanding or controlled-attention processes, it might still predict performance on some tasks that require attentional control, but that do not involve inhibition of interference or restraint of habitual responses. For example, performance on visual-search tasks that do not demand inhibitory control is linked with working-memory capacity if distractor grouping is not possible (Anderson, Vogel, & Awh, 2013). We explored whether individual differences in working-memory capacity are associated with individual differences in the breadth of attention, the ability to spread/split the focus of attention across space (Ball, Beard, Roenker, Miller, & Griggs, 1998; Hüttermann, Memmert, & Simons, 2014). Attentional-breadth tasks require attentional control, but do not require participants to resolve interference or overcome response conflict. Consequently, if working-memory performance is associated with attentional breadth, then the link between attention and working memory presumably involves more general attentional-control mechanisms (e.g., Kane et al., 2001). If, however, working-memory capacity is unrelated to attentional breadth that would strengthen the claim that the link between attention and working memory is primarily driven by inhibitory processes (e.g., Zacks & Hasher, 1994).

To provide a converging assessment of the relationship between attentional breadth and working memory, we used multiple measures of each construct. For working memory, these included an automated version of the operation span task (Aospan: Unsworth, Heitz, Schrock, & Engle, 2005) as well as both spatial and verbal 2-back tasks (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Owen, McMillan, Laird, & Bullmore, 2005). To measure attentional breadth, we used a variant of the useful-field-of-view task (UFOV; adapted from Ball et al., 1988) as well as a breadth-of-attention task (BoA; adapted from Hüttermann, Memmert, Simons, & Bock, 2013; Hüttermann et al., 2014). The UFOV requires participants to perform a task at fixation while measuring how well they can discriminate shapes presented at varying eccentricities in the periphery. The BoA requires participants to focus attention on two clusters of shapes positioned on opposite sides of fixation and systematically varies the distance between them. Both tasks measure the spatial distribution of attention, not peripheral visual acuity (Ball et al., 1988; Hüttermann et al., 2014), and both have proven useful in revealing individual differences in attentional breadth (Pringle, Irwin, & Kramer, 2001; Hüttermann et al., 2014).

Method

Participants

A total of 123 participants took part in the study ($M = 22.9$ years, $\mathrm{SD} = 4.0$ years, 45.5 % female). All reported normal or corrected-to-normal vision, gave written informed consent, and were paid 13 € for their participation.

Materials and procedure

A chin rest (NovaVision, Magdeburg, Germany) positioned 50 cm from a 24-in. display (resolution: 1,920 × 1,080 pixels, controlled by an Esprimo 710 3.3 GHz Core i3-3220 computer) was used for the BoA and the UFOV tasks. For all other tasks, participants were seated approximately 50 cm from the display. The Aospan was programmed and run in E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA, USA) and all other tests were programmed and run in Presentation (Neurobehavioral Systems, Albany, NY, USA). Participants responded using a standard keyboard or, in case of the Aospan, a standard mouse.

The tasks and data presented in this manuscript were part of a larger research project relating inattentional blindness to various individual-difference measures, but the question we address in this paper on the link between attentional breadth and working memory is distinct from those that will be addressed elsewhere. In addition to the tasks discussed here, the larger study included the following other measures: a static inattentional blindness task (Newby & Rock, 1998), an Eriksen Flanker task (Eriksen & Eriksen, 1974), and a German version of the Cognitive Failures Questionnaire (Klumb, 1995).

Participants were tested alone or in pairs in a single session lasting approximately 2 h. When tested in pairs, participants were separated by dividers so that they could not see each other, and they also were instructed to work quietly. Instructions appeared on the screen prior to each task, and participants were encouraged to ask questions before starting. The inattentional blindness task was always completed first. The six cognitive tasks were then presented in a randomized order for each participant, except that when two participants took part in the same session, they received the same task order to minimize interruptions and distraction. When participants were tested in pairs, the experimenter waited for both participants to complete each task before starting the next task. The five cognitive tasks relevant to the question addressed in this paper are described below.

2-back-identity

Participants monitored a sequence of 100 letters appearing on the computer display. The letters (drawn from C, F, K, M, P, S, W, X) appeared centrally on the display (1.7° of visual angle) for 500 ms each, with an inter-stimulus interval of 2,000 ms. Participants were instructed to press a response key if the current letter matched the letter presented two items earlier in the sequence. Twenty-five of the letters matched the one presented two items earlier and thus were targets. In addition, the sequence included exactly ten distractors (five letters that matched the just presented letter and five letters that matched the letter presented three items earlier in the sequence) for each participant. Participants were instructed to respond as quickly and accurately as possible. Prior to the experimental sequence participants completed a sequence of 20 practice letters (without feedback). We used Pr (i.e., hits minus false alarms; Snodgrass & Corwin, 1988) as the primary measure of working memory in the 2-back tasks.

2-back-spatial

The procedure was identical to the 2-back-identity task except that participants viewed circles (2° diameter) appearing sequentially at eight different spatial locations rather than letters appearing centrally on the screen. The eight possible spatial locations were arranged equally spaced on an imaginary circle with a diameter of 15°. Participants were instructed to press the response key whenever the current circle location matched the location two items earlier.

Automated operation span (Aospan)

We used the standard Aospan task (Unsworth et al., 2005) in which participants solve simple mathematical equations while simultaneously remembering lists of letters. The task included a total of 15 trials (3 trials each with 3, 4, 5, 6, and 7 letters to remember). The primary measure of working memory for the Aospan is the Ospan score (Unsworth et al., 2005), calculated as the total number of letters recalled across all error-free trials.

Useful-field-of-view test (UFOV)

In our version of the UFOV, participants judged whether a central arrow (< or >) pointed to the left or right while simultaneously trying to detect the location of a peripheral circle among seven square distractors. The eight peripheral stimuli were assigned to evenly spaced positions (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) on an imaginary circle centered on fixation (radius of either 6.3°, 9.5° or 12.7°). Following a 1,000-ms fixation cross, stimuli appeared for 150 ms and were followed by a 100-ms black-and-white pattern mask. After the mask, participants indicated by button press if the central arrow had pointed to the left or the right and then at which location the circle had emerged (one button assigned to each location). Each trial was followed by a 1,500-ms inter-trial interval. Participants completed 68 practice trials (without feedback) followed by 120 experimental trials (40 trials at each eccentricity). For each eccentricity, the target was presented exactly five times at each position and trial types were presented in a different random order for each participant. The primary measure of attentional breadth for the UFOV was the proportion of all trials for which participants responded correctly to the central task and also located the peripheral target.

Breadth-of-attention test (BoA)

We adapted the test from Hüttermann et al. (2013, 2014) to create a shortened version for presentation on a computer screen. Two clusters of stimuli appeared equidistant from and on opposite sides of fixation (vertically or horizontally). Each cluster comprised two adjacent shapes (circle or square, gray or black). Participants fixated centrally and pressed a button to indicate the total number of gray circles across both clusters. On each trial, following a 1,000-ms fixation cross, the clusters appeared for 200 ms followed by a 100-ms black-and-white pattern mask. The response screen was followed by a 1,000-ms inter-trial interval. We varied the separation of the two clusters using an adaptive staircase procedure (3-1 method; Levitt 1971). This thresholding determines the distance of the clusters from fixation (in pixels) at which participants can respond accurately 79 % of the time. It was performed separately for vertical and horizontal trials because the attentional window is wider on the horizontal axis than on the vertical axis (Hüttermann et al., 2014), but horizontal and vertical trials were randomly interleaved during testing. Finally, the horizontal and vertical threshold values were averaged to give a single measure of attentional breadth.

Results

Due to computer or experimenter error, data were missing from six subjects in the 2-back-identity task, four subjects in the 2-back-spatial task, and three subjects in the BoA task. For correlational analyses, we included all participants who had data for both tasks. Given that our analyses are largely exploratory, rather than conducting null-hypothesis significance tests, we follow recent recommendations for best reporting and analysis practices

Table 1 Descriptive data

	N	Mean	SD	*r*
2-Back-identity	117	17.18	4.82	0.78
2-Back-spatial	119	15.64	5.90	0.49
Aospan	123	37.01	17.55	0.69
BoA	120	284.55	60.60	0.77
UFOV	123	0.76	0.18	0.87

N = number of cases in the analysis, SD = standard deviation, r = test–retest reliability ($N = 19$, 2-week interval), mean of 2-back-identity and 2-back-spatial in Pr, mean of Aospan refers to the Ospan score, mean of BoA refers to the averaged threshold (in pixels), and mean of UFOV represents the proportion of correct responses

(Cumming, 2012, 2014) and report effect-size estimates and their precision in form of 95 % confidence intervals.

Descriptive statistics for all measures showed no obvious floor or ceiling effects with enough variability (as indicated by standard deviations) to analyze individual differences in performance (see Table 1). In addition to descriptive statistics, Table 1 also reports test–retest reliabilities for all measures based on retesting of 19 participants after a 2-week interval. Test–retest reliabilities of 2-back-identity, Aospan, BoA and UFOV were satisfactory while the test–retest reliability of 2-back-spatial was rather poor.

To create a single measure for the UFOV, we averaged performance across the three eccentricities. A descriptive analysis found that performance varied as a function of eccentricity: averaged across all participants, the near-eccentricity led to 88.8 % correct answers, the middle-eccentricity led to 76.0 % correct answers, and the far-eccentricity led to 67.4 % correct answers.

Correlational analyses

Table 2 provides the correlations (Pearson's r) among our five measures, along with their 95 % confidence intervals (in square brackets) and the sample sizes contributing to each correlation (below the diagonal). As expected, the three working-memory measures were moderately to strongly intercorrelated (Cohen, 1988). Only 2-back-spatial and Aospan were not as strongly correlated. The more reliable response-time measure of 2-back-spatial (response times of correct responses, $M = 628.31$ ms, SD = 175.26 ms, test–retest reliability = 0.79), however, showed a medium-sized association with the Aospan ($r = -0.27$ [−0.43, −0.09]). Thus, all three working-memory tests used in the present study shared common variance. Similarly, the two measures of attentional breadth, the BoA and the UFOV, were highly correlated with each other and shared about 23 % common variance. Most importantly, all three working-memory measures were correlated positively with each attentional-breadth measure. These medium-sized correlations were larger for the BoA than for the UFOV.

In addition to analyzing correlations among each of the tasks, we formed composite measures by z-scoring performance on each task across individuals and then averaging each individual's z-scores across the working-memory test scores and across the attentional-breadth test scores. Missing single values led to missing composite values. The composite measures were correlated 0.44 (0.28, 0.58) with each other, demonstrating that measures of working memory and attentional breadth are tightly related.[1]

Although the composite working-memory measure combined 2-back and Aospan tasks, a recent meta-analysis suggests that such measures are only weakly correlated and that they should not be treated as comparable measures of working memory (Redick & Lindsey, 2013). Although our composite 2-back measure was correlated with the Aospan in our sample ($r = 0.30$ [0.13, 0.46]), we also explored the correlation of each of these types of working memory with our attentional-breadth composite measure separately: the composite attentional-breadth measure correlated 0.32 [0.15, 0.47] with the Aospan and 0.39 [0.28, 0.58] with the 2-back composite. Thus, even if the 2-back tasks and the Aospan measure different underlying constructs, performance on each is correlated with attentional breadth to roughly similar extents.

Extreme-group comparison

A common approach for studying individual differences in the working-memory literature involves comparing people with high working-memory capacity to those with low working-memory capacity (Kane et al., 2006; Long & Prat, 2002). Although this approach discards data from what are otherwise more continuous distributions of performance, it can help to illustrate how individual differences in one task are related to those on another. As illustrated in Fig. 1, participants scoring in the top 25 % of the composite working-memory measure (high spans; scores ≥ 0.48) showed substantially higher scores on both attentional-breadth measures than those scoring in the bottom 25 % (low spans; scores ≤ -0.46). The difference between high- and low-span individuals was more pronounced for the BoA ($d = 1.50$ [0.90, 2.09]) than for the UFOV ($d = 0.69$ [0.16, 1.22]).

[1] A confirmatory factor analysis based on maximum likelihood estimates found a good fit for a two-factor model and a less good fit for a one-factor model. The two factors, working memory and attentional breadth, were correlated 0.63 in the two-factor solution. More detail concerning the factor analysis and the raw data for all five cognitive tests are available at https://osf.io/2hk4c/.

Table 2 Correlations (Pearson's *r*) among measures of working memory and attentional breadth

	1	2	3	4	5
(1) 2-back-identity	–	0.51 [0.36, 0.63]	0.30 [0.13, 0.46]	0.36 [0.19, 0.51]	0.25 [0.07, 0.41]
(2) 2-back-spatial	117	–	0.17 [−0.01, 0.34]	0.31 [0.14, 0.47]	0.24 [0.06, 0.40]
(3) Aospan	117	119	–	0.35 [0.18, 0.50]	0.19 [0.01, 0.36]
(4) BoA	114	116	120	–	0.48 [0.33, 0.61]
(5) UFOV	117	119	123	120	–

The lower and upper bounds of the 95 % confidence interval are shown in square brackets, and the number of cases contributing to each correlation appears below the diagonal

Discussion

We employed an individual-differences approach to investigate whether aspects of attentional control beyond inhibitory processes are associated with working-memory performance. We found medium-sized correlations between all three working-memory measures and both attentional-breadth measures and the composite working-memory measure and the composite attentional-breadth measure shared 20 % of their variance. Moreover, participants with high and low working-memory capacity showed substantial differences in their attentional-breadth performance. Because attentional-breadth measures require attentional control, but do not rely extensively on inhibitory processes, these findings provide converging evidence that individual differences in working memory are associated with attention processes other than inhibitory control.

Not surprisingly, our working-memory measures were all intercorrelated, as were our two measures of attentional breadth. Surprisingly, though, the correlations between measures of working memory and attentional breadth were just as strong as those among the measures of each construct. That is, the correlations between measures of attentional breadth and measures of working memory were as large as those among the measures of working memory. This pattern suggests that measures of both constructs might actually account for some of the same variation across individuals. Contemporary working-memory theories agree on the importance of attention in working-memory performance (e.g., Baddeley, 2003; Cowan et al., 2005), and many studies show a close link between working memory and a variety of attention tasks (Conway et al., 2001; Gazzaley & Nobre, 2012; Kane et al., 2001; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). Some models (e.g., Engle, 2002) even equate working memory with attentional control, which refers to those cognitive processes that focus attention in a goal-directed manner. In line with this view, the shared variance between working-memory capacity and attentional breadth in our study could be attributed to the similar demands of these tasks: The working-memory tasks require the flexible allocation of attention within the mental workspace, and the attentional-

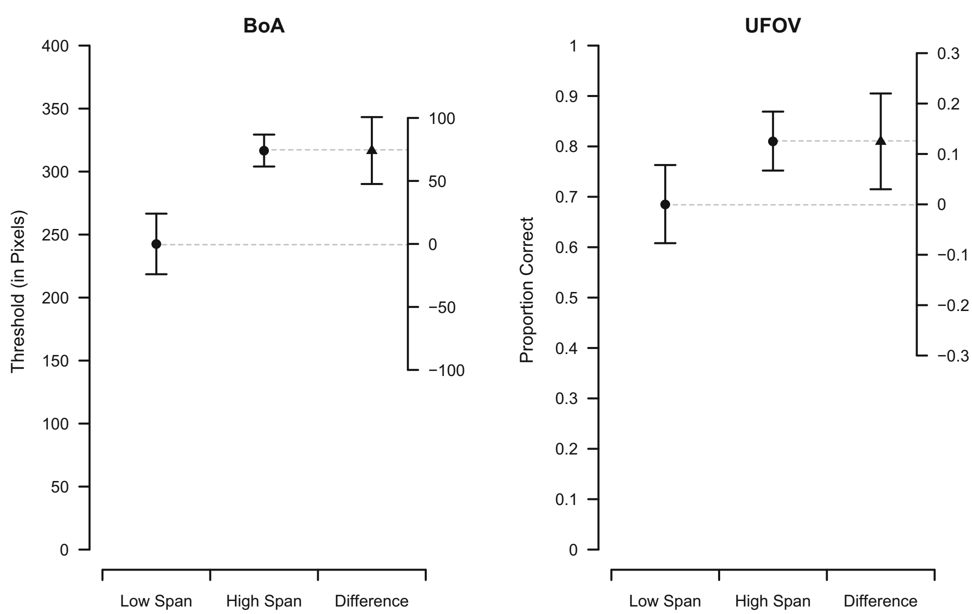

Fig. 1 Means and 95 % confidence intervals for low-span individuals (scoring in the bottom 25 % of the composite working-memory measure) and high-span individuals (scoring in the top 25 % of the composite working-memory measure) in the BoA (*left panel*) and the UFOV (*right panel*). The difference between the group means, with its 95 % confidence interval, is shown on a floating difference axis at the right in each panel. High-span individuals performed better than low-span individuals on both attentional-breadth tasks

breadth tasks require the flexible allocation of attention in space (Ball et al., 1988; Hüttermann et al., 2013, 2014). Hence, both types of tasks require controlled attention, either within working memory or in visual space.

Additional support for the idea that working-memory and attentional-breadth measures both rely on attention control comes from the stronger correlations of the working-memory measures with the BoA than with the UFOV. The BoA task requires a conjunction search, a process that should demand more attention resources than the feature search in the UFOV (Hüttermann et al., 2013; Treisman & Gelade, 1980). If so, the BoA might rely more heavily on attentional control, leading to a higher correlation with measures of working-memory capacity. This finding cannot be attributed to differences in the reliability of the measures because the UFOV showed higher test–retest reliability than the BoA. An alternative explanation for the association between working memory and attentional breadth might be the memory demands of the attentional-breadth tasks: observers had to remember their answer until they could respond. This demand is, however, constant across all eccentricities and, therefore, cannot explain individual differences in performance with varying eccentricity.

One finding that appears at odds with ours is the lack of a relationship between working memory and the uncued trials in a selective-attention task (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003). This task, much like the UFOV, includes both a central task and a peripheral task, with targets presented on one of three concentric rings. But the tasks differ in two ways that might account for the discrepant results. First, whereas the UFOV measures performance with large eccentricities, the selective-attention task used eccentricities of 1°, 2° and 3°. These proximal stimuli mean the task might have measured attentional allocation rather than attentional breadth. Second, the selective-attention task included no peripheral distractors, so target localization might not have required much attentional control.

Although the relationship between working memory and attention appears most consistently for attentional-control tasks that involve interference or response conflict, the executive-attention theory (executive attention is synonymous for controlled attention in this theory, Kane et al., 2006) proposes that working-memory capacity reflects general attentional abilities beyond inhibitory control. The claim is consistent with the association between working memory and a variety of higher-order cognitive tasks (e.g., Cowan et al., 2005; Daneman & Carpenter, 1980; Kyllonen & Christal, 1990) and with several studies demonstrating a link between working-memory and attention tasks in which the restraint of habitual responses plays a less obvious role (e.g., negative priming: Conway, Tuholski, Shisler, & Engle, 1999 or cued selective attention: Bleckley et al., 2003). These tasks, however, do contain distractor stimuli that must be actively ignored or uncued locations that may be selectively suppressed. Consequently, the link between working-memory capacity and performance in these tasks might still be driven primarily by inhibitory processes. Evidence from visual-search tasks that require attentional, but not inhibitory control is ambiguous, with some studies finding an association with working memory (Anderson et al., 2013) and some not (Kane et al., 2006).We provide evidence that attentional breadth, a cognitive ability that requires attentional control without depending on inhibitory processes, is closely linked to working-memory performance, thereby supporting the notion that the association between working memory and attention is not limited to interference resistance and inhibitory control.

Limitations of the current study

We find that individual differences in working-memory capacity vary with differences in attentional breadth, but from this finding we cannot infer that changes in one capacity cause changes in the other. Individual differences in each capacity and the relationship between them might be driven by a third variable (such as processing speed). A causal inference would require an experimental manipulation of one capacity to see an effect on the other. For example, future studies could manipulate the availability of working memory to explore whether that leads to accompanying changes in attentional-breadth performance (or vice versa). Our findings should not be used as the basis for claims that improving one capacity would lead to improvements on the other.

Also, our sample mostly consisted of university students who might have a relatively restricted range of performance on these tasks. Nevertheless, we had sufficient variability in our measures to find moderately strong correlations among them. However, both working-memory capacity and attentional breadth change across the lifespan (Hüttermann, Bock, & Memmert, 2012; Salthouse, 1991; Wingfield, Stine, Lahar, & Aberdeen, 1998), and the relationship between them might change as well. Moreover, it is possible that the relationship between these constructs might differ among people with higher or lower performance levels than in our university sample. Consequently, the pattern should be replicated with a more diverse sample to establish the strength of the correlations in the population at large.

Conclusion

We find a consistent association between working memory and attentional breadth across multiple measures of each construct. This finding is in line with a close link between working memory and controlled attention, and it demonstrates that working memory is associated with attention performance even for tasks that are not highly dependent on inhibitory processes.

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Ethical standard All participants gave their informed consent prior to their inclusion in the study and were debriefed afterwards. The study has been approved by the local ethical committee and has, therefore, been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

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