

## COMMENTARY

# The Impact of Alertness on Cognitive Control

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Many previous studies have found that an increase in phasic or tonic alertness impairs cognitive control, even though overall response times are decreased. This counterintuitive pattern of behavior is still poorly understood. Using a computational model, we show that the behavioral pattern follows directly from two simple and well-supported assumptions: increased alertness reduces the time needed for stimulus encoding; and cognitive control takes time to develop. The simulation results suggest that, although the arousal system and cognitive control system may be anatomically distinct, their effects on information processing may interact to produce a seemingly complicated pattern of behavior.

*Keywords:* temporal attention, temporal expectation, executive control, attentional network test, Spatial attention

In their taxonomy of attention, Posner and Petersen (1990) distinguished between three neural attention systems: an anterior system associated with cognitive control, which biases perception in favor of task-relevant information; a posterior system for orienting attention in space; and an arousal system that allows endogenous or exogenously triggered increases in alertness. Although it was originally thought that the contributions of these systems can be studied in relative isolation (Fan, McCandliss, Sommer, Raz, & Posner, 2002), later work suggested that these attention systems seemingly work in concert to produce complicated patterns of behavior. Here we focus on an interaction between alertness and cognitive control that has puzzled cognitive psychologists for a decade, and we attempt to explain why this interaction occurs.

Since 2002, this interaction has been reported in a large number of studies, many of which have used the Attentional Network Test (ANT; Fan et al., 2002), a reaction time (RT) test developed to simultaneously measure the efficiency of each of the three attention systems discussed above. In the standard ANT participants are required to produce fast and accurate button-press responses to the orientation of an arrow stimulus flanked by arrows pointing in the same direction (congruent, e.g., > > > > >) or in the opposite direction (incongruent, e.g., > > < > >). The difference in performance between these two conditions, the flanker interference effect, is widely used as a measure of the efficiency of cognitive control. Half a second before the onset of each arrow

stimulus, one of several cues is presented. In a low-alertness condition, participants receive no warning before the arrow appears. In another condition, a visual cue is presented for 100 ms, alerting participants to the upcoming arrow. As illustrated in Figure 1 (top left panel), RTs in this condition of high alertness are typically faster, even though the cue does not provide information about the identity of the arrow stimulus—a robust finding in experimental psychology (Hackley, 2009; Lawrence & Klein, 2013; Nobre, Correa, & Coull, 2007). Curiously, the increase in alertness is accompanied by an increased flanker interference effect, indicating impaired control of the focus of attention.

This behavioral pattern—decreased choice RTs accompanied by increased interference effects—is observed in virtually all studies using the ANT (MacLeod et al., 2010) and several other task paradigms (see Figure 1). It occurs with various manipulations of alertness (temporal cuing, fixed foreperiods, task-irrelevant accessory stimuli), with visual and auditory alerting signals, and with various measures of cognitive control (Böckler, Alpay, & Stürmer, 2011; Callejas, Lupiáñez, Funes, & Tudela, 2005; Correa, Capucci, Nobre, & Lupiáñez, 2010; Fan et al., 2009; Fischer, Plesow, & Kiesel, 2010; Klein & Ivanoff, 2011; MacLeod et al., 2010; Weinbach & Henik, 2012).

The impact of alertness on measures of cognitive control is still poorly understood, perhaps because it is counterintuitive: faster RTs are typically accompanied by smaller, not larger, effect sizes (as a result of scaling; Wagenmakers, Kryptos, Criss, & Iverson, 2012); and the finding that high alertness increases interference seems inconsistent with studies indicating that arousal biases attention toward goal-relevant stimuli (Mather & Sutherland, 2011). To account for the counterintuitive interaction, some authors have proposed that the arousal system directly inhibits the function of the cognitive control system and thus increases interference (Callejas et al., 2005; Fan et al., 2009). Other researchers have suggested that alerting signals activate stimulus–response associations, especially those that are well-established (Fischer et al., 2010; Böckler et al., 2011). When these associations are task-irrelevant, such as

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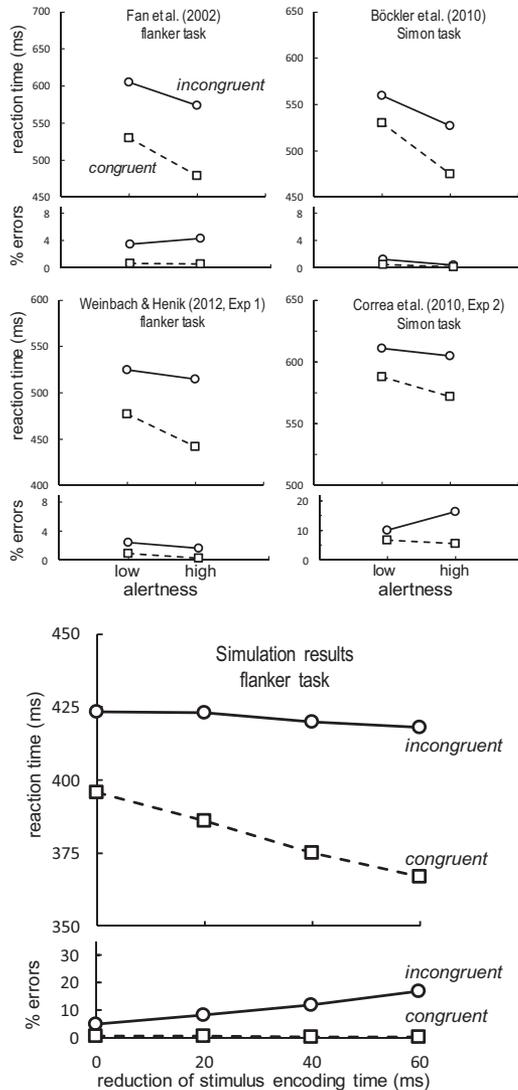


Figure 1. Top: Empirical examples of the interaction between alertness (low, high) and cognitive control demands (congruent vs. incongruent flanker/Simon task trials). Bottom: Simulated results showing the interaction between stimulus-encoding time and cognitive control demands.

the association between stimulus location and response in the Simon task, this activation can increase interference with the correct response. However, these hypotheses are not computationally explicit and thus leave doubt about the true explanatory power. Furthermore, they are based on ad hoc assumptions about how alerting modifies information processing.

### Early Onset Hypothesis

Here we present model simulations demonstrating that the critical pattern of behavior—alertness speeds up RTs but increases interference—follows directly from two solid assumptions:

**1. Alertness reduces stimulus-encoding time.** Converging evidence from several task paradigms indicates that increasing alertness reduces the time needed for stimulus encoding (i.e., arriving at a stable

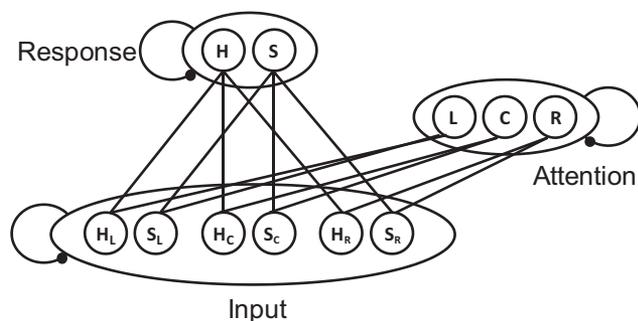
representation of the stimulus in visual cortex; Correa et al., 2005; Jepma, Wagenmakers, Band, & Nieuwenhuis, 2009; Rolke & Hoffmann, 2007; Seifried, Ulrich, Bausenhardt, Rolke, & Osman, 2010), possibly through stochastic resonance (Jepma et al., 2009) or phase-entrainment of oscillatory neural activity (Rohenkohl & Nobre, 2011). In contrast, increased alertness has little effect on decision-process parameters (decision threshold and evidence-accumulation rate) or the duration of response execution (Hackley & Valle-Inclán, 1998; Jepma et al., 2009; Jepma, Wagenmakers, & Nieuwenhuis, 2012; Leth-Stenssen, 2009; Seibold, Bausenhardt, Rolke, & Ulrich, 2011). Thus, increasing alertness speeds up RTs because it expedites early stimulus encoding and thus advances the onset of the decision process. This account, the *early onset hypothesis* (Seifried et al., 2010), can also explain the increase in interference, when the following assumption is taken into account.

**2. Cognitive control takes time to develop.** Empirical conditional accuracy functions (CAFs; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Hommel, 1994) and computational analyses (Cohen, Servan-Schreiber, & McClelland, 1992; White, Ratcliff, & Starns, 2011) of flanker- and Simon-task performance indicate that in these tasks cognitive control takes time to develop over the course of a trial. In CAFs, accuracy rates are plotted against RT. For the flanker task (see Figure 3) and Simon task such functions show large interference effects in accuracy rates for the fastest RT bins, indicating that in the first couple hundred milliseconds after stimulus onset the decision process is still strongly influenced by the task-irrelevant stimulus attribute. In the flanker task this shows that the “attentional spotlight” is diffuse at stimulus onset, allowing influence from the flankers, but over the course of the trial narrows in on the target, as attentional control is increased. Similarly, in the Simon task, time may be needed for the gradual decay of the response-code activation induced by the (task-irrelevant) stimulus location.

Taken together, our hypothesis proposes that the interaction between alertness and cognitive control demands reflects the differential timing of evidence accumulation: Increased alertness is associated with an earlier onset of evidence accumulation. Although this tends to decrease RTs, because the decision threshold is reached earlier, it also increases interference, because early in the trial cognitive control is relatively weak and hence the impact on evidence accumulation of task-irrelevant stimulus dimensions is increased.

### The Spencer and Coles (1999) Model

To provide a formal demonstration of our hypothesis, we simulated the behavioral effects of alertness using the model of information-processing dynamics in the Eriksen flanker task originally proposed by Cohen et al. (1992) and slightly modified by Spencer and Coles (1999). The model (see Figure 2) simulates a version of the Eriksen flanker task in which participants are instructed to respond to the central letter (H or S) of a three-letter array. The response cued by the task-irrelevant flankers can be congruent (e.g., HHH) or incongruent (e.g., HSH) with the required response. Stimuli are represented as patterns of activity across the input layer, which consists of one unit for each possible combination of letter and location. Activity flows from this layer through its connections to the response layer, which consists of one unit for each response. A response is generated when the activation of one of the response units exceeds a prespecified threshold. The



**Figure 2.** Illustration of the model of the flanker task used in the present simulations (Cohen, Servan-Schreiber, & McClelland, 1992; Spencer & Coles, 1999). Units within the same module inhibit one another, and connections between units in different modules are all excitatory. H and S are possible stimuli and corresponding responses. L, C, and R refer to left, center, and right. The results of the simulations reported here are based on 10,000 trials for each stimulus-encoding duration. On each trial, cognitive control demands (congruent, incongruent) and target identity (S, H) were randomly chosen.

control of spatial attention is simulated by the excitatory influence of the attention units on the letter units, which biases processing of target stimuli relative to the flankers, ensuring that even on incongruent trials the model usually produces the correct response. Occasional errors are caused by noise and early processing of the flankers.

Following Spencer and Coles (1999), on each trial, the model was run for 100 preparatory cycles, and then for 50 cycles after stimulus onset (1 cycle = 10 ms). At cycle 0, 1000 ms before stimulus onset, all units were at rest. At cycle 1, the attention and response units received a constant level of Gaussian noise input, that continued until trial termination. This simulated a state of readiness in the system and led the model to produce responses with a variable latency and to commit occasional errors. Stimulus presentation was simulated by activation of the letter units. First, from cycle 100 ( $t = 0$  ms) until trial termination, Gaussian noise was applied to the letter units, representing the effect of physical stimulus presentation. Then, at cycle 113 ( $t = 130$  ms), external activation, associated with the letters in the stimulus, was provided to the three corresponding letter units. The delay between noise onset and external activation represented the time taken for early stimulus-encoding processes.

At cycle 113 ( $t = 130$  ms), at the same time as the letter units, the center attention unit received external input, which increased activation of the center attention unit and, through inhibitory connections, decreased activation of the left and right attention units. Over the course of several cycles, this attentional biasing input influenced the activations of the letter units so that the center letter units gradually dominated activity in the input layer. Thus, as time passed after stimulus onset, the network changed from a state of diffuse spatial attention (low cognitive control) and a relatively large impact of the flankers on (correct or incorrect) response unit activation to a state of focused spatial attention (high cognitive control) and a corresponding increase in activation of the correct response unit.

Spencer and Coles (1999) assumed that a response-threshold crossing in the model corresponded to EMG onset. We followed

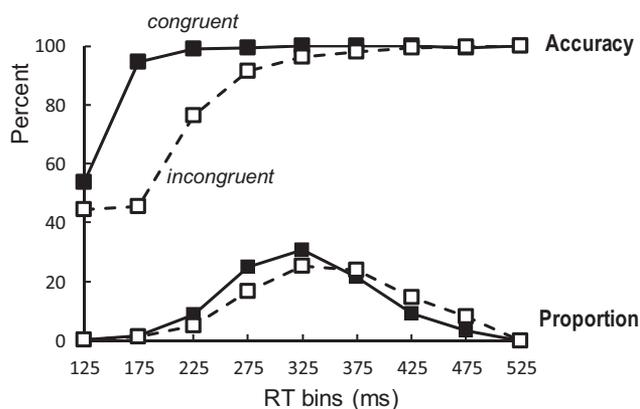
this assumption and added 75 ms to each simulated response time to account for the time between EMG onset and the mechanical response (Allain, Carbonnell, Burle, Hasbroucq, & Vidal, 2004). Nonetheless, in initial simulations the model responded much faster and made far more errors than participants in the experiments we intend to simulate. This probably reflects Gratton et al.'s (1988) instructions, which emphasized response speed over accuracy. Therefore, to better capture participants' performance in empirical studies, we increased the response-threshold parameter value from 0.18 to 0.25, resulting in slower responses and fewer errors.

With the exception of this change, all model parameter values in the control condition (relatively low alertness) were taken from Spencer and Coles (1999). In line with assumption 1, increased alertness was simulated by reducing, in three steps of 2 cycles (20 ms), the delay between stimulus onset and external activation of the input layer—the time needed for early stimulus encoding. This range is representative for the typical size of alerting effects: between 20 and 60 ms.

### Simulation Results

To demonstrate that in our model cognitive control takes time to develop (assumption 2), we constructed CAFs for the control condition by computing response accuracy for each of nine RT bins. As shown in Figure 3, accuracy in the fastest RT bin is at chance level. For slower RT bins, accuracy for congruent stimuli increases rapidly, whereas accuracy for incongruent stimuli takes substantially longer to approach asymptote, indicating that control develops over the course of a few hundred milliseconds. These results are similar to empirical and simulated CAFs reported previously for the flanker task (Gratton et al., 1988; Spencer & Coles, 1999).

For our main analyses, we examined correct RT and accuracy in congruent and incongruent trials as a function of stimulus-encoding duration, our proxy for degree of alertness (assumption 1). Figure 1 shows that a stepwise decrease of stimulus-encoding time led to a progressive decrease in RTs. The model shows this



**Figure 3.** Conditional accuracy functions (top) and RT distributions (bottom) based on the simulated RT data in the control condition, separately for congruent and incongruent trials. Bins were 50 ms wide and extended from 100 ms to 550 ms. Labels on the abscissae refer to the middle of the latency range associated with each RT bin.

Table 1  
*Mean Reaction Times and Flanker Interference Effect as a Function of Reaction-Time Bin*

Bin	Reduction of Stimulus Encoding Time							
	0 ms (low alertness)				60 ms (high alertness)			
	Incongr RT	Congr RT	Mean RT	Flanker interference	Incongr RT	Congr RT	Mean RT	Flanker interference
1	313	284	298	29	281	250	265	31
2	351	327	339	24	325	291	308	34
3	370	350	360	20	356	310	333	46
4	390	365	378	25	380	330	355	50
5	410	380	<b>395</b>	<b>30</b>	400	350	375	50
6	430	400	415	30	421	370	<b>395</b>	<b>51</b>
7	445	415	430	30	444	390	417	54
8	464	430	447	34	475	410	442	65
9	494	454	474	40	504	438	471	66
10	533	503	518	30	539	495	517	44

*Note.* Each bin contained an equal number of trials.

standard effect of alerting because a reduction in stimulus-encoding time means that evidence accumulation can start earlier. More importantly, the decrease in RTs is accompanied by an increase in the flanker interference effect, because congruent RTs decrease more rapidly than incongruent RTs. The simulation results mimic this crucial aspect of the empirical data because evidence accumulation takes place earlier in the trial, when cognitive control is still growing. A similar increase in interference is visible in the simulated error rates, a pattern that is also observed in empirical studies in which response accuracy is below ceiling (see Figure 1). Together, these simulations lend strong credence to the early onset hypothesis.

A previous study has shown that although the interaction between alertness and cognitive control demands occurs in the context of an average decrease in RTs, the interaction effect is not dependent on this decrease in RTs (Fischer et al., 2010). Our simulations replicate this result: When we categorized the trials in each condition in 10 RT bins and compared bins with a similar mean RT, the corresponding flanker interference effects were still larger in the high-alertness condition than in the low-alertness (control) condition (Table 1, e.g., the bold-faced numbers). So, the model predicts that the impact of alertness on flanker interference is not dependent on RT per se, only on changes in RT that reflect a change in stimulus-encoding time.

## Discussion

Numerous previous studies have found that increases in alertness impair cognitive control, even though choice RTs are typically decreased (e.g., Böckler et al., 2011; Callejas et al., 2005; Correa et al., 2010; Fan et al., 2009; Fischer et al., 2010; Klein & Ivanoff, 2011; Weinbach & Henik, 2012; see MacLeod et al., 2010 for a review of studies using the ANT). Simulations supported our novel hypothesis of this poorly understood phenomenon by showing that the behavioral pattern follows directly from two well-supported assumptions: alertness reduces stimulus-encoding time; and cognitive control takes time to develop. This early onset hypothesis differs substantially from existing verbal models, which propose that alertness influences cognitive control measures through an impact on the decision-making process or the cognitive control system itself. Our hypothesis suggests the effect occurs

through an impact on (the duration of) early encoding processes. It predicts that other manipulations of stimulus-encoding time should have a similar effect on cognitive control measures.

An important outstanding question is why the interaction between alertness and cognitive control demands occurs in some tasks but not others. Weinbach and Henik (2012) present evidence that the interaction occurs in tasks with a clear spatial component (e.g., Simon and flanker tasks), but not in nonspatial tasks (e.g., Stroop task).<sup>1</sup> A possible explanation is that our assumption that cognitive control increases over the course of a trial may not be true for all tasks. That is, spatial attentional control has a clear exogenous component, meaning that part of the spatial selection can occur only after presentation of the stimulus. This exogenous component may reflect the time needed to overcome simple attentional capture (e.g., in the Simon task), a potential alertness-induced bias toward processing global stimulus features (Weinbach & Henik, 2011), or other factors. In contrast, in tasks such as the Stroop task, in which the relevant stimulus dimension cannot be selected by spatial attention because relevant and irrelevant stimulus dimensions are integrated in one object, attentional control may have no exogenous component; performance on a given trial may only reflect the endogenous recruitment of control before stimulus onset (cf. Cohen, Dunbar, & McClelland, 1990).

In general, our findings suggest that although the three attention systems targeted by the ANT may be anatomically separate, their effects on information processing may interact to produce behavioral patterns that, on the surface, may seem rather complex. Formal models are quintessentially suited to reveal the (often) simple principles underlying this complex behavior.

<sup>1</sup> This dissociation resonates with several other lines of evidence for different attentional selection in flanker/Simon tasks and the Stroop task (Magen & Cohen, 2002; Verleger, 1997), which also reflect the unique role of space in visual attention (e.g., Magen & Cohen, 2005).

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