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Focusing the Spotlight: Individual Differences in Visual Attention Control

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A time-course analysis of visual attention focusing (attentional constraint) was conducted in groups of participants with high and low working memory spans, a dimension the authors have argued reflects the ability to control attention. In 4 experiments, participants performed the Eriksen flanker paradigm under increasing levels of speed stress. Conditional accuracy functions were derived to measure the time course of attentional constraint. The data showed that accuracy rates rose toward asymptote at different rates, with participants with high working memory spans reaching peak performance before participants with low working memory spans. The authors interpret these data in terms of a rate of attention constraint model.

Keywords: visual attention, attentional focus, working memory, flanker effect, time course

One of the most basic features of visual information processing is the ability to select and discard information. Often, the efficiency of selection is assessed through failures to discard task-irrelevant stimuli. As a case in point, consider the flanker effect (C. W. Eriksen & Hoffman, 1973). Participants must indicate the identity of a target item by pressing a key with their right or left hand. Responses to target stimuli are invariably slowed when nearby distractor items are mapped to the incompatible hand. This is explained as a failure to efficiently discard peripheral response-irrelevant information (C. W. Eriksen & Schultz, 1979; Lavie, 1995). In other words, an efficient selection mechanism would eliminate the influence of surrounding distractors—if responses to such stimuli are slowed relative to stimuli that include neutral or compatible peripheral information, then selection failed to limit processing to only relevant stimuli.

This online filtering and rejection of unwanted items is not all or none, however. Early studies (e.g., C. W. Eriksen & Hoffman, 1973; C. W. Eriksen & St. James, 1986) revealed that spatial filtering is a process that requires time—the more time allotted for selection, the more efficient the rejection of incompatible stimuli (Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). It is as if attention begins in a diffuse state and contracts to a focused state (Jonides, 1983). Recent research suggests that the extent of attentional focusing is mediated by a number of factors, including properties of the stimuli themselves. For instance, difficult perceptual discriminations tend to focus attention (LaBerge, Brown, Carter, Bash, & Hartley, 1991), leading to less processing of distractor information (Lavie, 1995; Rees, Frith, & Lavie, 1997) than comparatively less difficult discriminations.

In this article, we show that the constraint of visual attention is dependent not only on time since onset and difficulty of discrimination but also on individual differences in limited-capacity, top-down control. We argue that the time course of attentional constraint is related to cognitive ability. Specifically, participants thought to be low in attention control ability (i.e., those that have low working memory [WM] spans) require more time to adjust attentional allocation than do participants high in attention control ability (i.e., those with high WM spans). Before providing support for these contentions, we review evidence favoring a *dynamic spotlight* view of visual attention as well as an attention control perspective of WM. Finally, we show how a dynamic theory of visual attention requires experimental and statistical methodology that reflects this dynamic process. Our use of fine-grained time-course analysis reveals a pattern of data that would be obscured by more global measures of performance.

The Dynamic Spotlight

As a construct, attention is concerned with the control of behavior. At any given moment, behavior is under the control of a variety of external and internal stimuli. As noted by Luck and Vecera (2002), researchers infer that stimuli have been attended if they in some way affect behavior. For example, in the Eriksen flanker task, if response-incompatible information slows responding relative to neutral information, then it is inferred that attention must have encompassed those items, allowing them to be processed (C. W. Eriksen & Schultz, 1979; Lavie, 1995). The lack of a flanker effect suggests that this peripheral information has been filtered, and an attenuation of the flanker effect implies that distracting information has been partially filtered.

An efficient attentional system will eliminate the effects of items in the visual field that are irrelevant, particularly if those items are incompatible with current goals. In the visual domain, such flexibility suggests an attention system that may be configured to accommodate target elements to the exclusion of nontarget elements. When task goals require parallel processing of all infor-

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mation, a large allocation will be used; when attention must be limited to just a few regions of interest, a comparably smaller allocation will ensue.[1] Realizing this, Jonides (1983) proposed a two-process model of visual attention. In the diffuse mode, visual attention is allocated to all regions of the visual field in equal proportion; in the focused mode, attention is concentrated at one area of interest, specified by a central or peripheral cue. Although it may be true that participants can use either focused or diffuse modes of operation in response to different task contingencies, it is more likely that intermediate stages exist as well. One may also ask whether the act of switching from a diffuse to focused mode follows a time course (i.e., continuous versus discrete focusing).

To assess the extent of allocation at different time points, C. W. Eriksen and St. James (1986; see also C. W. Eriksen & Yeh, 1985) manipulated the stimulus onset asynchrony (SOA) between a peripheral bar cue and a circular target array. At short SOAs, it is assumed that participants have very little time to constrain attention. As SOA increases, however, more time is allowed for focusing attention, and one should observe less and less effect of incompatible stimuli. In C. W. Eriksen and St. James's study, participants were to report the identity of a target letter at the cued location; critically, peripheral letters were response compatible, response incompatible, or response neutral with respect to the cued target letter. They found decreasing effects of incompatible distractors with increasing SOA and increasing distance from the cued area. These data support a view whereby attention begins in a diffuse state but constrains over time so as to attenuate the effects of distractor items. Other research has provided further supporting evidence of a constraining spotlight of attention (Benso, Turatto, Mascetti, & Umilta, 1998).

Work by Lavie and colleagues (e.g., Lavie, 1995) has also shown that focusing visual attention leads to less processing of distractor items. Lavie (1995) presented participants with a version of the Eriksen flanker task (B. A. Eriksen & Eriksen, 1974) while manipulating the perceptual load of the stimuli. Participants were presented with an array of letters at the center and a single peripheral distractor letter. The central array consisted of either (low perceptual load) one letter or (high perceptual load) six letters. Participants were to indicate the presence of a *z* or a *p*, each mapped to a different hand. Note that the peripheral distractor letter could be compatible, incompatible, or neutral with respect to the critical target. Lavie (1995) found a flanker effect (slower responding on trials with an incompatible distractor than with a neutral distractor) in the low perceptual load condition but found no flanker effect under high perceptual load. It appears that the high perceptual load required visual attention to be more focused. As a result of this focusing, less attention was available at the distractor location, eliminating the flanker effect.

Strong evidence in favor of Lavie's (1995) theory is provided by neuroimaging research. Rees et al. (1997; see also Rees & Lavie, 2001, for a review) presented participants with a linguistic task. In the low load condition, participants simply had to indicate whether a word was presented in uppercase or lowercase. In the high load condition, they were to indicate whether the word had two syllables (as opposed to either one or three). At the same time, a field of dots was presented in the periphery. These dots either remained static or began to move in an outward direction. Rees et al. reasoned that visually sensitive area V5/MT should show a strong response to a moving dot pattern. However, if the load manipulation tends to reduce the amount of attention in the periphery, then there should be significantly less V5/MT activation to moving dot patterns in the high load condition as compared with the low load condition. This is exactly what they observed.

Further support for the contention that focusing attention leads to less processing of peripheral information is provided by Handy, Soltani, and Mangun (2001). In this study, participants were presented with a go/no-go flanker task. On each trial, participants saw a colored bar oriented either vertically or horizontally. At the same time, a central target letter and a peripheral distractor letter were presented, for a short duration. On go trials, participants were to identify the target letter; on no-go trials, no response was required. It is important to note that the peripheral distractor letter, which was always in the same location and always irrelevant, was response compatible, response incompatible, or response neutral with respect to the target letter. Handy et al. also included a blocked cognitive load manipulation. In the low load condition, the go signal was defined by the color of the bar. For example, go might be blue and no-go green. In the high load condition, the go/no-go signal was a color–orientation conjunction (e.g., blue and vertical).

Handy et al. (2001) measured the event-related brain potential to probe stimuli occurring in the location of the peripheral distractor location. If attention is more focused on the target in the high load block as compared with the low load block, then stimuli occurring in the peripheral location should elicit less of a visually evoked potential. This is exactly what Handy et al. (2001) observed. The P1 component of the event-related brain potential waveform was significantly larger in the low load condition. Again, this indicates that processing resources at the peripheral location was reduced in the high load condition.

In a somewhat different paradigm, LaBerge et al. (1991) showed that the influence of peripheral distractors can be attenuated by focusing attention. In this paradigm, participants were presented with a go/no-go flanker task. On each trial, participants saw two displays. The first display was a long string of alternating *T* and *Z* letters. At the very center of the array was either a *T* or a *7*. If participants detected a *7*, then they were to perform the subsequent flanker trial (in the case of a *T*, they were to do nothing). The subsequent flanker trial again consisted of a long array of letters. Participants had to identify the center target letter in the presence of compatible, incompatible, or neutral flanking letters. LaBerge et al. (1991) reasoned that one could manipulate the extent of attentional focus by changing the display duration of the leading go/no-go display. When this display is presented for a very short duration, participants presumably have to prefocus attention to a high degree in order to facilitate the difficult discrimination. With longer durations, then, a less constrained focus is needed. Consistent with this hypothesis, LaBerge et al. found a much attenuated flanker effect with shorter go/no-go durations.

The above research clearly indicates that visual attention can be focused to different extents. And, the constraint of visual attention has the benefit of attenuating the influence of distracting peripheral information. It is also the case that focusing visual attention

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[1] Throughout this work, we assume a variable field of activation, rather than inhibition. It is likely one can make equivalent predictions using an inhibitory mechanism. We explore this in the General Discussion.

enhances processing within the attended region. When attention is highly focused, there appears to be a greater density of resources within that region. As the attended region increases in size, fewer and fewer resources are available for each unit of area. C. W. Eriksen and St. James (1986) were one of the first to make this suggestion (see also C. W. Eriksen & Yeh, 1985). In their study, they cued one, two, or three letters in a circular array at a time. In support of a "zoom-lens" metaphor of visual attention, they found that reaction time (RT) generally decreased with smaller cued regions; thus, the more focused attention is, the higher the density of resources, and the faster the processing.

In later work, Castiello and Umiltá (1990) had participants perform a simple RT task to the onset of a small dot. Before the dot appeared, participants were cued with small-, medium-, or large-sized boxes. On compatible trials, the dot always fell in the center of the box. On these trials, RTs were significantly faster for small boxes than for large boxes. However, this effect held only for a 500-ms cue-to-target SOA. This indicates, quite importantly, that even when attention is cued exogenously, the focusing of attention takes time. At 500 ms, there was enough time for attention to focus to the size of the box, thereby facilitating detection.[2] At a 0-ms SOA, however, there was not enough time for attention to constrain to the size of the box; thus, there was no facilitation for small boxes over larger ones.

Comparable data were presented by Facoetti and Molteni (2000). In this study, participants performed a choice RT task to a colored central dot (green or red) that was flanked on either side with a response-compatible or a response-incompatible dot (denoted by color). Each trial began with a small or large circular cue, followed 0 or 500 ms later (SOA) by the appearance of the dot stimuli. Facoetti and Molteni observed a flanker effect (faster responding on compatible than incompatible trials) in all conditions except for a small cue with 500-ms SOA. They reasoned that the constraint of visual attention to the cued area takes time; given previous research (e.g., Benso et al., 1998), 500 ms should be ample. At a 0-ms SOA, neither a small nor a large cue had any differential effect because attention did not have time to constrain to that cue. After 500 ms, however, attention constrained to either the small or large cue. Unfortunately for participants, the large cue encompassed the flanker letters; only the small cue eliminated the effect of these distracting stimuli.

The above shows that visual attention can constrain to enhance processing of attended information and eliminate processing of peripheral information. One might wonder whether this constraint is a controlled, capacity-demanding activity.[3] In particular, we might ask how participants focus their attention at will, rather than in response to some external basis. Many of the studies discussed above cued attention with an exogenous cue. If there were no such cue but participants still need to constrain attention, it is likely that a capacity-limited control mechanism becomes important. There are two general ways to explore this. One way is to manipulate WM load in a task requiring effortful control of visual attention. Lavie's work (Lavie & DeFockert, 2005; Lavie, Hirst, De Fockert, & Viding, 2004) suggests that, indeed, WM load can affect certain operations of visual attention. Exactly how WM load affects visual attention, however, is an open question.

The second method is to use groups of participants that differ in attention control ability. Take, for example, work by Facoetti et al. (2003). On the basis of previous research beyond the scope of the present work, it is thought that persons with dyslexia have an impaired ability to focus visual attention. To test this, Facoetti et al. tested dyslexic and nondyslexic participants in a choice RT task. Participants were cued on each trial with a large or small circle cue, followed 100 ms or 500 ms (SOA) later by a left or right pointing arrow. Participants were to indicate the direction the arrow was pointing. Facoetti et al. found that there was a cue benefit (faster responding to arrows with a small cue than with a large cue) for nondyslexic participants at both the 100-ms and 500-ms SOAs. This indicates that nondyslexic participants can focus attention to a cued area in as little as 100 ms. In contrast, dyslexic participants exhibited a cue benefit only in the 500-ms SOA condition. There was no difference between a small and large cue at a 100-ms SOA. Facoetti et al. argued that dyslexic individuals have a "sluggish" orienting of visual attention.

We argue that sluggish orienting of visual attention is not a problem limited to dyslexia but rather is due to a limitation in general attention control ability. In our view, aspects of visual attention control such as focusing are subject to control processes that are known to exhibit individual differences. To the extent that an individual is low in attention control ability, he or she will have difficulty constraining visual attention in an effort to enhance processing at the center and exclude processing of peripheral information. We demonstrate this empirically in a population of individuals with high and low WM spans. As we detail in the next section, individuals high and low in WM capacity are dissociated in tasks that require effortful, top-down controlled attention.

WM Capacity and Attention Control

We view WM as the set of cognitive structures important for carrying out elementary cognitive operations (Baddeley & Logie, 1999; Cowan, 2001). As such, the construct differs quite markedly from earlier modal models (e.g., Atkinson & Shiffrin, 1968; Waugh & Norman, 1965) that primarily stressed the capacity of short-term storage. Much work, beginning with Baddeley and Hitch (1974), has shown that taxing the WM system has consequences not only for short-term storage but for such high-level

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[2] There is an apparent discrepancy between LaBerge et al. (1991) and Castiello and Umiltá (1990). Specifically, in the former case, a shorter duration of a leading stimulus led to a highly focused attentional allocation, whereas in the latter, a shorter cue–target SOA led to a less focused attentional allocation. However, the LaBerge et al. study blocked the duration of the go/no-go task. Thus, over time, participants learned just how focused their allocation should be for adequate performance. Also, the delay between the go/no-go trial and the flanker trial was kept constant; hence participants always had time to focus attention. In contrast, Castiello and Umiltá did not block trials—it is likely that participants began each trial with a diffuse allocation, only later focusing. Furthermore, participants had no time to focus attention in the 0 SOA condition, unlike the LaBerge et al. study, in which participants always had time to focus attention.

[3] We do not argue that attentional constraint is always effortful—there are situations in which the allocation is automatic. In many of the studies reviewed, participants were cued with an exogenous cue. It is highly likely that attention is automatically oriented to the onset stimuli. Our question concerns the subsequent operation—the constraint of attention following the initial orienting. Attention might be automatically directed to the shape of a circle cue, for example. After this initial orienting, however, participants may use capacity-limited control processes to further focus attention.

functions as reasoning and comprehension. Because such high-level functions have in common the need for attentional control, many have argued that WM is actually an attentional construct. More specifically, work has shown that participants rated high and low in WM capacity differ in a variety of cognitive tasks to the extent that those tasks require attentional control. Thus, WM capacity is a domain-general cognitive ability (Heitz, Unsworth, & Engle, 2005; Kane et al., 2004). We have shown that participants with high WM capacity outperform participants with low WM capacity only in conditions that require attention control; conditions that can be performed automatically do not lead to group differences (e.g., Unsworth, Schrock, & Engle, 2004).

Some of the best evidence for WM as an attentional construct comes from its relation to performance in low-level tasks. In other words, a view of WM as a strictly memory phenomenon would not predict any relationship to such tasks as the Stroop, for example. However, a variety of studies have indicated just such a relationship. Kane and Engle (2003) had participants with low WM spans and high WM spans perform the Stroop task (Stroop, 1935). In this task, participants view color words such as *blue* and *green*. Note that the actual color of these words is manipulated so as to be congruent, incongruent, or neutral. (In actuality, neutral trials were simply unpronounceable letter strings.) For example, an incongruent trial might be the word *green* presented in blue ink. Participants must name the color, not the word—a task that is quite difficult when word names and color names mismatch. Kane and Engle found that participants with low WM spans were at a relative disadvantage compared with those with high WM spans in conditions containing a large or small proportion of incongruent trials (see Kane & Engle, 2003, for a full review). Note that the Stroop task is quite low level and requires much in terms of interference resolution from incongruent stimuli. A WM system couched in terms of the size of an information store would have difficulty predicting this result, particularly when the proportion of incompatible trials is large (i.e., each trial reminds participants of the task requirements). It is probably for this reason that it is a gold standard in the neurosciences for testing controlled (prefrontal) activity. Indeed, the Stroop task is often used to dissociate patients with prefrontal cortex damage and healthy controls (Kane & Engle, 2002).

Probably more germane to the present work is an article by Unsworth et al. (2004). These researchers had participants with low and high WM spans perform the antisaccade task (Hallet, 1978). In the antisaccade task, participants must make a saccade toward (prosaccade) or away from (antisaccade) a flashing exogenous cue. Participants begin by focusing on a central fixation point. After a variable delay, two boxes appear 11° to the right and left of fixation, one of which begins to flash. Participants must then make the appropriate saccade. Unsworth et al. (2004; see also Kane, Bleckley, Conway, & Engle, 2001) found that participants with low and high WM spans performed equivalently (in error rate and RT) in the prosaccade condition. This is not surprising, as orienting toward an exogenous cue is an automatic response (Sokolov, 1963). However, participants with low WM spans made significantly more errors than did participants with high WM spans in the antisaccade condition. That is, participants with low WM spans tended to look toward the flashing cue when the appropriate response was to look away from that cue. And, even when the participants with low WM spans made the correct saccade, they were much slower to do so than were participants with high WM spans. Note that the antisaccade task consists of two components. First, there is inhibition of the prepotent response to orient toward the exogenous cue. Second, there is an effortful orienting of visual attention in the opposite direction, followed by the overt eye movement. Hence, WM span differences on these trials constitute evidence that WM is related to effortful orienting of visual attention.

It is as yet unclear whether WM span differences exist in the Eriksen flanker paradigm. Redick and Engle (2006) found evidence for a Span × Compatibility interaction in Posner's Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002), whereas others have reported a near-zero correlation between WM span and performance in the flanker task (Friedman & Miyake, 2004). Part of the discrepancy may be due to how long participants take to complete the trials. On the basis of the above review, we know that focusing attention is a dynamic process that requires time. If participants with both high WM spans and low WM spans respond too quickly, then no span differences will emerge because neither group will have had time to constrain attention. On the other hand, if participants with both high WM spans and low WM spans respond with relatively long latencies, then both groups will have had time to constrain attention, leading to a lack of a flanker effect for both groups and, consequently, no group differences. However, according to a constraining spotlight view, span differences should occur with intermediate RTs if the difference between the two groups is in the sluggishness of attentional focusing. Stated differently, if span differences exist in the flanker task, they will emerge only during time points in which the spotlight of attention has begun, but not finished, focusing. Clearly, global measures such as mean RT or mean accuracy rate would be ineffective in this regard, as they would combine data from all time points. To evaluate our claim, we must somehow track the time course of attentional constraint, such that we can gauge changes in performance levels during the constraining operation.

Tracking Attentional Constraint

Generally, experimenters attempt to capture something about attentional focusing by manipulating the SOA between a cue and the onset of an array and examining mean latency and accuracy. This technique has been used in the flanker task (C. W. Eriksen & Hoffman, 1973; C. W. Eriksen & St. James, 1986) with circular arrays of letters. In these stimuli, the actual location of the target letter is unknown until a bar cue indicates its position. The delay between the bar cue and the onset of the array allows time for (a) attentional orienting and (b) attentional focusing. We wanted to eliminate spatial uncertainty so as to eliminate possible alternative explanations for WM span differences. Thus, we decided to use B. A. Eriksen and Eriksen's (1974) version of the flanker task, in which the location of the target letter is always in the center and the distractors are always to either side of the target. There is no comparable manipulation of SOA for this task, because no cue is required to indicate the location of the target.

To deal with this, we decided to do a time-course analysis. Presumably, if we track participants' performance along a variety of time points, we can watch the constraint of visual attention. That is, temporal changes in accuracy rate should reflect the size of the attentional allocation. One study in particular makes this point quite eloquently. Gratton et al. (1988; see also Coles, Gratton, Bashore, Eriksen, & Donchin, 1985) had participants perform B. A. Eriksen and Eriksen's (1974) flanker task over thousands of trials. In the analysis, Gratton et al. partitioned the data into a number of RT bins. They then plotted accuracy rate as a function of RT bin. Figure 1 displays their data. The left panel shows how accuracy rate varies with RT, and the right panel shows the comparable data using electromyogram onset as a measure of overt response production. As illustrated, at very fast latencies, responses to both compatible and incompatible trials are at chance. In other words, participants do not base their responses on any meaningful information at this point. Given a bit more time, however, participants begin to accumulate information from the display (C. W. Eriksen & Schultz, 1979). Notice that accuracy for incompatible trials drops significantly below chance. This indicates that at this point, there was more information in favor of the incorrect response. We treat this dip below chance as diagnostic—it is difficult to account for in models that do not assume a dynamic spotlight of attention. One would have to propose a view whereby flanking letters are given more weight or sampled from more often than the central target letter, but only at certain time points. This would be easily predicted by a constraining spotlight model that has just begun to constrict—when the attentional allocation contains the entire flanker array, more information is in favor of the incorrect response. Over time, the RT–accuracy function continues to increase, and at very long latencies, the flanker effect disappears (accuracy for compatible and incompatible trials are virtually identical). This suggests that at long latencies, participants were able to constrain their attentional allocation to effectively filter out all peripheral distracting information. Thus, compatible and incompatible performance does not differ.

If we are correct that participants with low and high WM spans differ in the ability to control attention, then it is likely that they will constrain their attention at different rates. Similar to the Facoetti et al. (2003) study, if participants with low WM spans demonstrate sluggish attentional allocation, then the RT–accuracy functions should be different for participants with low and high WM spans, but only for incompatible trials. Specifically, the function for incompatible trials should indicate that participants with low WM spans approach asymptotic performance at a slower rate than do participants with high WM spans. However, we would expect that at very long time points, once both groups have constrained their attention to the same extent, performance should be equivalent. Although our hypothesis predicts such a pattern, there is no a priori reason to expect the data to turn out this way. As we mentioned, the literature is unclear as to whether span differences should occur at all in the flanker task. It is also equally plausible that people with high WM spans have higher asymptotic accuracy rates than do people with low WM spans. Each of these possibilities is borne out in the time-course functions.

To preview, the data show that participants with low WM spans indeed exhibit sluggish attentional focusing. Specifically, accuracy rates on incompatible trials increase at different rates between the two groups, with participants with high WM spans reaching peak performance before participants with low WM spans. Critically, the peak level of performance (asymptote) is identical for the two groups. We conclude that participants who are deficient in attention control ability are slower to constrain attention than are participants who have high attention control ability. We argue that these conclusions have broad applicability outside the domain of both WM and visual attention—specifically, in groups of partici-

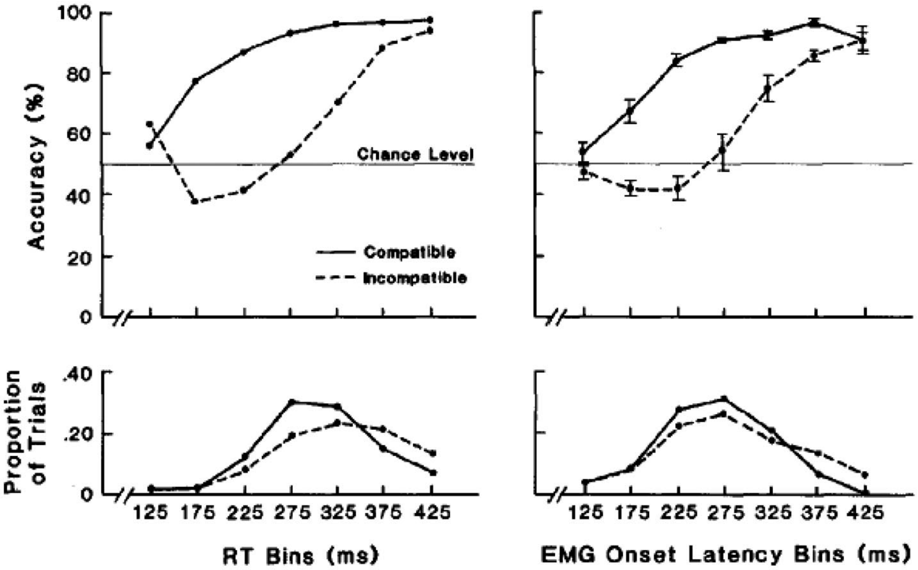

Figure 1. Conditional accuracy functions (top row) and proportion of trials for each response latency bin (bottom row) reported in Gratton et al. (1988). The top left panel plots accuracy rate against reaction time (RT), and the top right panel uses electromyogram (EMG) as a measure of response onset. Error bars represent standard errors. From "Pre- and Poststimulus Activation of Response Channels: A Psychophysiological Analysis," by G. Gratton, M. G. H. Coles, E. J. Sirevaag, C. W. Eriksen, and E. Donchin, 1988, *Journal of Experimental Psychology: Human Perception and Performance, 14,* p. 335. Copyright 1988 by the American Psychological Association. Reprinted with permission.

pants defined on other individual differences characteristics (e.g., age, intelligence, psychopathology, brain trauma).

Experiment 1

Method

Participants

Participants were recruited through the Georgia Institute of Technology participant pool and through newspaper advertisements as part of an ongoing screening procedure. Participants ranged in age from 18 to 35, were native English speakers, and had normal or corrected-to-normal vision by Snellen chart. Participants received pay or course credit as compensation.

Stimuli and Procedures

Operation span task. All individuals completed the operation span task (Turner & Engle, 1989), a task commonly used to measure WM capacity, which is both reliable and valid (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Conway et al., 2005; Engle, Tuholski, Laughlin, & Conway, 1999; Klein & Fiss, 1999). The task consists of remembering words while solving simple math equations. For example, an individual may encounter the string *IS* $(5 \times 2) + 3 = 7?$ *BEACH*. The participant is required to read the equation out loud, answer "yes" or "no," and then say the word out loud. After reading the word, the experimenter advances the screen and a new string appears. After from two to five of these equation–word pairs, participants are prompted to recall the words, in the same order that they appeared, by writing them on a response sheet. In total, there are three repetitions of each set size, for a total of 15 trials and a maximum possible score of 42 (excluding three practice problems with a set size of two). Set sizes are initially randomized, with all participants receiving the same order. In addition, participants not achieving an 80% accuracy rate for the arithmetic strings were not considered for further experimentation.

Participants' scores are computed as the sum of all perfectly recalled set sizes. So, for example, if an individual recalled perfectly a set size of three and a set size of four but recalled only four words in a set size of five, the resulting score would be $(3 + 4 + 0) = 7$. We have previously established quartiles on the basis of a large database of over 3,000 participants from multiple universities. Participants falling in these upper and lower quartiles are classified as having high and low WM spans, respectively.

Flanker task. We selected 15 individuals with high WM spans and 15 individuals with low WM spans from the above population and asked them to return to perform a version of the Eriksen flanker task (Gratton et al., 1988). Participants viewed a string of letters composed of *S* and *H* characters and responded to the central letter. Strings were compatible or incompatible. The two compatible strings were *SSSSS* and *HHHHH*, and the two incompatible strings were *SSHSS* and *HHSHH*. Half of the trials were compatible, and half were incompatible (50/50). Participants indicated a center letter of *S* by pushing a key with their left hand or *H* with their right hand, or the reverse. Stimuli were presented in white against a black background. Strings subtended approximately 2.5° of visual angle, with participants seated approximately 76 cm (30 in.) from the screen.

Each trial began with the presentation of a 50-ms auditory cue followed 1,000 ms later by the letter string, which remained visible for 100 ms. Response collection began with the onset of the stimulus and continued for 1,100 ms. Trials were separated by a random interval of 3,000, 3,500, 4,000, or 4,500 ms.

To increase the number of responses at the short, intermediate, and long end of the RT distribution, we imposed response deadlines (Yellott, 1971). Trials were blocked by deadline, beginning with a deadline of 700 ms, followed by blocks with deadlines of 600, 500, 400, 300, and 200 ms.[4] Six blocks of 80 trials, each separated by a 30-s rest, followed a response mapping practice block. If a deadline was not met on a given trial, a message appeared to the participant as "Deadline Missed. Faster!" The program kept a running average of the number of missed deadlines. Every 15 trials, this was evaluated, and if more than 33% of deadlines were missed, a message appeared indicating that they were missing too many deadlines and that it was imperative that the deadline be met, even if errors result. The first 20 trials of each block were considered practice and were not included in any analyses. This allowed participants to acclimate to the deadline for that block. Thus, there were 60 experimental trials per block, leading to an overall total of 360 experimental trials.

The experiment was thus a 2 (WM span: high vs. low) × 2 (trial type: compatible vs. incompatible) × 6 (deadline: 700 ms, 600 ms, 500 ms, 400 ms, 300 ms, or 200 ms) design, with trial type and deadline as within-subjects factors.

Results

General Analyses

The following analyses exclude trials on which no response was produced (less than 5% of the data) but include trials in which the deadline was missed. Our rationale was that participants would not know that they had missed the deadline until after responding. Thus, an RT of 500 ms when the deadline was missed should be psychologically equivalent to an RT of 500 ms when the deadline was made.

Overall, responses on incompatible trials were less accurate, $F(1, 28) = 91.11$, $p < .001$, partial $\eta^2 = .77$, and slower, $F(1, 28) = 120.06$, $p < .001$, partial $\eta^2 = .81$, than responses on compatible trials (accuracy: incompatible, $M = .70$, $SD = .07$; compatible, $M = .81$, $SD = .07$; RT: incompatible, $M = 378.39$ ms, $SD = 23.64$; compatible, $M = 348.93$ ms, $SD = 20.23$). Participants with high and low WM spans did not differ in overall RT, although those with high WM spans were significantly more accurate than those with low WM spans, $F(1, 28) = 7.91$, $p < .01$, partial $\eta^2 = .22$. There were no interactions regarding span.

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[4] The reader might object that the deadline condition was perfectly confounded with practice. However, there is good reason to structure the task in this manner. First, the deadline procedure must be blocked. Participants learn, through trial and error (in the practice portion of each block) how fast the deadline will be. Second, we reasoned that had we blocked the task differently (e.g., beginning with the 200-ms deadline), participants would adjust their criterion and be more likely to respond randomly in later, longer deadline blocks.

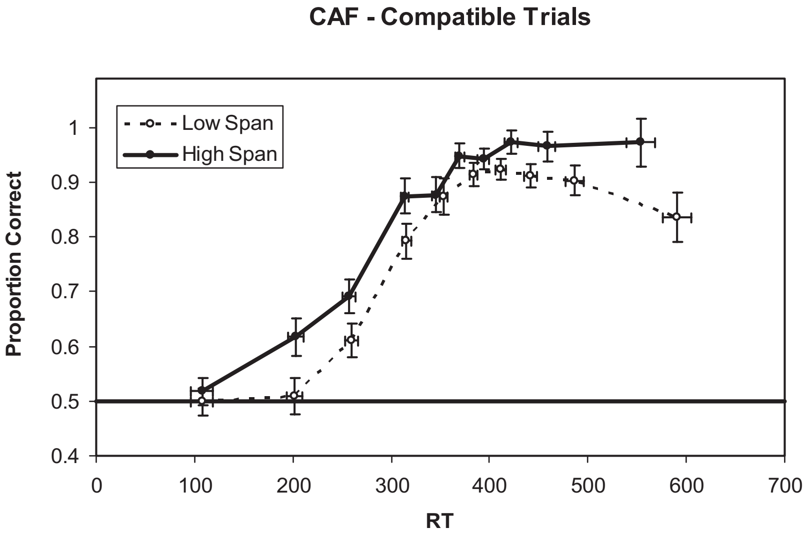

Figure 2. Conditional accuracy functions (CAFs) for compatible trials in Experiment 1. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

Time-Course Analyses

To study the temporal constraint of visual attention, we required a function that relates changes in accuracy rate with time. The appropriate function for this type of analysis is known as the conditional accuracy function (CAF). Because there are alternative (but less meaningful) ways of looking at these data and because the CAF requires certain assumptions, we have included an Appendix. There, we explain why the CAF is most germane to the present hypotheses and provide both theoretical and empirical justification for its use. Most important, even when we eliminated potential problems with using the CAF method, our conclusions remained exactly the same. The reader may wish to review the Appendix after review of Experiment 1.

To compute the CAF, we computed 10 Vincentized (quantile averaged) *n*tiles on each participant's rank-ordered RTs, separately for compatible and incompatible trials. Thus, each RT bin corresponded to 10% of each participant's data for compatible or incompatible trials. Bin 1 reflects the fastest 10% of RTs, Bin 2 the next 10%, and so on. Note that we are not analyzing deadline condition (i.e., 700 ms, 600 ms, etc.). The deadline manipulation was used solely to widen the distribution of useable RTs. Therefore, each block of deadlines contributes a range of RTs (see the Appendix).

Compatible trials. The CAFs for compatible trials are depicted in Figure 2. First, it appears that participants with high WM spans are overall more accurate than participants with low WM spans. Second, the RTs for each point appear equal between the two groups, with the exception of the final two points. Third, performance at long latencies is lower than at intermediate latencies in participants with low WM spans. Last, and most important, asymptotic performance is equivalent for the two groups and is reached at about the same time.

We first subjected the RTs for each latency bin to a 2 (span) × 10 (bin) repeated measures analysis of variance (ANOVA).[5] Despite that participants with low WM spans exhibited longer latencies than did those with high WM spans at late RT bins, the Span × Bin interaction did not reach significance. Also, there was no significant main effect of span. Thus, it was deemed appropriate to enter the accuracy rates of the latency bins into an ANOVA.

Supporting what is apparent in Figure 2, participants with high WM spans had a significantly larger mean accuracy rate than did participants with low WM spans, $F(1, 28) = 8.04$, $p < .01$, partial $\eta^2 = .22$. No interactions with span were apparent. Furthermore, asymptotic performance was not different between the span groups, $t(28) = -0.74$, *ns*, and occurred at the same point (Latency Bin 7). Accuracy rate at the first latency bin was not significantly different from chance, indicating that at these RTs, participants were likely guessing.

Incompatible trials. The CAFs for incompatible trials are presented in Figure 3. We first consider the dip below chance performance. Participants with high WM spans performed significantly below chance at Bin 3, $t(14) = -2.28$, $p < .05$, although performance did not quite reach significance for participants with low WM spans (although in Experiments 2 and 3, both groups showed the significant dip below chance). Asymptotic performance (Bin 10) was not significantly different between the two groups, nor was it significantly different between compatible and incompatible bins. Finally, performance was not significantly different from chance at the first latency bin.

There are three salient properties of the CAFs in Figure 3: Both span groups showed a tendency to perform below chance at Latency Bin 3, both groups had equivalent performance at long latencies, and participants with high WM spans approached as-

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[5] The ANOVA tests the accuracy rate between each *n*tile latency bin. Figure 2, however, plots obtained RT on the *x*-axis, not latency bin. To show that the ANOVA is appropriate, we must first show that it is tenable that the latency bin means are equivalent between the two span groups.

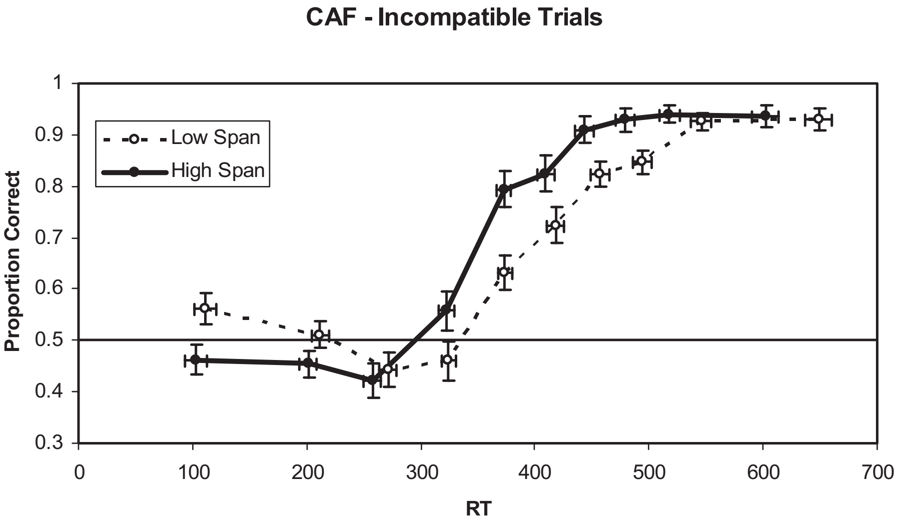

Figure 3. Conditional accuracy functions (CAFs) for incompatible trials in Experiment 1. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

ymptotic performance faster than did participants with low WM spans.

As for the compatible trials, we first tested the mean latencies of the *n*tile bins. A 2 (span) × 10 (bin) repeated measures ANOVA yielded no significant main effects or interactions. We evaluated the rate of attention constraint (RAC) hypothesis in two ways.[6] First, we tested for a Span × Bin linear interaction in Bins 4–10. Second, we performed successive paired *t* tests, separately for the high and low WM span groups. The point at which any bin is significantly different from Bin 10 (for both groups, Bin 10 had the highest accuracy rate) is the point at which asymptotic performance is attained.

The Span × Bin interaction was significant, $F(4.26, 119.26) = 2.20$, $p < .05$, partial $\eta^2 = .07$, with Greenhouse–Geisser correction for violation of sphericity. Also, the Span × Bin linear component was significant, $F(1, 28) = 7.19$, $p < .05$, partial $\eta^2 = .20$. Sequential paired *t* tests revealed that participants in the high WM span group reached asymptote at Bin 7 (Bin 6 vs. Bin 10 significant), $t(14) = -2.75$, $p < .02$. For participants in the low WM span group, asymptotic performance was not reached until Bin 9 (Bin 8 vs. Bin 10 significant), $t(14) = -2.23$, $p < .025$.

Discussion

We interpret these data in terms of an RAC model of visual attention constraint. At the beginning of each trial, participants fixate on a central point. After a variable amount of time, the flanker array appears. The onset of this array automatically orients attention to the size of the entire array (Castiello & Umiltá, 1990; Facoetti et al., 2003; Kramer & Hahn, 1995). At this point, information begins to accumulate in continuous fashion, priming response channels (C. W. Eriksen & Schultz, 1979; Gratton et al., 1988).

If participants respond very quickly after array onset, before any information has been accumulated, the participant makes a fast guess at chance-level accuracy (Ollman, 1966; Yellott, 1971). This would explain why responses for both compatible and incompatible trials were at chance for the fastest latency bin. If participants make responses at a bit longer latencies (corresponding approximately to Latency Bins 2, 3, and 4), responses are based on whatever partial information has been accumulated thus far. At this point, we argue that responses are based on information from the entire flanker array. In other words, participants do not guess—they accumulate information—but base their responses on the entire flanker array, because attention has not yet had time to constrain. At this point, responses to compatible trials steadily increase, whereas responses to incompatible trials fall below chance. Recall that accuracy rates for incompatible trials were significantly below chance for participants with high WM spans; the accuracy rates for participants with low WM spans did not attain significance, but they did in Experiments 2 and 3.

As time progresses within the trial, accuracy rates for compatible trials continue to rise, and incompatible performance rises above chance levels and climbs toward asymptote. On compatible trials, participants simply base their responses on information from the entire array, as all letters facilitate the same response. On incompatible trials, however, participants begin to use limited-capacity executive control in an effort to constrain the spotlight of attention. As mentioned earlier, constraining visual attention has the benefit of increasing the density of resources within the allocation (C. W. Eriksen & St. James, 1986) while eliminating processing of distractors outside the allocation (Lavie, 1995; Handy et al., 2001). For this reason, performance gradually rises for incompatible trials, with accuracy rates reflecting the extent of attention constraint at the associated RT.

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[6] Previous research (McElree & Dosher, 1989) has evaluated similar functions by fitting a three-parameter exponential approach to a limit. Unfortunately, this function did not fit our data well; in cases in which fit was acceptable, the conclusions were always in line with our ANOVA results.

For reasons mentioned earlier, we expected that participants who are deficient in attention control ability would demonstrate sluggish attentional constraint. Participants with low WM spans, who are thought to be low in such control ability, did in fact demonstrate a slower constraint of visual attention. Support for this contention arises from the fact that participants with low WM spans approach asymptotic accuracy rates more slowly than do participants with high WM spans. But, critically, both groups reach the same asymptotic level of performance, suggesting that given enough time, both groups are able to constrain to the same extent. Figure 4 depicts this simple RAC model.

There are notable limitations to Experiment 1. First, performance on the compatible trials was quite noisy, and participants with low WM spans exhibited impairment at long latencies. Second, on incompatible trials, we replicated the dip below chance for participants with high WM spans but not for participants with low WM spans. For these reasons, we decided to replicate Experiment 1 with one modification. In Experiment 1, 50% of the trials were compatible and 50% incompatible. In Experiment 2, we changed these proportions to 80% compatible and 20% incompatible. Research has shown that such manipulations have strong effects on behavior (Logan & Zbrodoff, 1979), and participants with low WM spans have been shown to have much difficulty when the number of incompatible trials is lessened (Kane & Engle, 2003). We additionally thought that this change would increase the stability of compatible trials and accentuate span differences on incompatible trials.

Experiment 2

Method

Participants

We recruited 20 new participants with high WM spans and 20 new participants with low WM spans from the same participant pool as participants from Experiment 1, using the same selection criteria. Participants received pay or course credit as compensation. One participant in the low span group was dropped because of failure to complete the task.

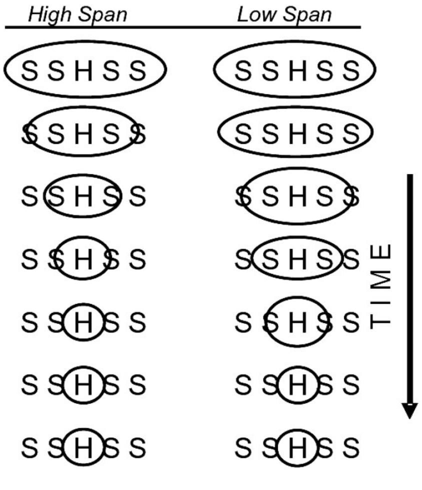

Figure 4. The rate of attention constraint model for individual differences in visual attention.

Flanker Task

All task parameters were the same as Experiment 1 except that 80% of the trials were compatible and 20% were incompatible.

Results

General Analyses

Overall, performance on incompatible trials was less accurate, $F(1, 37) = 194.99$, $p < .001$, partial $\eta^2 = .84$, and slower, $F(1, 37) = 177.52$, $p < .001$, partial $\eta^2 = .83$, than performance on compatible trials (accuracy: incompatible, $M = .65$, $SD = .08$; compatible, $M = .83$, $SD = .05$; RT: incompatible, $M = 397.38$ ms, $SD = 39.68$; compatible, $M = 351.77$ ms, $SD = 33.47$). There was no main effect of span for either RT or accuracy rate, nor was there a Compatibility × Span interaction.

Time-Course Analyses

As in Experiment 1, 10 Vincentized *n*tile bins were computed separately for compatible and incompatible trials, for each participant. Also, performance was not significantly different from chance at Latency Bin 1, and asymptotic performance was not different between compatible and incompatible trials.

Compatible trials. Compatible CAFs are depicted in Figure 5. A 2 (span) × 10 (bin) repeated measures ANOVA yielded no main effects or interactions in the latencies of the 10 *n*tile bins, nor were there any apparent effects involving span in the accuracy rates of the CAFs. As is evident, the data in Figure 5 are much cleaner than that in Experiment 1 and confirm our prediction that no span differences should emerge on compatible trials.

Incompatible trials. Incompatible CAFs are depicted in Figure 6. Again, a 2 (span) × 10 (bin) repeated measures ANOVA indicated no main effects or interactions regarding span in the latency bin mean RTs. Asymptotic levels of performance were not different between the two groups, indicating that given sufficient time, both groups can focus attention to the same extent. Both groups showed a significant dip below chance, confirming that attentional constraint indeed occurred; in the low span group, participants performed below chance at Bin 2, $t(18) = -2.36$, $p < .05$; in the high span group, participants performed below chance at Bin 4, $t(19) = -2.97$, $p < .01$.

We again evaluated the rate model in two ways: a test for trend component interactions and sequential *t* tests to find the point at which participants reached asymptotic performance. For the trend test, we considered Bins 4–10. The Span × Bin interaction was significant, $F(4.25, 157.22) = 2.54$, $p < .05$, partial $\eta^2 = .06$, with Greenhouse–Geisser correction for violation of sphericity. The Span × Bin quadratic interaction was also significant, $F(1, 37) = 11.80$, $p < .01$, partial $\eta^2 = .24$. Our sequential paired *t* tests also confirmed what is evident in Figure 6. For the low span group, peak performance was not attained until Bin 9 (Bin 8 vs. Bin 10 significant), $t(18) = -2.62$, $p < .025$. For the high span group, peak performance was reached at Bin 8 (Bin 7 vs. Bin 10 significant), $t(19) = -2.80$, $p < .017$.

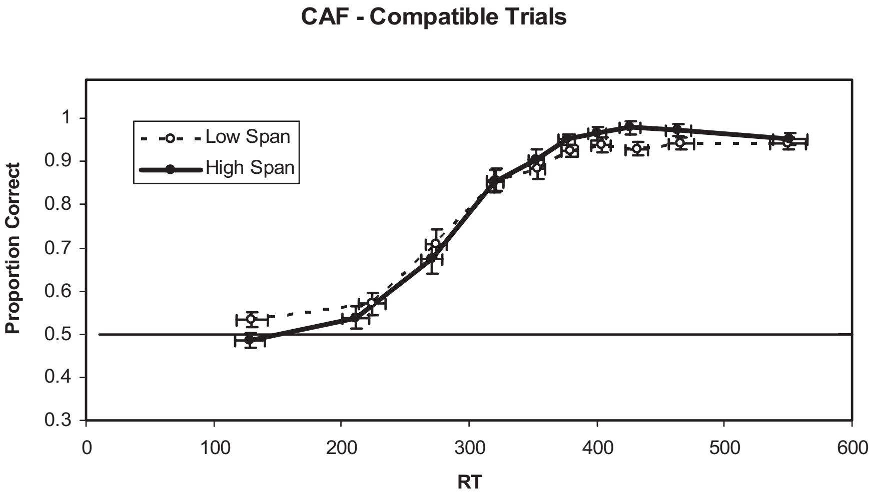

Figure 5. Conditional accuracy functions (CAFs) for compatible trials in Experiment 2. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

Discussion

The data presented in Experiment 2, like Experiment 1, suggest that participants focus attention over time, continually eliminating the influence of peripheral distractor items. The dip below chance performance indicates that when participants base their responses on the entire array but have not yet constrained attention, more information exists in favor of the opposite response—hence, below chance performance. The fact that both groups reach the same asymptotic levels of performance indicates that the lower limit of attentional constraint is not different between participants with high and low control ability.

However, participants with high WM spans again approached asymptotic performance before participants with low WM spans did. We interpret this in terms of our RAC model—participants with high WM spans can constrain attention more quickly than can participants with low WM spans. Yet, there is one potential problem with the data from Experiments 1 and 2, and this concerns the possibility of a ceiling effect. Both groups have quite high accuracy at long latencies (approximately .95). This ceiling effect could make it appear that asymptotic performance is equivalent between the two groups and that participants with high WM spans approach this point more quickly. Experiment 3 was conducted to control for this possibility. In Experiment 3, we degraded the flanker stimuli to reduce peak performance. If the rate differences in Experiments 1 and 2 were due to ceiling effects, then reducing discriminability should cause asymptotic accuracy to differ between the high and low span groups.

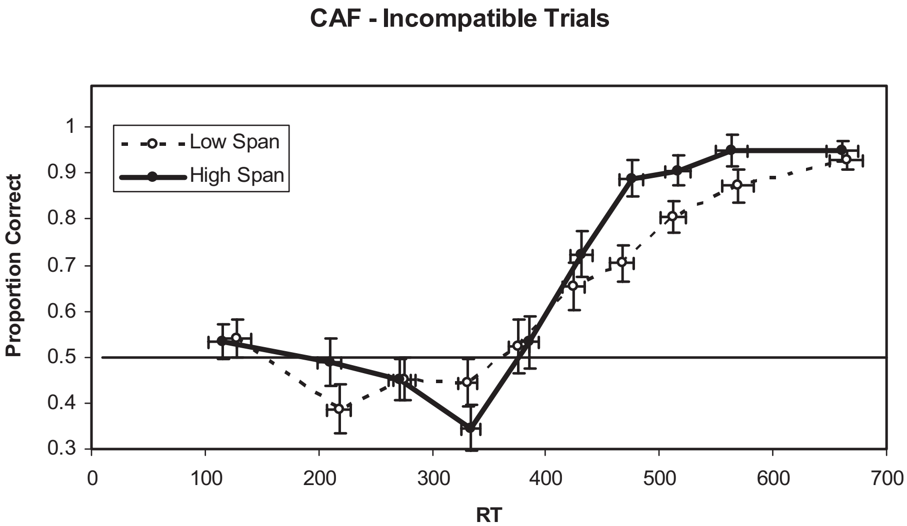

Figure 6. Conditional accuracy functions (CAFs) for incompatible trials in Experiment 2. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

Experiment 3

Two main changes were implemented in Experiment 3 to (a) obtain more stable data and (b) attenuate the ceiling effect. To obtain more stable data, we classified participants with high and low WM spans on the basis of a stringent *z*-score composite based on three WM measures. To attenuate the ceiling effect, we reduced the contrast of the flanker arrays.

Method

Participants

Participants were prescreened with the automated version of the operation span task (Unsworth, Heitz, Schrock, & Engle, 2005) as well as the automated symmetry span task (adapted from Kane et al., 2004) and automated reading span task (adapted from Daneman & Carpenter, 1980). The automated operation span task is similar to the Turner and Engle (1989) operation span task but includes single letters instead of words and set sizes of three through seven. Furthermore, the experiment is completely computer driven. Participants view single letters (presented for 800 ms each) presented after arithmetic strings. Each arithmetic string is followed by the words *True* and *False*; participants must click one of these to indicate the veracity of the prior string. After each string–letter sequence is presented, participants view a 3 × 3 matrix of letters. Participants must click the letters in the same order in which they were presented. Feedback is provided in the form of "you recalled *x* out of *y* letters correctly." The score is computed as the total number of letters correct in the correct order. The automated operation span task has been shown to have excellent test–retest reliability and validity, correlates well with traditional WM measures including the original operation span task, and loads with other WM tasks in a factor analysis (Unsworth et al., 2005). The automatic reading span task was virtually identical to the automatic operation span task, except that participants verified sentences as meaningful or not meaningful instead of solving operations (see Unsworth et al., 2005, for a detailed review of the automatic operations span task and Kane et al., 2004, for a detailed review of symmetry span).

Participants were selected on the basis of upper and lower quartiles derived from a *z*-score distribution of three tasks—automated operation span, symmetry span, and reading span. These three tasks are part of a screening procedure that is constantly ongoing in our lab. Participants who are prescreened consist of Georgia Tech undergraduates and community volunteers. From this prescreening distribution, 20 participants with low WM spans and 20 participants with high WM spans were selected. All participants had normal or corrected-to-normal vision as rated by Snellen chart. Participants received pay or course credit as compensation. Three participants with low WM spans were dropped because of technical difficulties.

Flanker Task

The flanker task was identical to that used in Experiment 1 (50/50), with one exception. The stimuli in Experiment 3 were degraded by reducing the contrast of the stimuli. This was accomplished by presenting the flanker arrays near to perceptual threshold. Pilot testing revealed that using an RGB value of 12 (red: 12; green: 12; blue: 12) in E-Prime Version 1.1 would accomplish this. To perform adequately, participants would need to expend attentional resources to enhance the perceived contrast of the stimuli (Lu & Dosher, 1998).

Participants were also required to use a chin rest in Experiment 3, holding viewing distance at 76 cm. As in Experiments 1 and 2, the flanker arrays subtended 2.5° of visual angle.

Results

The stimulus degradation manipulation successfully decreased asymptotic accuracy (.91). Although the drop in performance was small, this left enough room for differences in asymptotic accuracy to emerge. As shown below, this did not occur; Participants with high and low WM spans again reached the same level of peak performance, and at different rates.

General Analyses

Overall, performance on incompatible trials was slower, $F(1, 35) = 29.50$, $p < .001$, partial $\eta^2 = .46$, and less accurate, $F(1, 35) = 249.38$, $p < .001$, partial $\eta^2 = .88$, than performance on compatible trials (accuracy: incompatible, $M = .62$, $SD = .07$; compatible, $M = .73$, $SD = .07$; RT: incompatible, $M = 402.96$ ms, $SD = 49.25$; compatible, $M = 386.69$ ms, $SD = 46.24$). There were no interactions regarding WM span, although there was a main effect of span in accuracy rate, $F(1, 35) = 7.30$, $p < .05$, partial $\eta^2 = .17$, indicating that participants with high WM spans were, on average, more accurate than participants with low WM spans.

Time-Course Analyses

As before, 10 Vincentized *n*tile bins were computed separately for compatible and incompatible trials, for each participant. Performance was not significantly different from chance at Latency Bin 1, nor was asymptotic accuracy different between compatible and incompatible trials.

Compatible trials. The CAFs for compatible trials are depicted in Figure 7. We first tested the mean latencies of the *n*tile bins. A 2 (span) × 10 (bin) repeated measures ANOVA showed that unlike in Experiments 1 and 2, there was a Span × Bin interaction, $F(2.67, 93.40) = 5.10$, $p < .01$, partial $\eta^2 = .13$, with Greenhouse–Geisser correction for violation of sphericity. Because span interacted with bin, an ANOVA is inappropriate in testing the CAFs. For this reason, we had to resort to a nonparametric test. Figure 7 shows that participants with high and low WM spans performed equivalently, with the exception of one aberrant mean (Bin 7). To test this, we performed the Mann–Whitney *U* test, which is among the most powerful nonparametric tests for independent samples (Siegel, 1956). We performed the test twice—once using the entire set of accuracy rates and once excluding accuracy rates occurring between 425 ms and 475 ms. If these curves are not significantly different except for the one aberrant mean, then Test 1 should be significant and Test 2 nonsignificant. This was in fact the case. For the first test including all the data, the difference between participants with high WM spans and participants with low WM spans was significant ($U = 110$, $p = .069$). For the second test excluding the time points when

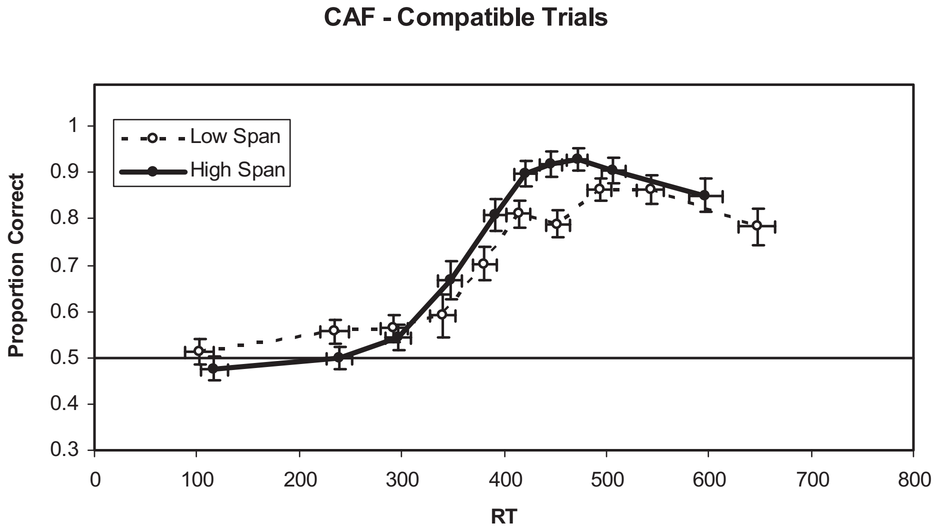

Figure 7. Conditional accuracy functions (CAFs) for compatible trials in Experiment 3. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

the aberrant mean fell, the difference was nonsignificant ($U = 127.5$, $p = .20$). Hence, it is tenable that participants with low and high WM spans performed equivalently on compatible trials, excluding the one outlying mean. However, this is speculative, and we must admit the possibility that the groups do in fact differ on compatible trials in this experiment; in particular, it appears that asymptotic levels of accuracy are different between the two groups.

Incompatible trials. The incompatible CAFs are depicted in Figure 8. The pattern is quite straightforward: Both groups performed significantly below chance at Bin 4, the asymptotic performance was equivalent between the two groups, and the rate of approach to asymptote was slower for participants with low WM spans than for participants with high WM spans. Indeed, the dip below chance was significant at Bin 4 for both groups: low span group, $t(16) = -2.75$, $p < .025$; high span group, $t(19) = -2.04$, $p = .055$. Also, asymptotic performance was not significantly different between the two groups, nor was asymptotic performance different between compatible and incompatible trials.

The latency bin means were first submitted to a 2 (span) × 10 (bin) repeated measures ANOVA. Although there was no main effect of span, the Span × Bin interaction did attain significance, $F(2.70, 94.32) = 3.91$, $p < .025$, partial $\eta^2 = .10$, with Greenhouse–Geisser correction for violation of sphericity. Hence, use of ANOVA is inappropriate. We instead focus on the sequential paired *t* tests used in Experiments 1 and 2. As Figure 8 makes

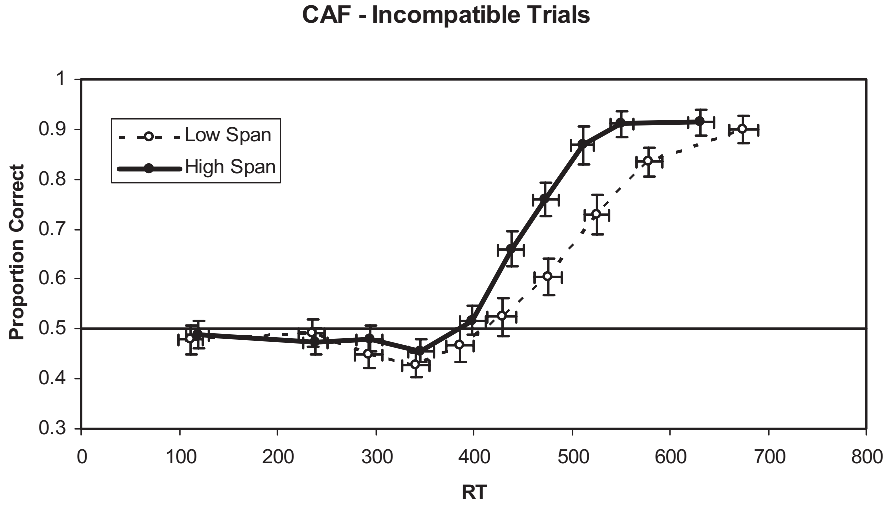

Figure 8. Conditional accuracy functions (CAFs) for incompatible trials in Experiment 3. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

clear, participants with high WM spans approached peak performance before participants with low WM spans: Participants with high WM spans reached peak performance at Bin 8 (Bin 7 vs. Bin 10 significant), $t(19) = -4.84$, $p < .001$, and participants with low WM spans reached peak performance at Bin 10 (Bin 9 vs. Bin 10 significant), $t(16) = -2.87$, $p < .025$. (We note that had we disregarded the span differences in *n*tile latency and performed the ANOVA anyway, we would still obtain a Span × Bin interaction, $F[4.45, 155.67] = 2.39$, $p < .05$, partial $\eta^2 = .06$, and a Span × Bin quadratic component, $F[1, 35] = 8.95$, $p < .01$, partial $\eta^2 = .20$.)

Discussion

Experiment 3 attempted to eliminate alternative explanations based on ceiling effects in Experiments 1 and 2. Although the drop in asymptotic performance in Experiment 3 was modest, it is evident that the manipulation did decrease scores. The fact that the decrease was equivalent for participants with low and high WM spans indicates that the previous results are not due solely to a ceiling effect. Had this been true, then only the performance of participants with low WM spans should have dropped, leading to differences in asymptotic accuracy.

For the third time, participants with low and high WM spans were found to approach the same level of asymptotic performance, but at different rates. Once again, we take this as support for our RAC model, which states that individual differences in controlled attention can manifest in focusing visual attention. Specifically, the rate at which attention is focused is dependent on executive control. Participants who are deficient in executive control are slower to constrain attention; although given sufficient time, all participants are able to constrain to the same extent.

Note also the regularity of the incompatible trial data in this experiment. In Experiments 1 and 2, it remained a possibility that participants with high and low WM spans differ in intercept—the point at which participants begin to depart from chance-level performance. If this was indeed the case, then one could argue that participants with low WM spans require more time before any meaningful information is accumulated. This would be problematic because what appear to be differences in rate can emerge through changes in intercept. Experiment 3 argues against this explanation. Here, participants from both span groups performed significantly below chance at the same latency and began to perform above chance at the same point. Hence, the two groups do not need different amounts of time before accumulating meaningful information. The difference is in how quickly they can eliminate the influence of distractor letters.

The arguments furthered here rest on a critical assumption—that participants actually do focus attention over time during a trial. We have a number of reasons for asserting this. For example, the dip below chance reported here (and in Gratton et al., 1988) is predicted by a variable spotlight model in which responses are based on a process of continuous flow (C. W. Eriksen & Schultz, 1979). At any given time point, one's response is determined by the amount of information accumulated thus far. Early in a trial, once responses are based on meaningful information (i.e., just beyond chance-level guessing), the spotlight of attention encompasses the entire flanker array. On incompatible trials, there is more information in favor of the opposite response. Over time, as the spotlight constrains, accuracy continually rises. Given sufficient time, compatible and incompatible accuracy is virtually identical.

However, one might make the argument that some peripheral variable leads to span differences in the Eriksen flanker task. In other words, perhaps there is something about incompatible flanker arrays per se that leads to span differences. For example, perhaps participants with low WM spans have more difficulty picking out the target location unless provided with sufficient processing time. This might lead to increased sampling from outside letters, increasing error rates. Compatible trials would not suffer from this because it doesn't matter which location is sampled (all letters are the same). We refer to this as the *sampling* hypothesis. Although this would not explain all aspects of the data reported here (i.e., the dip below chance performance), we decided it worthy of test.

One other alternative argument concerns susceptibility to interference. It has been suggested that participants with low WM spans are more susceptible to interference; conditions that create interference, in conflicting goals, response tendencies, and so on, often lead to decrements in the performance of participants with low WM spans as compared with the performance of participants with high WM spans (Bunting, Conway, & Heitz, 2004; Redick, Heitz, & Engle, in press, for a review). In the flanker task, response-incompatible letters give rise to much interference. Specifically, it is known that information accumulated from the flanker displays continuously primes response channels (Coles et al., 1985; Gratton et al., 1988). When response-incompatible information is encountered, response conflict emerges. Perhaps it is the case that participants with low WM spans are more susceptible to such conflict, and this in some way leads to the differing CAFs reported here. We refer to this as the *conflict* hypothesis.

Finally, we wish to address an inhibitory view. Hasher and Zacks (1988) proposed the view that what differs between individuals high and low in WM, or between older and younger adults, is an inhibitory mechanism. When this inhibitory mechanism fails, participants are confronted with a variety of competing information. To the extent that distracting information can be inhibited, performance will increase. In other words, it might be the case that participants with low WM spans simply have trouble inhibiting distracting letters. That is, perhaps the span differences we observed are not due to differences in constraining visual attention but rather are due to one's ability to inhibit irrelevant items. If this is true, then we should observe span differences in a task that consists of incompatible trials but does not require attentional constraint. We refer to this as the *inhibition* hypothesis.

To test these alternatives, we presented participants with blocks of incompatible-only trials. No compatible trials were included. In such a situation, there is no need to constrain attention, as responses can be based on the entire array. For example, in the string *HHSHH*, the outer letters determine the identity of the target letter; it is always the opposite of the outside letters. In some sense, participants institute a "code flip," whereby outer letters become compatibly mapped. Participants can, and should, perform such trials with a diffuse attentional allocation (participants' subjective reports confirmed this). And, as noted earlier, attention is automatically drawn to the extent of the entire array; hence, participants cannot simply focus on a single peripheral letter.

If the span differences observed in Experiments 1–3 are due to sampling differences, participants with low WM spans should still be at a relative disadvantage compared with those with high WM spans, as on occasion they will sample from inappropriate locations, regardless of a code flip. Likewise, because response conflict will always be present in the task (the central letter becomes response incompatible), the conflict hypothesis also predicts span differences. Given previous research, any incompatibly mapped letter will prime response channels (Gratton et al., 1988). Finally, because participants need to inhibit the now-incompatible central letter, the inhibition hypothesis similarly predicts span differences. Participants that cannot reduce the influence of this location will perform less well. However, if differential performance on incompatible trials requires active attention constraint, no span differences should emerge, having eliminated the need for such action.

Experiment 4

Method

Participants

Participants were sampled from the same pool as in Experiments 1 and 2 and were classified as having low or high WM spans on the basis of the criteria used in Experiments 1 and 2. A total of 15 participants with low WM spans and 15 participants with high WM spans participated for pay or course credit. Five participants with low WM spans and 2 participants with high WM spans were dropped because of failure to complete the task.

Flanker Task

The flanker task was identical to that used in Experiment 1 (50/50), except that all 60 experimental trials in a block were incompatible.

Results

General Analyses

There were no main effects of span with regard to accuracy rate or RT. For participants with high WM spans, mean accuracy was .79 (*SD* = .04), and mean RT was 381.88 ms (*SD* = 23.69); for participants with low WM spans, mean accuracy was .77 (*SD* = .05), and mean RT was 395.71 ms (*SD* = 19.19).

Time-Course Analyses

The CAFs for Experiment 4 are presented in Figure 9. There was no significant dip below chance in these data, which is consistent with our argument that participants were not constraining attention in this task. The latencies of the *n*tile bins were first submitted to a 2 (span) × 10 (bin) repeated measures ANOVA. No span effects reached significance. We next tested the CAFs. Again, no main effects or interactions including span attained significance. However, it is possible that the data presented in Figure 9 consist of a mixture of participants who instituted a code flip and others who did not. This stems from the fact that there is a small, yet nonsignificant, dip below chance. If participants instituted a code flip, there should be no dip below chance, as most information in the arrays leads to the correct response. For those other participants, however, the initial information leads to the incorrect response. To deal with this, we plotted CAFs for each individual participant. The dip below chance is robust enough to detect on a participant-level basis. It was clear that some participants did indeed show this dip, and they were eliminated (2 participants with low WM spans, 3 participants with high WM spans). This abolished the trend toward a "Gratton dip," and after rerunning the analyses, we rested with the same conclusion. Namely, no span differences emerge when the need to constrain attention is eliminated.

Discussion

Unlike Experiments 1–3, which used both compatible and incompatible trials, there were no span effects in Experiment 4, which included only incompatible trials. This suggests to us that the span effects previously observed were not due to differences in sampling, susceptibility to response conflict, or differences in the

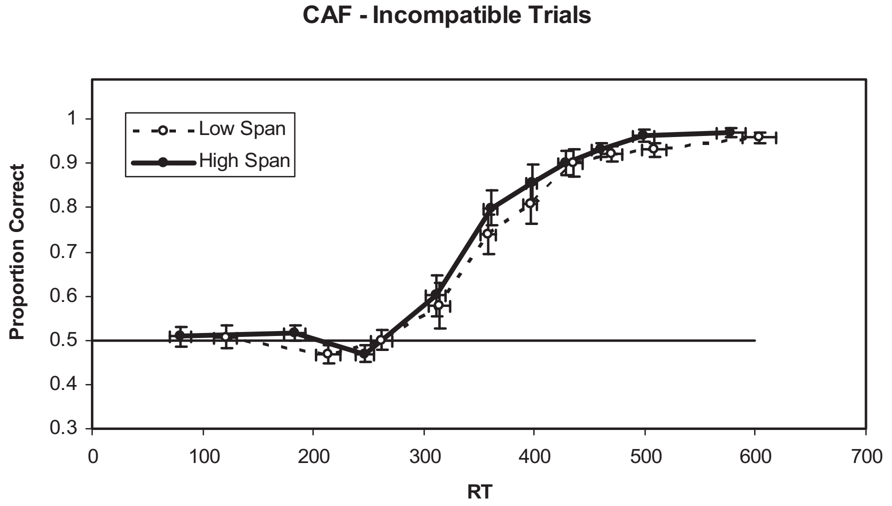

Figure 9. Conditional accuracy functions (CAFs) for incompatible trials in Experiment 4. Vertical and horizontal error bars represent ±1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively.

ability to inhibit distractor letters. Only when the active constraint of visual attention is needed do span effects appear.

General Discussion

In the four experiments above, we have shown that individuals low in attention control ability focus their visual attention at a slower rate than do individuals high in attention control ability. We first briefly review the evidence for this claim. The time-course functions presented here and elsewhere (e.g., Gratton et al., 1988) are consistent with a spotlight of attention that gradually focuses on a target element, reducing the influence of peripheral distractors. This pattern of data consisted of four main components: (a) chance accuracy at very fast latencies, (b) below-chance performance for incompatible trials at fast latencies, (c) gradually increasing performance for compatible and incompatible arrays, and finally, (d) asymptotic accuracy rates that were not significantly different between compatible and incompatible trials. Again, the time-course functions (i.e., CAFs) indicate the extent of attention constraint at given latencies. At very fast latencies (corresponding to Bin 1), accuracy rate is at chance because participants are guessing—thus responses are not based on any useful information. Given a bit more time, participants begin to accumulate useful information. At this point, attention has been exogenously drawn to the entire flanker array. For this reason, incompatible trials fall below chance, whereas compatible trials begin a fast, monotonic rise toward asymptotic levels. As response latencies become longer, participants have more time to focus attention on the central target letter, attenuating the influence of response-incompatible distractors on incompatible trials. Finally, at the longest latencies, attention has focused to such an extent that response-incompatible letters have no detrimental effect. Therefore, accuracy rates are not different for compatible and incompatible trials at the longest latencies.

On the basis of our review of the literature, we had reason to believe that participants with low WM spans would exhibit sluggish attentional focusing as compared with participants with high WM spans. Because we were predicting differences in the rate of focusing and not in some other component such as the lower limit of attentional constraint, we expected differences to emerge in how quickly the time-course functions approached asymptotic performance, but not asymptotic performance per se. This is exactly what we observed. The CAFs derived in Experiments 1 and 2 indicated differences in performance at intermediate time points, with participants with high WM spans reaching asymptotic performance before participants with low WM spans. In Experiment 3, we attenuated the ceiling effect apparent in Experiments 1 and 2 and rested with the same conclusion. In Experiment 4, we eliminated the need to actively focus attention and did not observe any span differences.

A Rate Model of Individual Differences in Executive Control

In a larger perspective, we concluded that executive control predicts the rate at which one focuses attention. This view is applicable in a wide variety of research domains. WM, and executive control in general, has recently seen application in such diverse disciplines as clinical, social, neuropsychological, and cognitive psychology. And, much of this work has made clear that one of the most important consequences of decreased executive control (or *dysexecutive syndrome*, as some have called it) is an inability to filter potentially distracting sources of information. WM capacity has been shown to be related to the ability to filter intrusive thoughts (Klein & Boals, 2001), stereotype threat (Schmader & Johns, 2003), and thoughts of a white bear in that self-titled phenomenon (Brewin & Beaton, 2002). WM capacity is also related to suppression of first-list items in a paired-associates task and already-recalled items in a category fluency task (Rosen & Engle, 1997, 1998, respectively). Also, individuals with schizophrenia or prefrontal cortex lesions tend to produce very specific errors on tasks such as the Wisconsin Card Sort (Kane & Engle, 2002). Specifically, they show perseveration of a previous task set once the sorting rules have been changed. It is as if the previously learned associations are not filtered and become distractors during learning of the new task set. In still other fields, some have suggested that depression reduces WM by acting as a cognitive load, perhaps by increasing rumination due to intrusion of negative thoughts (Hester & Garavan, 2005). This is in addition to a plethora of other data from this and associated labs showing that people with low WM spans are more susceptible to potentially distracting information (e.g., Conway, Cowan, & Bunting, 2001).

However, to say that these individuals have an inability to filter distracting information is somewhat nondescript. On the one hand, we know that there is something common in the deficits suffered by all of these subject populations. On the other hand, we do not know the specific nature of the deficit. Specifically, we cannot say whether participants with low executive control ability cannot filter information or whether it simply takes them longer. Resolution of this issue has clear implications for how we discuss executive control. For instance, consider why participants with low WM spans and older adults perform less well in the antisaccade task mentioned previously (Unsworth et al., 2004). Is it that participants with low WM spans cannot disengage attention from the prepotent, flashing cue and move their eyes in the opposite direction, or is the deficit something more detailed? The present work suggests that all participants are reflexively drawn to the exogenous cue, but those with deficits in executive control require more time to refocus attention on the correct location. The present methodology allows such a speculation to be empirically verified using time-course analysis.

We might similarly reevaluate span differences in the Stroop task. Kane and Engle (2003) showed that in a high-incongruency block of Stroop trials, participants with low WM spans are slower to react to incongruent stimuli than are participants with high WM spans. If we examine the Stroop task, it becomes clear that on incongruent trials, attention is prepotently focused on the word stimuli. To respond correctly, participants must somehow unfocus attention on the word and refocus on the color. The fact that participants with low WM spans were shown to be slower to do so is another example of a rate conception of attention control.

We might also speculate how a rate model might explain memory performance in a WM task. In a WM task (see the *Method* section of Experiment 1), participants maintain information while performing an unrelated, distracting task. One possibility is that the unrelated task disrupts rehearsal mechanisms. To counteract this, attention must be switched back and forth between the information to be maintained and the distracting task. Such a view of

WM is not novel and is often referred to as the *task-switching* model (Towse & Hitch, 1995). We argue that participants with both high and low WM spans can, and do, switch attention back and forth. However, because participants with high WM spans are faster to do so, they experience more repetitions and likely stronger memory traces at recall.

Other conceptions of WM highlight a malleable focus of attention in much more abstract terms. In Cowan's (2001) theory, the focus of attention is the component of the WM system that maintains online access to a limited set of information. Items within the focus of attention may be said to be within the span of consciousness. Recently, Cowan (2005) suggested that this focus of attention may be flexible: "Attention can *zoom in* to hold onto a goal despite the presence of interference but it can also *zoom out* to apprehend up to about 4 separate chunks of information at once in the absence of interference" (p. 482). We find this view intriguing, particularly because it is far removed from the domain of visual attention. Our rate model predicts that participants with high and low WM spans differ in how fast they can adjust the size of the focus of attention.

Inhibition

Although we argued against a general inhibition view in Experiment 4, the data presented here cannot dissociate a constraining field of activation from a spreading field of inhibition. Essentially, both views make identical predictions, so long as the group differences reflect the rate of resizing the attentional field. Both a constraining spotlight and spreading inhibition would predict below-chance performance at fast latencies on incompatible trials and steadily increasing accuracies thereafter. However, much research has shown that the spotlight of attention is best described as a field of activation. For example, consider work by Castiello and Umiltá (1990) and C. W. Eriksen and St. James (1986). This work shows that the efficiency of processing is directly related to the size of the attended region; faster processing ensues with smaller allocations, and processing tends to slow down as larger regions are attended. How might an inhibitory mechanism accommodate these findings? Consider the Castiello and Umiltá (1990) study. Participants performed simple RT tasks to the onset of a target dot, having been previously cued with a large or small box. Detection responses were faster with small-box cues and slower with large-box cues. An inhibitory view would have to assume that with a small-box cue, more of the visual field is inhibited, and with a large-box cue, less of the peripheral visual field is inhibited. However, in such a paradigm, there are no peripheral distractors to inhibit. Thus, it is unclear why inhibiting peripheral areas should facilitate detection. The data do support a variable spotlight of activation, in which smaller cued regions benefit from a higher density of resources. Still, one may argue that inhibiting more of the visual field (i.e., small-box cue) would reduce uncertainty of the target location and speed detection responses.

Perhaps an inhibitory view is inappropriate for such impoverished displays. After all, it is possible that inhibition is only necessary when there exists distracting peripheral information (Dosher & Lu, 2000), such as in the flanker arrays presented here. However, given the long history of research showing that changes in the size of attended regions directly affect the efficiency of processing (Castiello & Umiltá, 1990; C. W. Eriksen & St. James, 1986; C. W. Eriksen & Yeh, 1985), it is more likely that inhibition and activation coexist. We cannot discount such a view; future research should address this. Even if a spreading inhibition account is correct, our general conclusion does not change—namely, that differences in attention control ability manifest as changes in the rate of resizing visual attention, regardless of the role visual attention is playing.

Relation to Lavie's (1995) Perceptual Load Theory

Lavie (1995; Lavie et al., 2004) has proposed an influential theory of selective attention—one that appears to reconcile the early–late selection debate. According to the theory, when perceptual load is high, less capacity remains left over to process peripheral distractors. When perceptual load is low, spare capacity is obligatorily allocated to all areas of the visual field. Hence, when response-incompatible distractors are presented in the periphery, they should slow responding only to the extent that attentional capacity spills over into that area. Under high perceptual load, flanker effects are attenuated, indicating that attention was focused to the central task; under low perceptual load, flanker effects emerge. This finding has firm empirical support from behavioral studies (Lavie, 1995) as well as neuroimaging (Rees et al., 1997) and electrophysiological recordings (Handy et al., 2001).

An extension of Lavie's (1995) theory (Lavie et al., 2004; see also Lavie & DeFockert, 2005) stresses the importance of WM. Accordingly, under conditions of low perceptual load, when irrelevant distractors are not filtered, WM must be used to deal with the conflict arising from the incompatible information, now processed. Conversely, WM is unimportant under high perceptual load, as attention has focused to the relevant items; thus there is nothing for WM to suppress.

Our view is consistent with Lavie's (1995; Lavie et al., 2004) theory, although Lavie has not directly addressed the time course of attentional focusing. One interesting prediction might be that at early points in a trial, flanker interference is always observed, regardless of perceptual load. Then, if the perceptual load is high, participants should begin to focus attention; this might be reflected in a CAF derived from such a data set. If the perceptual load is low, perhaps no focusing operation occurs. Our data cannot address such a question, as perceptual load was held constant. Another interesting prediction is in regard to the influence of WM during low perceptual load. It is likely that WM capacity comes into play comparatively late in a trial. Thus, a time-course function might show increasing flanker interference early in a trial, followed by a decrease in flanker interference as time progresses and WM comes into play. This would be consistent with work by Botvinick, Braver, Barch, Carter, and Cohen (2001), who implicated the anterior cingulate cortex for conflict detection and the recruiting of control from the prefrontal cortex.

There is at least one point on which our view differs from that of Lavie. In Lavie's (1995; Lavie et al., 2004) theory, participants cannot prevent the processing of irrelevant peripheral items under low perceptual load. We have argued, however, that the focusing of visual attention is a capacity-demanding activity and thus must be to some extent under conscious control. We cannot at this point reconcile this discrepancy, but it is likely that future research will be illuminating.

Speed of Processing

One alternative to the model presented here is the idea that people with high WM spans simply process information faster than do people with low WM spans. This might in some way give rise to the differences in CAFs we observed here. There are aspects of our data that are not well accommodated by such a theory. In particular, the RT distributions were generally not significantly different for participants with low and high WM spans. And, a glance at any of our CAFs makes clear that groups are exhibiting responses at approximately the same time, although one group (the high WM span group) tended to have a higher accuracy rate. The speed-of-processing argument also predicts span differences on compatible trials—a prediction that is not supported by the current data. If people with high WM spans always process information faster, then their entire CAF should be shifted earlier in time as compared with people with low WM spans.

Finally, and probably most conclusively, are data from an unreported experiment that we conducted. It is known that the spotlight of attention cannot focus smaller than about 1° of visual angle (B. A. Eriksen & Hoffman, 1972; C. W. Eriksen, & Hoffman, 1973). In one experiment, we presented participants with very small flanker arrays—all other procedures were the same as Experiment 1. The entire array subtended 0.87° of visual angle. A single-letter control condition verified that all participants could resolve these small letters at high accuracy and that there were no span differences in resolving a single letter. The processing speed argument, in this situation, predicts span differences. If the differential CAFs are caused not by constraining attention but rather by differences in the speed of accumulating information, then the size of the arrays should not matter, particularly when it is known that all participants can indeed resolve the letters. Our view, in contrast, predicts no span differences in this case, because even if attention were focused to the maximal point, the entire array would still reside within the attended area, for both groups of participants. If visual attention cannot focus smaller than the size of our flanker arrays, participants with high WM spans will have no added benefit over participants with low WM spans, as they will not filter out incompatible information any faster. The data support our view—no span differences emerged in a task with flankers smaller than 1°, suggesting that span differences occur only when the constraint of attention can benefit the high WM span group and are not due to differences in processing speed.

Although we have argued quite emphatically for a rate model of attention control, we do not argue that our model can explain all aspects of attention performance; clearly, many findings are beyond the scope of a rate model and there exist many more detailed models, particularly of visual attention (e.g., Bundesen, 1990; Logan, 1996). This is not to say that the present data cannot be accounted for by those theories, yet they would need to be modified to more directly account for the time course of processing. For instance, in Logan's (1996) CODE theory of visual attention, items in the visual field are mapped into a CODE surface, with each item giving rise to a probability distribution representing the likelihood of sampling from that item. When these distributions overlap, features from these items are processed together, and information is separated when the distributions do not overlap. It is possible that the construction of the CODE surface follows a time course. If this is so, then it is possible that participants with high WM spans can limit their feature catch to central items on incompatible trials more quickly than can participants with low WM spans. This would lead to less processing of response-incompatible letters in the former group. Alternatively, participants with high WM spans may be able to more quickly set what Logan referred to as "pertinence values," which directly affect the selection of and categorization of items. In fact, Logan (1996) stated that "the homunculus can use [these values] to focus in on relevant items" (p. 612). Because categorizations are not instantaneous but instead follow a race model, the setting of pertinence values will affect the rate of information accumulation in the race.

The view presented here should not be considered an argument for rate as the only important factor in attention but rather as one major component, particularly for bringing about individual differences. We encourage others to examine time-course functions, with the expectation that groups can, and often do, perform equivalently at certain time points. Whether groups differ in performance on a criterion task is always informative, but knowing how, and when, these differences emerge provides a more thorough picture of mechanism and offers critical constraints on theory.

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Appendix

Conditional Accuracy Functions (CAFs)

The present work extensively uses the CAF as a measure of performance. Unfortunately, CAFs have attracted some criticism, particularly from Wood and Jennings (1976) and Wickelgren (1977). These researchers advocate use of an alternative, known as the speed–accuracy trade-off function (SATF). Here, we briefly review the difference between CAFs and SATFs. Then, we detail why the SATF is inappropriate for the present work and justify our use of the CAF. Finally, we conduct analyses circumventing potential issues. These analyses lead to the same conclusions as those in the main text.

The CAF, as mentioned in the body of this work, reveals how accuracy rate changes as a function of obtained RT. Say we obtain an accuracy rate of .80 at an RT of 550 ms. This point on the CAF implies that with 550 ms of processing time, one's accuracy rate will be exactly .80. In the present context, this value tells us something about how small the attentional field has constricted given 550 ms. However, the CAF is derived from data from a number of different conditions. Recall that we used a response deadline manipulation to widen the distribution of trials. Thus, data contributing to the .80 accuracy rate at 550-ms RT might come from the 200-, 300-, 400-, 500-, 600-, and 700-ms deadlines. For example, in the 600-ms deadline block, participants might have some trials that are very fast and inaccurate as well as comparatively slow trials with higher accuracy rates. When computing the CAF, these trials make contributions to different portions of the function—the fast trials contribute to fast latency bins and slow trials to slow latency bins. This is problematic to the extent that the deadline manipulation changes not only how long participants wait before making a response but also their response criterion.

The response criterion, or speed–accuracy setting, reflects one's momentary willingness to commit errors in favor of a faster RT, or vice versa (see Lohman, 1989). If we assume that forcing participants to be faster and faster across conditions changes this setting, then the accuracy rate at 550 ms from the 600-ms deadline is not equivalent to the accuracy rate at 550 ms from, say, the 700-ms deadline. Most likely, a 550-ms trial from the 700-ms block will contribute a higher accuracy rate than the comparable trial in the 600-ms block. Thus, any given point on a CAF, which ignores deadline condition, may consist of both high and low accuracy criterion responses (Wood & Jennings, 1976). The CAF is thought to be appropriate to the extent that it remains invariant to changes in criterion—an assumption that is readily testable. We call this the *assumption of criterion invariance*.

In contrast, the SATF plots accuracy rate against some external basis; here, this would be deadline condition. The resulting function reflects mean accuracy rate at a given deadline, presumably holding criterion constant within any one point on the function (because deadline condition is blocked). Although this method sidesteps the criterion invariance assumption inherent in the CAF, it is less meaningful for the current work. Recall that the central tenet of the present work concerns the time course of attentional focusing. That is, we are interested in how accuracy rate changes as a function of time (RT). The SATF, because it includes data from a variety of RTs, both fast and slow, precludes our ability to perform this analysis. Each point along an SATF includes fast trials with low accuracy rates and slow trials with high accuracy rates. The CAF, on the other hand, gives us a picture of performance levels at any given time point.

(*Appendix continues*)

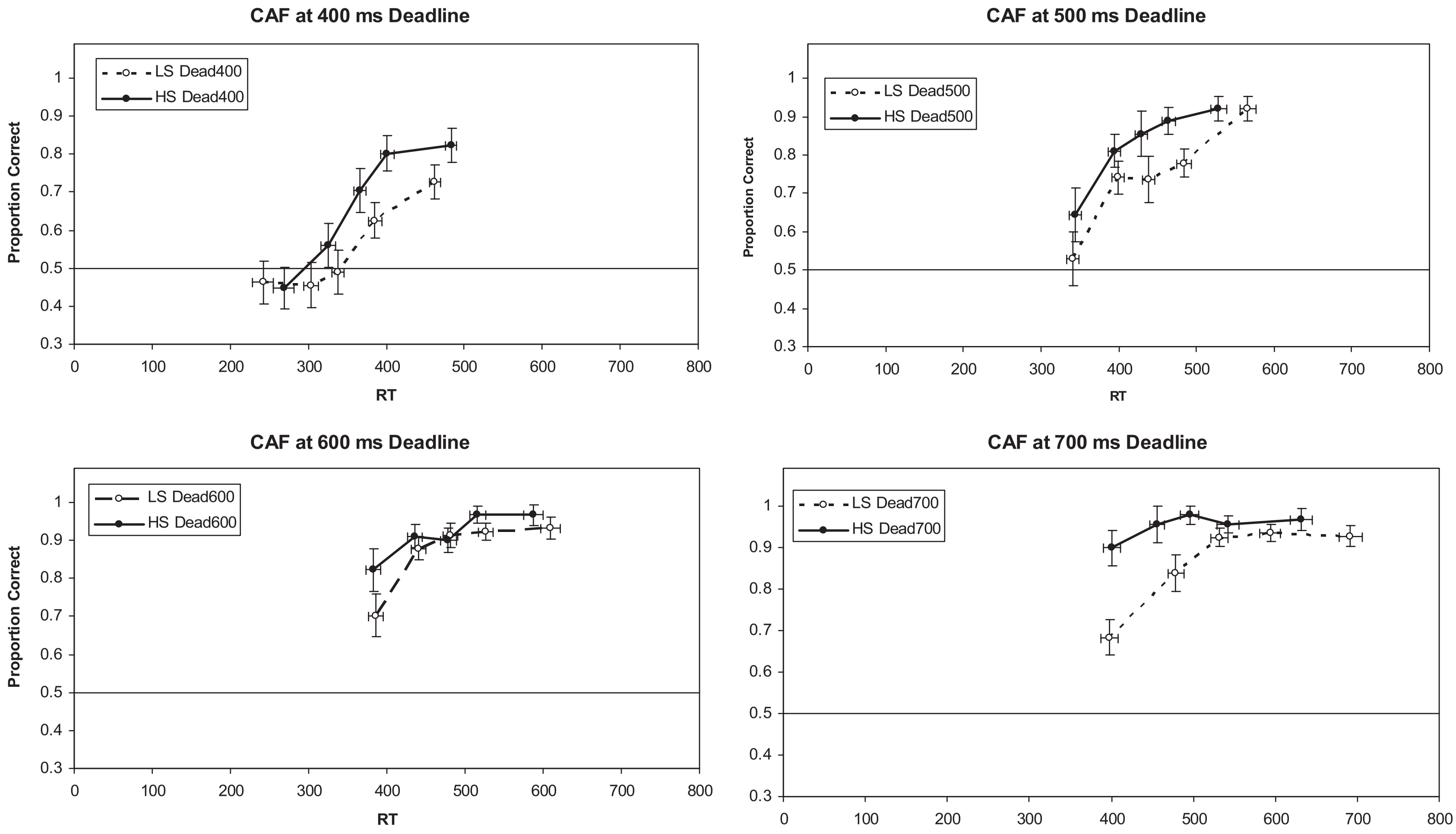

Figure A1. High and low span incompatible conditional accuracy functions (CAFs) for the 400- (upper left), 500- (upper right), 600- (bottom left), and 700- (bottom right) ms deadlines in Experiment 1. Vertical and horizontal bars represent ± 1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively. LS = participants with low working memory spans; HS = participants with high working memory spans; Dead = deadline.

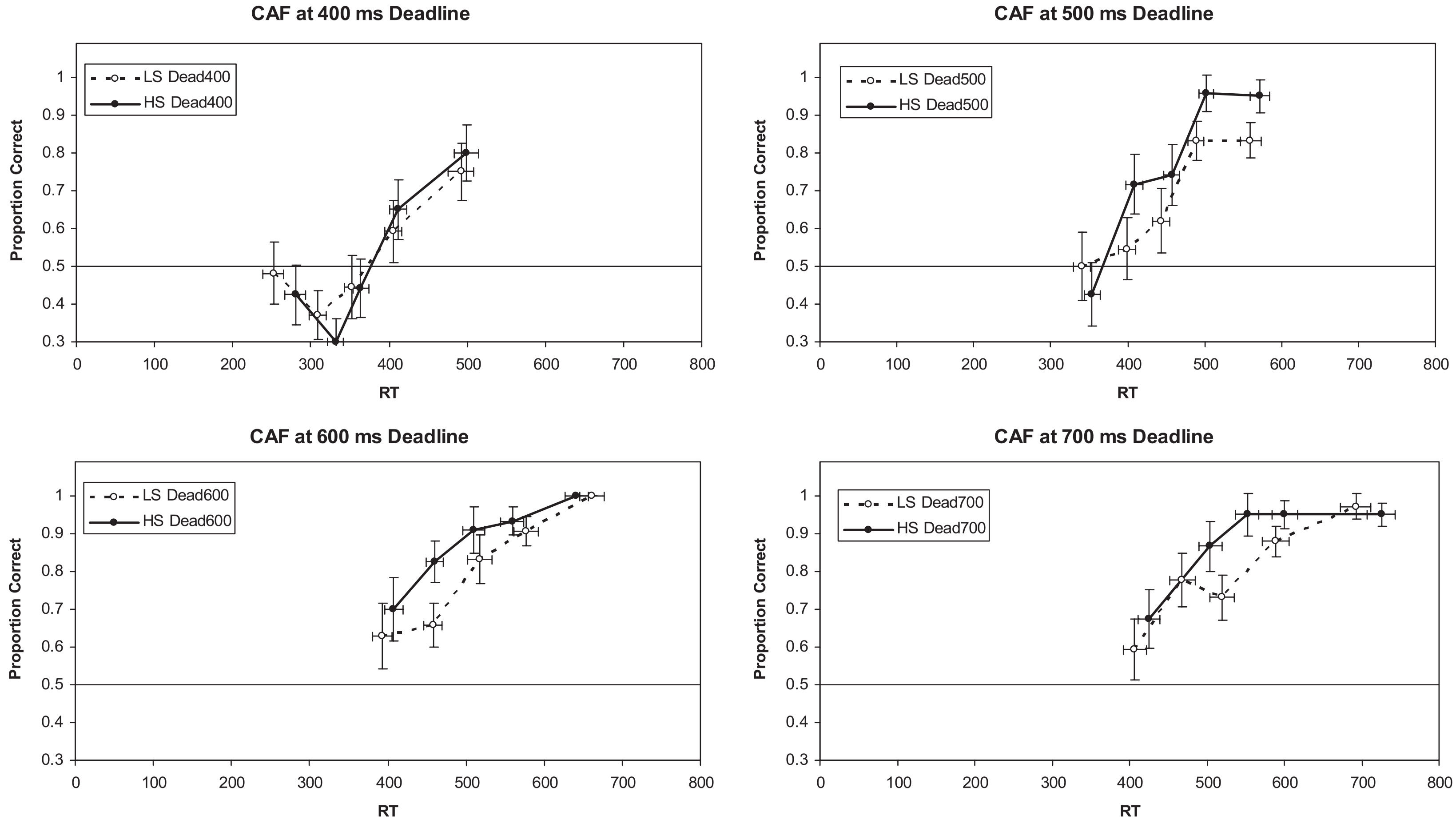

Figure A2. High and low span incompatible conditional accuracy functions (CAFs) for the 400- (upper left), 500- (upper right), 600- (bottom left) and 700- (bottom right) ms deadlines in Experiment 2. Vertical and horizontal bars represent ± 1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively. LS = participants with low working memory spans; HS = participants with high working memory spans; Dead = deadline.

(*Appendix continues*)

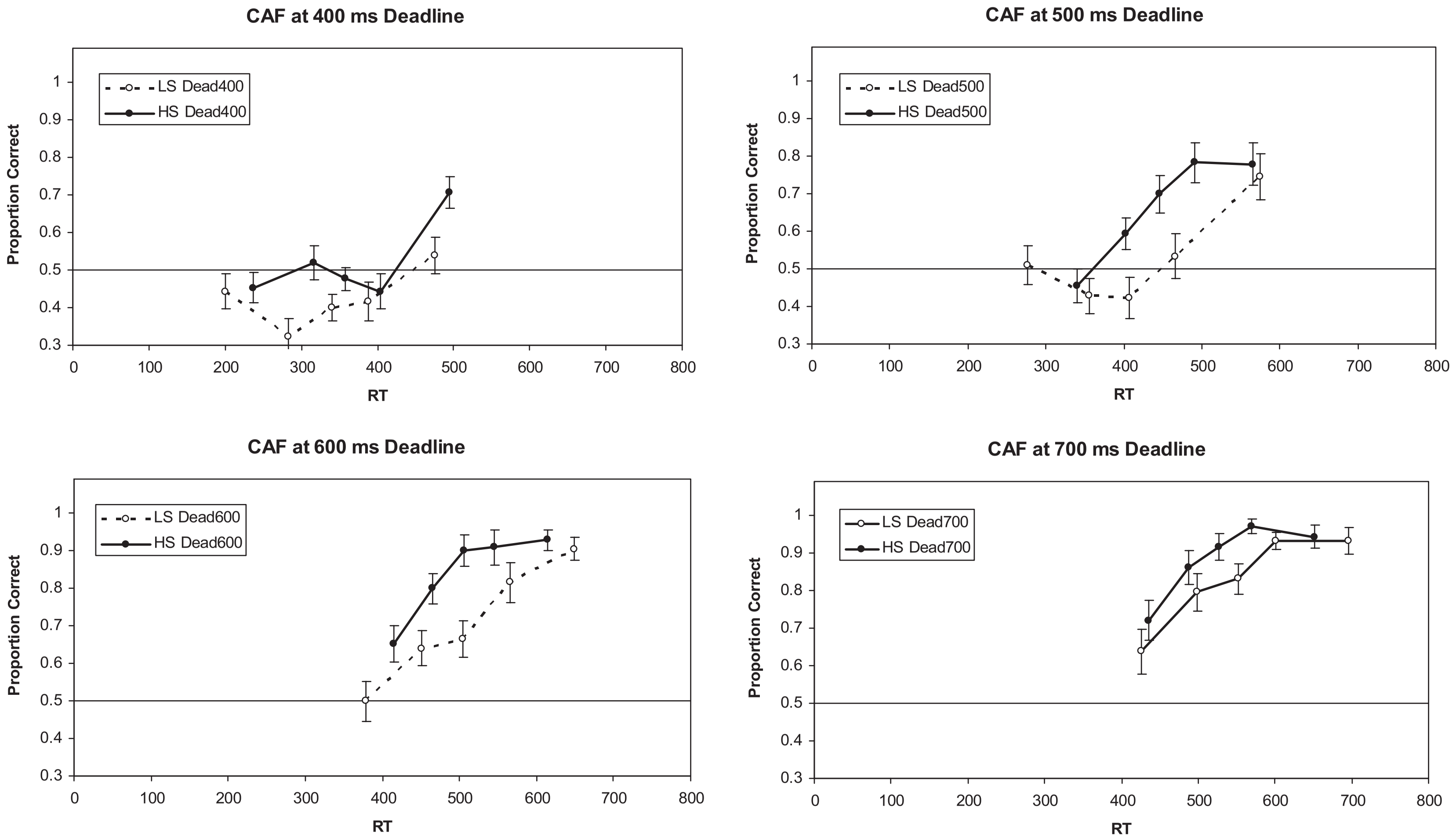

Figure A3. High and low span incompatible conditional accuracy functions (CAFs) for the 400- (upper left), 500- (upper right), 600- (bottom left) and 700- (bottom right) ms deadlines in Experiment 3. Vertical and horizontal bars represent ± 1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively. LS = participants with low working memory spans; HS = participants with high working memory spans; Dead = deadline.

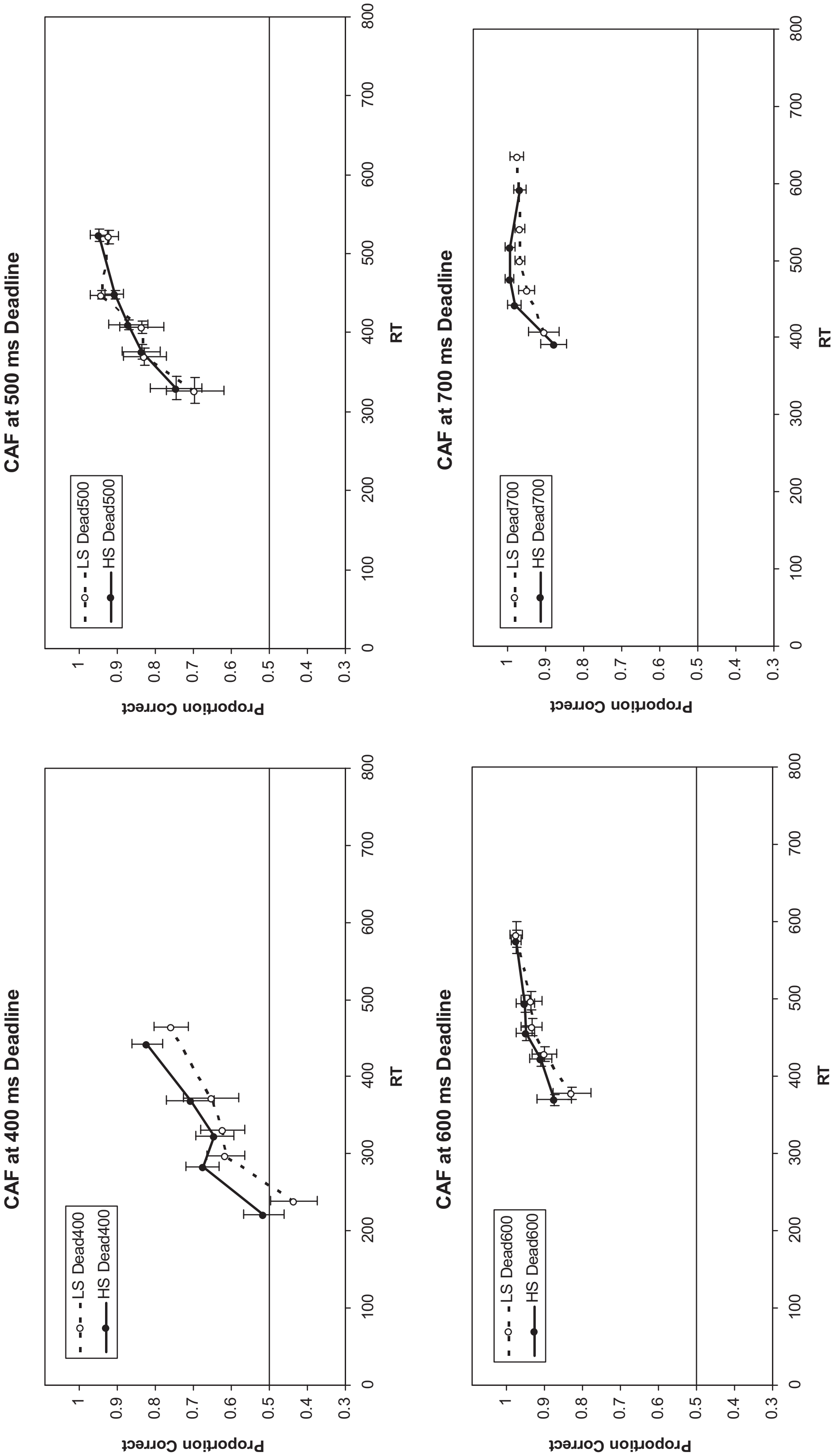

Figure A4. High and low span incompatible conditional accuracy functions (CAFs) for the 400- (upper left), 500- (upper right), 600- (bottom left), and 700- (bottom right) ms deadlines in Experiment 4. Vertical and horizontal bars represent ± 1 standard error of the mean for accuracy rate and reaction time (RT, in milliseconds), respectively. LS = participants with low working memory spans; HS = participants with high working memory spans; Dead = deadline.

(*Appendix continues*)

The best way to accommodate both our desire to use CAFs and the need to deal with potential shifts in criterion across blocks is to compute CAFs separately for each deadline condition. Each set of CAFs, then, holds criterion constant while still providing a time-course function. And, it should be noted that because the 700-ms deadline was always the first block of trials, the CAFs for this block should be a relatively pure measure of performance before any adjustments to response criteria have been made. To limit the number of examinations required, we consider only incompatible trials from the 400-, 500-, 600-, and 700-ms deadline blocks. Additionally, because there were less data available for each plot, we computed 5 *n*tile bins instead of 10.

Figure A1 depicts the time course of processing holding criterion constant in Experiment 1. Likewise, Figure A2 presents comparable data for Experiment 2, Figure A3 for Experiment 3, and Figure A4 for Experiment 4. The similarities between these functions and those presented in the main text are striking. One can observe each piece of the overall CAF (dip below chance performance, divergent accuracy rates at intermediate RTs, and finally, equivalent asymptotic performance) for Experiments 1–3. Note also that this pattern is quite strong for the 700-ms deadline, which was the first block of trials—thus this pattern holds before any change in criterion takes place. Again, we take this to mean that participants with high WM spans can focus their spotlight of attention faster than can participants with low WM spans (see main text). Similarly, for Experiment 4 (see Figure A4), there are no differences between participants, regardless of which block one considers.

In conclusion, although the CAFs presented in the main text are likely not invariant to changes in criterion invoked by the deadline manipulation, the overall pattern of data is. That is, even if we plot the data separately for each deadline condition, the same pattern emerges. Thus, the differences in rate observed earlier are not an artifact of our time-course functions.

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Correction to Schneider and Logan (2006)

In the article “Hierarchical Control of Cognitive Processes: Switching Tasks in Sequences,” by Darryl W. Schneider and Gordon D. Logan (*Journal of Experimental Psychology: General*, 2006, Vol. 135, No. 4, pp. 623–640), two task transitions were classified incorrectly in Table 7 (p. 634). The task transition at Serial Position 1 for sequence switches of the AABB sequence should be TR instead of TS. The task transition at Serial Position 1 for sequence switches of the ABBA sequence should be TS instead of TR.

Two sections of text in the *Results and Discussion* section of Experiment 4 were affected by the misclassifications. In the *Error rate analysis* section (pp. 634–635), the text

> For sequence switches, overall switch costs were –1.8% and 2.7% for the AABB and ABBA sequences, respectively, which were significantly different, $F(1, 69) = 69.45$, $p < .001$, $\eta_p^2 = .50$. Consistent with the sequence repetition data, there was a nonsignificant switch cost of 0.5% between first serial positions, $F(1, 69) < 1$.

should now read

> For sequence switches, overall switch costs were –1.4% and 2.1% for the AABB and ABBA sequences, respectively, which were significantly different, $F(1, 69) = 31.28$, $p < .001$, $\eta_p^2 = .31$. Consistent with the sequence repetition data, there was a nonsignificant switch cost of –0.5% between first serial positions, $F(1, 69) < 1$.

In the *RT analysis* section (p. 635), the text

> For sequence switches, overall switch costs were 690 ms and –374 ms for the AABB and ABBA sequences, respectively, which were significantly different, $F(1, 69) = 1{,}336.80$, $p < .001$, $\eta_p^2 = .95$.

should now read

> For sequence switches, overall switch costs were –312 ms and 574 ms for the AABB and ABBA sequences, respectively, which were significantly different, $F(1, 69) = 694.86$, $p < .001$, $\eta_p^2 = .91$.

These corrections do not alter any of the conclusions drawn from the original text.

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