

## Testing the behavioral interaction and integration of attentional networks

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### ABSTRACT

One current conceptualization of attention subdivides it into functions of alerting, orienting, and executive control. Alerting describes the function of tonically maintaining the alert state and phasically responding to a warning signal. Automatic and voluntary orienting are involved in the selection of information among multiple sensory inputs. Executive control describes a set of more complex operations that include detecting and resolving conflicts in order to control thoughts or behaviors. Converging evidence supports this theory of attention by showing that each function appears to be subserved by anatomically distinct networks in the brain and differentially innervated by various neuromodulatory systems. Although much research has been dedicated to understanding the functional separation of these networks in both healthy and disease states, the interaction and integration among these networks still remain unclear. In this study, we aimed to characterize possible behavioral interaction and integration in healthy adult volunteers using a revised attention network test (ANT-R) with cue-target interval and cue validity manipulations. We found that whereas alerting improves overall response speed, it exerts negative influence on executive control under certain conditions. A valid orienting cue enhances but an invalid cue diminishes the ability of executive control to overcome conflict. The results support the hypothesis of functional integration and interaction of these brain networks.

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## 1. Introduction

One of the most important goals of cognitive neuroscience is in understanding of the sources of voluntary control of thoughts, feelings, and actions. One view of attention refers to it as the activity of a set of brain networks that influence the priority of computations of other brain networks for access to consciousness and observable behavior (Posner & Fan, 2008; Raz & Buhle, 2006). According to this description, attention serves as the basis of various control systems. This view conceptualizes the attentional system in specific functional and anatomical terms as comprising three separable functional components of alerting, orienting, and executive control (Posner & Fan, 2008; Posner & Petersen, 1990).

### 1.1. The attentional networks

#### 1.1.1. Alerting network

Alerting provides the capacity to increase vigilance to an impending stimulus. While tonic or intrinsic alertness is defined

as wakefulness and arousal, phasic alertness represents the ability to increase response readiness to a target subsequent to an external warning stimulus. Alerting involves a change in the internal state in preparation for perceiving a stimulus. For example, following presentation of a warning signal, there are a variety of changes in heart rate and brain oscillatory activity that serve to inhibit competing activities (Kahneman, 1973). The alert state is critical for optimal performance in tasks involving higher cognitive functions (Fan, Raz, & Posner, 2003). Alerting function has been associated with thalamic, frontal, and parietal regions, and is influenced by the cortical distribution of the brain's norepinephrine (NE) system that arises from the midbrain nucleus locus coeruleus (LC) (Coull, Sahakian, & Hodges, 1996; Marrocco, Witte, & Davidson, 1994).

#### 1.1.2. Orienting network

The orienting function involves aspects of attention that support the selection of specific information from numerous sensory inputs. Orienting can be reflexive (exogenous), as when a sudden target event draws attention to its location; or it can be voluntary (endogenous), as when a person searches the visual field looking for a target. Overt orienting is often associated with head and/or eye movements toward the target; however, it is also possible to enhance target processing by orienting attention covertly, that is,

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without a change in posture or eye position. Orienting involves rapid or slow shifting of attention among objects within a modality or among various sensory modalities, with three elementary operations: disengaging attention from its current focus, moving attention to the new target or modality, and engaging attention at the new target or modality (Posner, Walker, Friedrich, & Rafal, 1984). In behavioral studies, orienting is often manipulated by presenting a cue indicating where a subsequent target will (or will not) appear (Posner, 1980). A valid cue indicates the location in which an impending target will appear. If the cue is invalid, the target appears in a different location, often opposite to the location indicated by the cue. The benefit in terms of target processing efficiency conferred by valid cues is less in magnitude than the cost associated with orienting to an incorrect location. The orienting system for visual events has been associated with such brain areas as the superior and inferior parietal lobule, frontal eye fields (FEF), and subcortical areas such as the superior colliculus of midbrain and the pulvinar and reticular nuclei of the thalamus (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Corbetta & Shulman, 2002; Posner, 1980; Posner & Cohen, 1984; Posner, Cohen, & Rafal, 1982). These areas are thought to carry out different elementary operations involved in the act of orienting. Cholinergic systems arising in the basal forebrain play an important role in modulating orienting.

#### 1.1.3. Executive control network

The executive control function of attention involves more complex mental operations in detecting and resolving conflict between computations occurring in different brain areas (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Bush, Luu, & Posner, 2000). A number of studies have examined executive control under this framework by using variants of the color Stroop task that require people to respond to one dimension of a stimulus rather than another stronger, but conflicting, dimension (Botvinick et al., 2001; Bush et al., 2000; Fan, Flombaum, McCandliss, Thomas, & Posner, 2003; Liu, Banich, Jacobson, & Tanabe, 2004; MacDonald, Cohen, Stenger, & Carter, 2000). Other tasks involving cognitive conflict, such as variants of the flanker task developed by Eriksen and Eriksen (Eriksen & Eriksen, 1974), have also been used to evaluate the efficiency of executive control (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Casey et al., 2000; Fan, Flombaum, et al., 2003). In everyday life, executive control is most needed in situations that involve planning or decision-making, error detection, novel or not well-learned responses, conditions judged difficult or dangerous, and in overcoming habitual actions. Executive control of attention has been associated with the anterior cingulate cortex (ACC) and lateral prefrontal cortex (Matsumoto & Tanaka, 2004), which are target areas of the ventral tegmental dopamine system (Benes, 2000).

#### 1.2. The separation of the attentional networks

Alerting, orienting, and executive control have been thought to be relatively independent aspects of attention with each subserved by separable brain networks. In the original report of our work with the Attention Network Test (ANT) (Fan, McCandliss, Sommer, Raz, & Posner, 2002) (see Fig. 1 of this ref.), we found that there was a good deal of support for independence across networks. This was shown by the lack of correlation between the performance scores obtained for each network. We conducted an event-related fMRI study to explore the brain activity of the three attention networks (Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). We found the expected brain areas unique to each network. However, we also found substantial areas of overlap. Our most recent finding of distinctive time-frequency patterns associated with each attentional function (Fan, Byrne, et al., 2007) provides further support for the separation of attention into distinct functional networks

and suggests that these attentional networks are associated with network-specific oscillation patterns and time courses.

#### 1.3. The interaction and integration of the attentional networks

Although the original configuration of the ANT demonstrated independence of the networks, it would be surprising if the networks did not subservise attentional functions through coordinated activity. The networks should interact in the performance of many acts of attention. Evidence of interaction appeared even in our early studies. For the behavioral performance, where there were two small but significant interactions in which the alerting cue (including the center cue and double-cues, in which the cues are displayed at two possible locations but provide only temporal information and not spatial information) conditions, compared to no-cue and orienting cue (spatial-cue, in which the cue predicts the location of the target and provides both temporal and spatial information) conditions, the efficiency of the executive control network for target response was reduced (Fan et al., 2002). In a study with a larger sample using the ANT, we found a small but significant negative correlation between the alerting and executive control scores (Fossella et al., 2002). In studies using a tone for the auditory alerting signal, alerting inhibits executive control and orienting enhances executive control (Callejas, Lupianez, Funes, & Tudela, 2005; Callejas, Lupianez, & Tudela, 2004), while alerting has been shown to enhance orienting (Fuentes & Campoy, 2008). We have shown that alerting modulates the overall activity of the executive control network, and that orienting interacts with executive control (Fan, Byrne, et al., 2007). For the brain response, we have observed that the ACC is involved in both response anticipation (alerting) and response conflict (executive control) (Fan, Kolster, et al., 2007).

#### 1.4. Motivation for the current study

This body of evidence leads us to hypothesize that there exist subtle yet significant interactions and integrations among attentional networks that some previous studies have failed to detect. Such interactions, if found, would shed important new light on how anatomically distinctive attentional networks in the brain work together to support the function of attention. Our strategy to find such interactions is to design tasks in which possible but subtle interactions among attentional networks can be magnified via manipulations so that their effects can be detected at the behavioral level.

One important attentional network that may contribute to such interactions and integrations might be the orienting network. However, the original ANT did not incorporate invalid cues. Therefore, the interaction between orienting and executive functions could not be explicitly examined. In this study, we manipulated the validity of the cue. We know from previous work that using partial validity would allow one to compare valid and invalid trials and get a much more specific measure of the shift of orientation from an expected to an unexpected location. This manipulation enabled us not only to test the validity effect and its interaction with conflict processing, but also to measure the elementary operations of orienting. We predicted that the invalid cues with low probability may demand more attentional resources than the valid cues with high probability. Therefore, the former may have negative impact on the conflict processing by the executive control network.

The second important interaction lies between the alerting and executive control networks. This is related to the finding that alerting and executive control share some common brain structures. In this study, we manipulated the cue-target interval so that the interaction between alerting and conflict processing can be examined. We predicted that, although alerting improves overall RT,

there would be a negative impact of alerting on executive control under a certain cue-target interval because of overlap of attentional processes involving shared resources. In addition, for target processing, the flanker and location conflicts were manipulated so that we were able to examine dual-conflict processing. It should be noted that only the conflict processing function of the executive control network was tested in this study. Uncovering the patterns in which these networks interact with each other will shed new light on understanding how attention works as a whole.

**2. Methods**

**2.1. Participants**

Thirty young adult volunteers (15 females and 15 males; mean age, 25.4 years; range, 22–34 years) participated in this study. The consent procedure was approved by the institutional review board and written informed consent was obtained from each participant.

**2.2. The revised attention network test (ANT-R)**

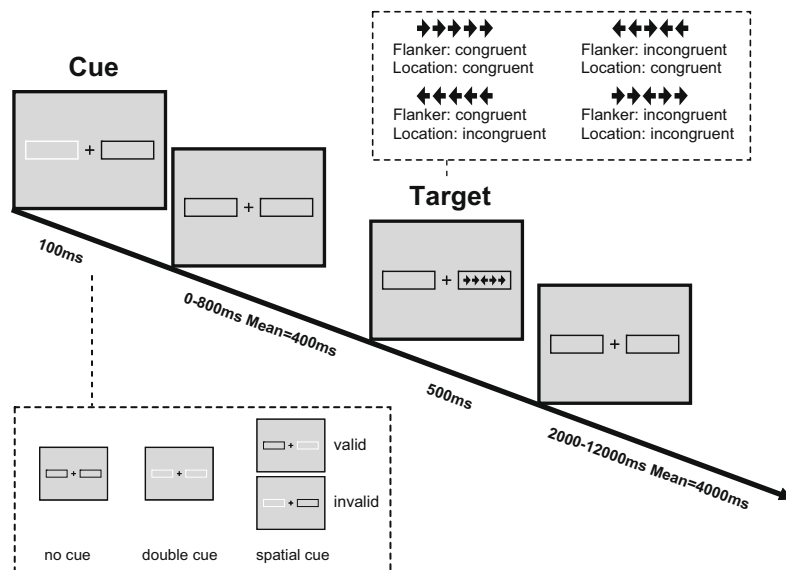
We designed the ANT-R based on the original ANT (Fan et al., 2002) in order to optimize the attentional contrasts and to examine the interaction between attentional networks. The revised version uses three, instead of four, cue conditions (no-cue, double-cue, spatial-cue) and reduces the target conditions to two (congruent and incongruent). More importantly, a cue validity manipulation is now incorporated. This is different from a lateralized design (Greene et al., 2008) and our previous fMRI study (Fan et al., 2005), both of which used a center cue condition instead of a double-cue condition. This version is similar to another version that also incorporated cue validity manipulation (Bish, Ferrante, McDonald-McGinn, Zackai, & Simon, 2005). In the ANT-R the cue-target interval is also manipulated to examine the alerting and orienting speed and the interaction between alerting and conflict processing. In addition, the flanker congruency and location congruency are manipulated.

The details of the ANT-R are illustrated in Fig. 1. Stimuli consist of a row of five horizontal black arrows (one central target plus four flankers, two on each side), pointing leftward or rightward,

against a gray background. A single arrow subtends 0.58° of visual angle and the contours of adjacent arrows are separated by 0.06° of visual angle, so that the target + flanker array subtends a total of 3.27° of visual angle. Participants' task is to identify the direction of the center arrow by pressing a key with the index finger of the left hand for the left direction and a key with the index finger of the right hand for the right direction, while ignoring the spatial location (left or right) of the target relative to the fixation crosshair. Participants are instructed to make their response to the direction of the center target as quickly and accurately as possible. The experimental program is written in E-prime and is publicly available via email request to the first author.

A cue, in the form of cue box flashing, may be shown before the target appears, which may or may not help the participants' target detection depending on the cue conditions. There are three cue conditions in each run: no-cue (no-cue box flashes before the target appears; 12 trials), double-cue (both cue boxes flash before the target appears, so the cue is only temporally informative; 12 trials), and spatial-cue (one cue box flashes before the target appears, so the cue is temporally and possibly spatially informative; 48 trials). RTs for the no- and double-cue conditions are used to assess the alerting benefit. To introduce the orienting component, a spatial-cue and the subsequent stimulus are presented 4.69° left or right of a fixation crosshair continuously shown in the center of the screen. Participants have to shift attention from the fixation point to the target stimulus on each trial in order to determine the proper response. If attentional movements occur with a speed of about 8 ms/degree (Tsal, 1983), this visual angle should result in a cost of at least 37 ms. The validity of the spatial-cue is manipulated in order to measure the disengage and move operations (see (Posner et al., 1984). Specifically, 75% of the 48 spatial-cues (36 trials) are valid and 25% (12 trials) are invalid. The probability of valid cue is the sum of the individual conditions of no-cue, double-cue, and invalid cue.

To introduce the conflict effect, the target (center arrow) is flanked on either side by two arrows of the same direction (congruent condition), or of the opposite direction (incongruent condition). To challenge the executive control function, double conflict that combines the flanker conflict effect (Eriksen & Eriksen, 1974) and the location conflict (Simon) effect (Simon & Berbaum, 1990) are



**Fig. 1.** Schematic of the Attention Network Test (ANT). In each trial, depending on the cue condition (none, double, and valid or invalid cues), a cue box flashes for 100 ms. After a variable duration (0, 400, or 800 ms), the target (the center arrow) and two flanker arrows on the left and right side (congruent or incongruent flankers) are presented for 500 ms. The participant makes a response to the target's direction. The post-target fixation period varies between 2000 and 12,000 ms.

introduced. There are two flanker congruency (congruent, incongruent) and two location congruency (congruent, incongruent) conditions. For example, assume that the target is displayed on the right side of the fixation. If the center target points to right and the flankers point to right, this is the flanker congruent with location congruent condition. If the center target points to right and the flankers point to left, this is the flanker incongruent with location congruent condition. If the center target points to left and the flankers point to left, this is the flanker congruent with location incongruent condition. If the center target points to left and the flankers point to right side, this is the flanker incongruent with location incongruent condition.

A fixation cross is visible at the center of the screen throughout the duration of the task. In each trial, depending on the condition, either a transient cue (brightening of the cue box surrounding the stimulus row) is presented for 100 ms (the cued conditions) or the stimulus display remains unchanged (the no-cue condition). After a variable duration (either 0, 400, or 800 ms, mean = 400 ms), the target and flankers are presented and remain visible for 500 ms. Cue-to-target intervals are selected based on previous studies on normal participants and patients (Fan et al., 2002; Posner et al., 1984). The duration between the offset of the target and the onset of the next trial is varied systematically, approximating an exponential distribution ranging from 2000 to 12,000 ms and having a mean of 4000 ms (10 intervals from 2000 to 4250 ms with an increase step of 250 ms, then one 4750 ms interval and one 12,000 ms interval). The mean trial duration is 5000 ms. The response collection window closes 1700 ms after the onset of the target and flankers as used in our original study (Fan et al., 2002).

The experiment consists of 4 runs, each with 72 test trials. Across 2 runs consisting of a total of 144 trials: (1) The cue conditions are classified into six cue cells (one for no-cue, one for double-cue, one for invalid spatial-cue, and three for valid spatial-cue) although there are only four cue types (no-cue, double-cue, invalid spatial-cue, valid spatial-cue). This is for counterbalancing purposes because the number of trials with valid cues is equal to the sum of the number of trials under the no-cue, invalid cue, and double-cue conditions. The order of the cue presentation is predetermined to ensure that each cue type is followed by every other cue type equally as often; (2) The order for 24 combinations of the 3 cue-to-target intervals (0, 400, and 800 ms) by 2 flanker congruencies (congruent, incongruent) by 2 target locations (left, right) by 2 target directions (left, right) is nested within each cue condition and is randomized; (3) Since the 12 intervals between target and next trial do not lend themselves to counterbalancing within 24 trials for each cue type, the  $2 \times 12$  intervals are randomized within each cue type until the Spearman's rank correlation between the 24 ranks (for the 24 combinations)  $\times$  6 cue types and 12 ranks (for 12 interval pairs)  $\times$  12 repetitions is less than .005. The 144 trials are evenly split into 2 runs with 72 trials and the same run duration in each. The same arrangement is repeated once resulting in 4 runs in total. The total duration for each run is 420 s. The total time required to complete this task is about 30 min.

The manipulation in this version of the ANT compared to our original design (Fan et al., 2002), namely (1) manipulating the cue-to-target interval (0, 400, 800 ms) and using the brightening box for alerting; (2) displaying the target on the left or right side of the fixation, manipulating cue validity to introduce the disengagement component, and extending the visual angle to create a larger size of the orienting effect; and (3) introducing the flanker by location dual conflict, and displaying the target for 500 ms instead of 1700 ms, were made in order to increase the attentional demands of the task. Thus, the new design should offer a better chance to reveal network interactions.

### 2.3. Operational definitions

The function of each of the three attentional networks is operationally defined as a comparison of the performance (*RT* and accuracy) between one condition and the appropriate reference condition, resulting in scores for the attentional networks.

(1) The phasic alerting (benefit) effect is defined as:

Alerting =  $RT_{\text{no-cue}} - RT_{\text{double-cue}}$  representing the benefit of the target response speed because of alerting.

(2) The ability to disengage attention can be measured by comparing the *RTs* to targets following double-cue and invalid cue presentation; a deficit in the moving of attention can be inferred when the *RT* to targets is slow regardless of where attention was engaged prior to target appearance; a deficit of an engagement of attention can be indexed if there is a *RT* deficit despite the targets having been validly cued and the cue-to-target interval is long enough to allow attention to move to the new target. Corresponding to this model, orienting operations can be separately measured as:

$$\begin{aligned} \text{Validity effect} &= \text{Disengaging} + (\text{Moving} + \text{Engaging}) \\ &= RT_{\text{invalid cue}} - RT_{\text{valid cue}} \end{aligned}$$

Moving + Engaging =  $RT_{\text{double-cue}} - RT_{\text{valid cue}}$  for the benefit of target response under valid cue condition because of orienting and engaging in advance. Here, the Moving + Engaging is equivalent to the "orienting" effect we defined in our previous study (Fan et al., 2002).

Disengaging =  $RT_{\text{invalid cue}} - RT_{\text{double-cue}}$  for the cost of disengaging from invalid cue.

In addition, Orienting time =  $RT_{\text{valid cue}, 0 \text{ ms cue-to-target interval}} - RT_{\text{valid cue}, 800 \text{ ms cue-to-target interval}}$  for benefit of the target response because of the advanced orienting.

(3) The conflict (cost) effect is defined as:

$$\begin{aligned} \text{Flanker conflict effect} &= RT_{\text{flanker incongruent}} - RT_{\text{flanker congruent}} \\ \text{Location conflict effect} &= RT_{\text{location incongruent}} - RT_{\text{location congruent}} \\ \text{Flanker by location interaction} &= (RT_{\text{flanker incongruent, location incongruent}} - RT_{\text{flanker congruent, location incongruent}}) - (RT_{\text{flanker incongruent, location congruent}} - RT_{\text{flanker congruent, location congruent}}) \end{aligned}$$

A positive value of this effect indicates that flanker conflict effect under the location congruent condition is less than under the location incongruent condition, whereas a negative value of this effect indicates that flanker conflict effect under the location incongruent condition is less than under the location congruent condition.

(4) The interaction effects between alerting and flanker conflict, between orienting and flanker conflict, and between validity and flanker conflict can be calculated by comparing the conflict scores under different cue conditions:

Alerting by flanker conflict =  $(RT_{\text{no-cue, flanker incongruent}} - RT_{\text{no-cue, flanker congruent}}) - (RT_{\text{double-cue, flanker incongruent}} - RT_{\text{double-cue, flanker congruent}})$ . A negative value indicates a negative impact of alerting on flanker conflict processing.

Orienting by flanker conflict =  $(RT_{\text{double-cue, flanker incongruent}} - RT_{\text{double-cue, flanker congruent}}) - (RT_{\text{valid cue, flanker incongruent}} - RT_{\text{valid cue, flanker congruent}})$ . A positive value indicates a more efficient conflict processing because of orienting.

Validity by flanker conflict =  $(RT_{\text{invalid cue, flanker incongruent}} - RT_{\text{invalid cue, flanker congruent}}) - (RT_{\text{valid cue, flanker incongruent}} - RT_{\text{valid cue, flanker congruent}})$ . A positive value indicates a less efficient flanker conflict processing because of invalid orienting.

The interaction effects between alerting and location conflict, between orienting and location conflict, and between validity

and location conflict can be calculated by comparing the conflict scores under different cue conditions:

Alerting by location conflict =  $(RT_{\text{no-cue, location incongruent}} - RT_{\text{no-cue, location congruent}}) - (RT_{\text{double-cue, location incongruent}} - RT_{\text{double-cue, location congruent}})$ .

Orienting by location conflict =  $(RT_{\text{double-cue, location incongruent}} - RT_{\text{double-cue, location congruent}}) - (RT_{\text{valid cue, location incongruent}} - RT_{\text{valid cue, location congruent}})$ .

Validity by location conflict =  $(RT_{\text{invalid cue, location incongruent}} - RT_{\text{invalid cue, location congruent}}) - (RT_{\text{valid cue, location incongruent}} - RT_{\text{valid cue, location congruent}})$ . A positive value indicates a less efficient location conflict processing because of invalid orienting, whereas a negative value indicates a more efficient location conflict processing.

The inhibition of return (IOR) effect (Posner & Cohen, 1984; Posner, Rafal, Choate, & Vaughan, 1985) (if the difference is positive) or the cost of invalid cue under shorter (0 ms) compared to longer (400 ms) cue-target interval (if the difference is negative) =  $(RT_{\text{invalid cue, 0 ms cue-to-target interval}} - RT_{\text{valid cue, 0 ms cue-to-target interval}}) - (RT_{\text{invalid cue, 400 ms cue-to-target interval}} - RT_{\text{valid cue, 400 ms cue-to-target interval}})$ .

The effects in accuracy follow the same formulas. A mirrored positive and negative pair indicate that there is no speed-accuracy trade-off.

2.4. Apparatus and testing procedure

The task was compiled and run on a PC, with a 17 inch LCD monitor, using E-Prime™ software (Psychology Software Tools, Pittsburgh, PA). The task was first explained using a paperboard illustrating each target and response condition. Participants then performed a brief practice task on a PC with step by step instructions illustrating the cue and target conditions, and then they made responses to six practice trials with an infinite response time window, and then to 32 practice trials with the same timing parameters as the actual test. The practice was continued until participants demonstrated at least 90% accuracy. Participants then performed the actual test. They were always instructed to respond as quickly and accurately as possible.

2.5. Data analysis

Mean RTs for each condition were calculated. Error trials (incorrect and missing responses) were excluded from the mean RT calcu-

lation. The significance of the operationally defined effects was tested using two-tailed one-sample *t* tests. The effects of the factors of cue (no-cue, double-cue, invalid cue, and valid cue), cue-target interval (0, 400, 800 ms), flanker congruency (congruent, incongruent), and location congruency (congruent, incongruent) were examined using repeated measures analysis of variance (ANOVA) for each attentional network effect separately. Pearson's correlation coefficients were also calculated to explore the strength and direction of linear relationship between attentional network scores. The outliers outside the 1700 ms window (due to either omission error or long RT) were excluded by the task program and we did not further exclude outliers with the method based on the standard deviation used in our original report (Fan et al., 2002).

3. Results

Tables 1 and 2 show the RT and accuracy (mean and SD) under all the conditions. The overall RT was 604 ms (SD = 59 ms) and the overall accuracy of the task performance was 94% (SD = 4%).

3.1. The attentional network effects

Fig. 2a shows the operationally defined effects and two-way interactions calculated based on the RT differences and Fig. 2b shows the accuracy differences corresponding to those RT differences. Table 3 lists the values of these attentional effects. A positive difference in RT with a corresponding negative difference in accuracy, and vice versa, indicates that there is no speed-accuracy trade-off.

3.1.1. The alerting effect

The comparison between the no-cue condition and double-cue condition showed that the benefit of the RT related to double-cue was  $29 \pm 24$  (mean  $\pm$  SD) ms,  $t(29) = 6.53$ ,  $p < 0.01$ . There was no difference on accuracy ( $0 \pm 4\%$ ),  $t(29) = -0.42$ , n.s., indicating that alerting improved overall response speed but not accuracy.

3.1.2. The orienting effects

The validity effect on RT of  $95 \pm 32$  ms was significant ( $t(29) = 16.12$ ,  $p < 0.01$ ). Breaking down the orienting effect, the moving + engaging ( $41 \pm 21$  ms) and disengaging ( $54 \pm 24$  ms) effects were also significant ( $t(29) = 10.97$  and  $t(29) = 12.44$ ,  $ps < 0.01$ , respectively). The cost of invalid cue under 0 ms cue-target interval ( $-60 \pm 39$  ms) and orienting time ( $57 \pm 31$  ms) were also significant ( $t(29) = -8.30$  and  $t(29) = 9.93$ ,  $ps < 0.01$ , respec-

Table 1 Mean reaction times (ms) and standard deviations of correct responses.

Cue-target interval (ms)	Flanker congruency	Location congruency	Cue type							
			No-cue		Double-cue		Invalid cue		Valid cue	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
NA	Congruent	Congruent	558	67						
NA	Congruent	Incongruent	560	66						
NA	Incongruent	Congruent	687	83						
NA	Incongruent	Incongruent	687	77						
0	Congruent	Congruent			541	78	560	64	549	61
0	Congruent	Incongruent			556	58	549	53	530	65
0	Incongruent	Congruent			684	90	823	107	654	74
0	Incongruent	Incongruent			671	86	694	79	648	81
400	Congruent	Congruent			480	47	563	73	453	51
400	Congruent	Incongruent			519	61	566	78	476	63
400	Incongruent	Congruent			685	91	740	94	581	72
400	Incongruent	Incongruent			642	93	707	101	590	87
800	Congruent	Congruent			513	54	572	54	502	67
800	Congruent	Incongruent			534	85	567	67	476	57
800	Incongruent	Congruent			670	95	747	101	592	80
800	Incongruent	Incongruent			634	78	694	81	585	89

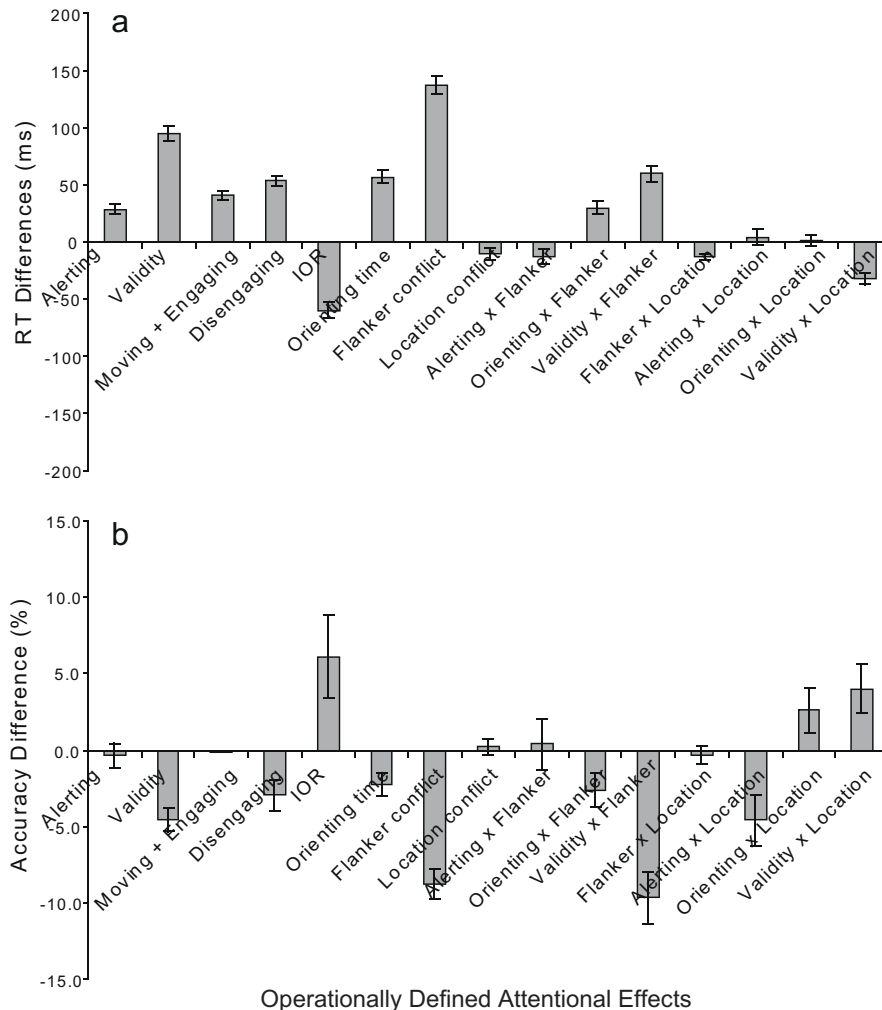
**Table 2**  
Mean accuracy (%) and standard deviation.

Cue-target interval (ms)	Flanker congruency	Location congruency	Cue type							
			No-cue		Double-cue		Invalid cue		Valid cue	
			Mean	SD	Mean	SD	Mean	SD	Mean	SD
NA	Congruent	Congruent	97	6						
NA	Congruent	Incongruent	99	3						
NA	Incongruent	Congruent	93	8						
NA	Incongruent	Incongruent	86	13						
0	Congruent	Congruent			98	6	99	5	97	6
0	Congruent	Incongruent			99	5	100	0	99	3
0	Incongruent	Congruent			95	10	67	27	93	9
0	Incongruent	Incongruent			88	17	93	18	88	11
400	Congruent	Congruent			97	9	100	0	99	3
400	Congruent	Incongruent			99	5	97	9	99	3
400	Incongruent	Congruent			80	20	83	23	94	8
400	Incongruent	Incongruent			88	18	83	18	93	10
800	Congruent	Congruent			99	5	100	0	99	3
800	Congruent	Incongruent			98	6	98	6	100	2
800	Incongruent	Congruent			89	17	84	20	94	7
800	Incongruent	Incongruent			98	6	87	16	93	7

tively). The cost of invalid cue under 0 ms cue-target interval here is the cost under short cue-target interval and the “orienting time” is an index of the orienting cost in time.

For accuracy, the cost was  $5 \pm 4\%$  for target response under invalid cue condition compared to valid condition ( $t(29) = -5.68$ ,  $p < 0.01$ ), indicating that there were more error responses made

under the invalid cue condition compared to the valid cue condition. This validity effect was not due to the moving + engaging effect ( $0 \pm 0\%$ ,  $t(29) = -1.79$ , n.s.), but instead due to disengaging ( $-3 \pm 5\%$ ,  $t(29) = -2.93$ ,  $p < 0.01$ ). The cost of invalid cue under 0 ms cue-target interval was  $6 \pm 15\%$ ,  $t(29) = 2.22$ ,  $p < 0.05$ , indicating that the validity effect under 0 ms cue-target interval condition



**Fig. 2.** Attentional network and two-way interaction scores in terms of RT (ms) and accuracy (%) differences. The error bars represent standard error.

**Table 3**  
Means and standard deviations of the attentional effects in RT and accuracy.

	RT (ms)		Accuracy (%)	
	Mean	SD	Mean	SD
Alerting	29	24	-0.35 <sup>a</sup>	4.48
Validity	95	32	-4.57	4.31
Moving + Engaging	41	21	-0.14 <sup>a</sup>	0.26
Disengaging	54	24	-2.95	5.49
IOR	-60	39	6.11	14.91
Orienting time	57	31	-2.29	4.18
Flanker conflict	137	43	-8.77	5.34
Location conflict	-11	27	0.21 <sup>a</sup>	2.83
Alerting × Flanker	-13	33	0.42 <sup>a</sup>	9.24
Orienting × Flanker	30	32	-2.59	5.84
Validity × Flanker	60	42	-9.68	9.00
Flanker × Location	-13	14	-0.36 <sup>a</sup>	3.25
Alerting × Location	4 <sup>a</sup>	39	-4.58	9.11
Orienting × Location	1 <sup>a</sup>	28	2.59 <sup>a</sup>	8.08
Validity × Location	-32	31	4.01	8.82
Overall RT	604	59	94.25	3.75

<sup>a</sup>  $p > 0.05$ .

was greater than under 400 ms cue-target interval condition. The orienting time effect was  $-2 \pm 4\%$ ,  $t(29) = -2.98$ ,  $p < 0.01$ , indicating more response errors were made under 0 ms cue-target interval compared to under 800 ms cue-target interval condition.

**3.1.3. The conflict effects**

The flanker conflict effects of  $137 \pm 43$  ms on RT and  $9 \pm 5\%$  on accuracy were significant ( $t(29) = 17.51$  and  $t(29) = -9.02$ ,  $ps < 0.01$ ) and the location conflict effect of  $-11 \pm 27$  ms on RT was significant ( $t(29) = -2.12$ ,  $p < 0.05$ ), but not for accuracy ( $0 \pm 3\%$ ,  $t(29) = 0.27$ , n.s.). The negative value of the location conflict effect indicates that the RT was shorter under the location incongruent condition, indicating an opposite direction of the location conflict effect.

**3.2. The interactions**

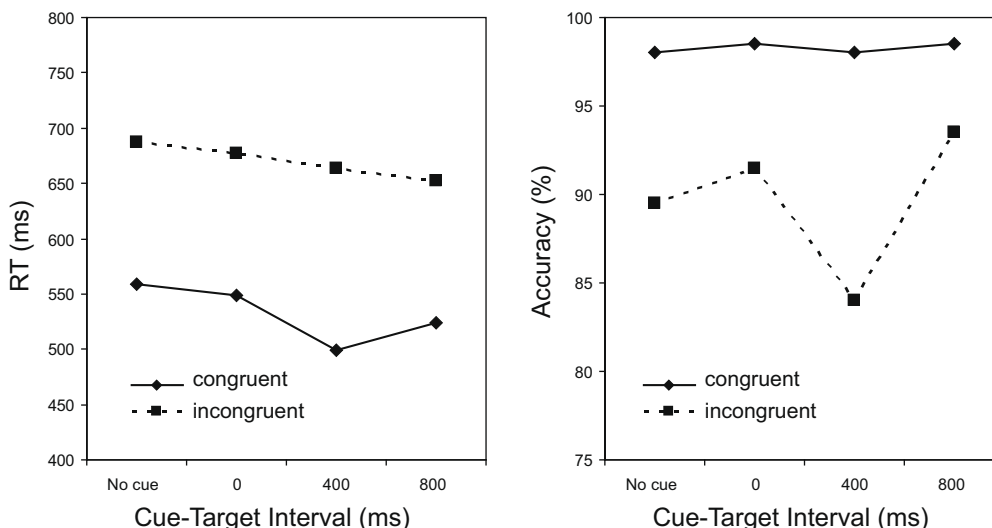
**3.2.1. The alerting by conflict interaction**

The alerting by flanker conflict interaction was significant on RT ( $-13 \pm 33$  ms,  $t(29) = -2.07$ ,  $p < 0.01$ ) but not on accuracy ( $0 \pm 9\%$ ,  $t(29) = 0.20$ , n.s.), indicating that the conflict effect on RT under

the double-cue condition was greater than that under the no-cue condition, a negative effect of the alerting on the conflict processing. The RTs for the congruent and incongruent flanker trials under no-cue condition were 559 and 687 ms, and were 524 and 664 ms under double cue condition. Although the RTs were generally improved (shorter RT) under the double-cue condition, the conflict effect increased by 13 ms. The alerting by location conflict on RT ( $4 \pm 38$  ms) was not significant ( $t(29) = 0.63$ , n.s.) but was significant ( $t(29) = 2.80$ ,  $p < 0.01$ ) in terms of accuracy ( $5 \pm 9\%$ ).

Further examination revealed that this negative interaction was due to the stronger conflict effect under 400 ms, but not at 0 and 800 ms cue-target intervals for the double-cue condition compared to no-cue condition. The significant interval by flanker congruency interaction indicated that alerting may exert influence on the conflict processing. Fig. 3 shows the RT and accuracy under the congruent and incongruent flanker conditions as a function of the cue-target interval (no-cue, and 0, 400, and 800 ms of double-cue conditions). As is shown in Fig. 3, alerting improved the RT for processing of targets with congruent flankers under 400 ms cue-target double-cue condition. However, there was a speed-accuracy trade-off for processing of targets with incongruent flankers. This resulted an increased conflict effect under the 400 ms cue-target interval condition.

The ANOVAs of cue-target interval (no-cue, and 0, 400, and 800 ms of double-cue conditions) by flanker congruency (congruent, incongruent) by location congruency (congruent, incongruent) showed that for RT, the interval factor was significant,  $F(3,87) = 22.26$ ,  $p < 0.01$ ; the flanker congruency factor was significant,  $F(1,29) = 252.99$ ,  $p < 0.01$ ; the location congruency factor was not significant,  $F < 1$ ; the interval by flanker congruency interaction was significant,  $F(3,87) = 4.82$ ,  $p < 0.01$ ; the interval by location congruency interaction was not significant,  $F < 1$ ; the flanker congruency by location congruency interaction was significant,  $F(1,29) = 45.56$ ,  $p < 0.01$ ; and the interval by flanker congruency by location congruency interaction was significant,  $F(3,87) = 3.68$ ,  $p < 0.05$ . For accuracy, the interval factor was significant,  $F(3,87) = 7.00$ ,  $p < 0.01$ ; the flanker congruency factor was significant,  $F(1,29) = 80.42$ ,  $p < 0.01$ ; the location congruency factor was not significant,  $F < 1$ ; the interval by flanker congruency interaction was significant,  $F(3,87) = 4.83$ ,  $p < 0.01$ ; the interval by location congruency interaction was significant,  $F(3,87) = 4.82$ ,  $p < 0.01$ ; the flanker congruency by location congruency interaction was



**Fig. 3.** Alerting by flanker conflict processing interaction in terms of RT (ms) and accuracy (%) differences.

not significant,  $F < 1$ ; and the interval by flanker congruency by location congruency interaction was significant,  $F(3,87) = 4.54$ ,  $p < 0.01$ .

The significant flanker congruency by location congruency effect for the RT was related to the fact that the flanker conflict effect was greater under the congruent location condition (158 ms, 523 vs. 681 ms for congruent and incongruent flankers) than under the incongruent location condition (116 ms, 542 vs. 658 ms for congruent and incongruent flankers). There was no speed-accuracy trade-off for this interaction.

### 3.2.2. The orienting and validity by conflict interaction

The orienting by flanker conflict effect was  $30 \pm 32$  ms on RT ( $t(29) = 7.89$ ,  $p < 0.01$ ) and  $-3 \pm 6\%$  on accuracy ( $t(29) = -2.49$ ,  $p < 0.05$ ), indicating orienting reduced conflict effect (141 vs. 111 ms for double and valid cue conditions, respectively). The validity by flanker conflict effect was  $60 \pm 42$  ms on RT ( $t(29) = 7.89$ ,  $p < 0.01$ ) and  $-10 \pm 9\%$  on accuracy ( $t(29) = -5.90$ ,  $p < 0.01$ ), indicating that invalid cue was associated with greater conflict effect compared to valid cue (171 vs. 111 ms). The orienting by location conflict on RT ( $2 \pm 28$  ms) and on accuracy ( $3 \pm 8\%$ ) were not significant ( $t(29) = 0.31$  and  $t(29) = 1.72$ ,  $ps > 0.05$ ). The validity by location conflict interactions on RT ( $-32 \pm 31$  ms) and on accuracy ( $4 \pm 9\%$ ) were significant ( $t(29) = -5.74$ ,  $p < 0.01$  and  $t(29) = 2.54$ ,  $p < 0.05$ ).

The ANOVAs of cue (double vs. valid) by cue-target interval (0, 400, 800 ms) by flanker congruence (congruent, incongruent) by location congruency (congruent, incongruent) showed that for RT, the main effect of cue (594 vs. 553 ms) was significant,  $F(1,29) = 120.64$ ,  $p < 0.01$ . The main effect of interval (604, 553, and 563 ms) was significant,  $F(2,58) = 92.14$ ,  $p < 0.01$ . The main effect of flanker congruency (511 vs. 636 ms) was significant,  $F(1,29) = 252.91$ ,  $p < 0.01$ . The location congruency effect was not significant,  $F < 1$ . The cue by interval interaction was significant,  $F(2,58) = 14.23$ ,  $p < 0.01$ . Importantly, the cue by flanker congruence effect was significant,  $F(1,29) = 25.98$ ,  $p < 0.01$  (see Fig. 4 left). The interval by flanker congruency effect was significant,  $F(2,58) = 6.34$ ,  $p < 0.01$ . The cue by location congruency effect was not significant,  $F < 1$ . The interval by location congruency effect was significant,  $F(2,58) = 3.29$ ,  $p < 0.05$ . The flanker by location congruency interaction was significant,  $F(1,29) = 24.75$ ,  $p < 0.01$ . Higher order interactions were analyzed but not reported here.

For accuracy, the main effect of cue (94% vs. 96%) was significant,  $F(1,29) = 7.86$ ,  $p < 0.01$ . The main effect of interval (95%, 94%, and 96%) was significant,  $F(2,58) = 5.75$ ,  $p < 0.01$ . The main effect of flanker congruency (98% vs. 91%) was significant,  $F(1,29) = 80.50$ ,  $p < 0.01$ . The location congruency effect was not significant,  $F < 1$ . The cue by interval interaction was significant,  $F(2,58) = 11.34$ ,  $p < 0.01$ . The cue by flanker congruence interaction was significant,  $F(1,29) = 5.90$ ,  $p < 0.05$  (see Fig. 4 right). The interval by flanker congruence interaction was significant,  $F(2,58) = 4.36$ ,  $p < 0.05$ . The cue by location congruency interaction was not significant,  $F(1,29) = 3.09$ , n.s.. The interval by location congruency interaction was significant,  $F(2,58) = 3.54$ ,  $p < 0.05$ . The flanker by location congruency interaction was not significant,  $F < 1$ . Higher order interactions were analyzed but not reported here.

The ANOVAs of cue (valid vs. invalid) by cue-target interval (0, 400, 800 ms) by flanker congruence (congruent, incongruent) by location congruency (congruent, incongruent) (1 case rejected because of missing data in one condition) showed that for the RT, the main effect of cue (553 vs. 649 ms) was significant,  $F(1,28) = 242.47$ ,  $p < 0.01$ . The main effect of interval (625, 584, and 591 ms) was significant,  $F(2,56) = 39.96$ ,  $p < 0.01$ . The main effect of flanker congruency (530 vs. 671 ms) was significant,  $F(1,28) = 317.43$ ,  $p < 0.01$ . The location congruency effect (611 vs. 590 ms, RT was shorter under the incongruent location condition) was significant,  $F(1,28) = 15.07$ ,  $p < 0.01$ . The cue by interval interaction was significant,  $F(2,56) = 39.82$ ,  $p < 0.01$ . Importantly, the cue by flanker congruence effect was significant,  $F(1,28) = 57.32$ ,  $p < 0.01$  (see Fig. 5 left). The interval by flanker congruence interaction was significant,  $F(2,56) = 7.49$ ,  $p < 0.01$ . The cue validity by location congruency integration was significant,  $F(1,28) = 45.17$ ,  $p < 0.01$ , indicating that under invalid cue the opposite location conflict effect was even less ( $-4$  vs.  $-38$  ms). The interval by location congruency integration was significant,  $F(2,56) = 23.11$ ,  $p < 0.01$ . The flanker by location congruency interaction was significant,  $F(1,28) = 20.08$ ,  $p < 0.01$ . Higher order interactions were analyzed but not reported here.

For accuracy, the main effect of cue (96% vs. 91%) was significant,  $F(1,29) = 32.08$ ,  $p < 0.01$ . The main effect of interval (92.0%, 93.5%, and 94.4%) was not significant,  $F(2,58) = 3.03$ , n.s.. The main effect of flanker congruency (99% vs. 88%) was significant,  $F(1,29) = 75.98$ ,  $p < 0.01$ . The location congruency effect (92% vs. 94%) was significant,  $F(1,29) = 4.44$ ,  $p < 0.05$ . The cue by interval

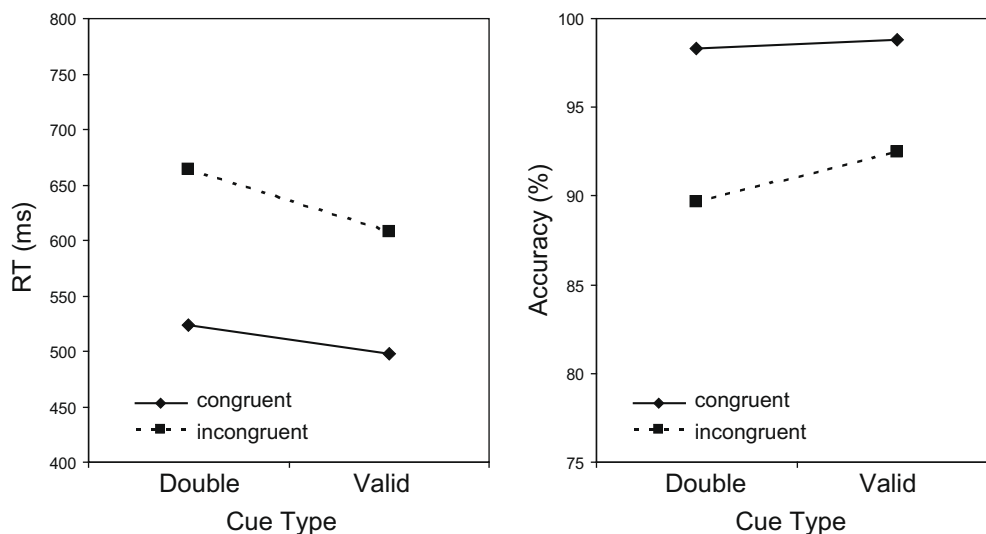


Fig. 4. Orienting by flanker conflict processing interaction in terms of RT (ms) and accuracy (%) differences.



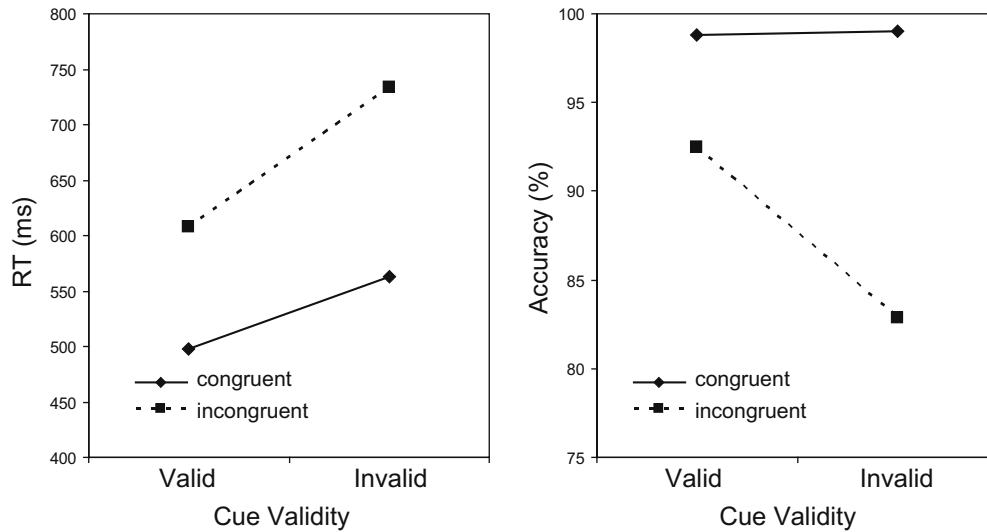


Fig. 5. Cue validity by flanker conflict processing interaction in terms of RT (ms) and accuracy (%) differences.

interaction was not significant,  $F < 1$ . The cue by flanker congruence interaction was significant,  $F(1,29) = 34.03$ ,  $p < 0.01$  (see Fig. 5 right). The interval by flanker congruence interaction was not significant,  $F(2,58) = 2.68$ , n.s.. The cue validity by location congruency interaction was significant,  $F(1,29) = 9.82$ ,  $p < 0.01$ . The interval by location congruency interaction was significant,  $F(2,58) = 10.41$ ,  $p < 0.01$ . The flanker by location congruency interaction was significant,  $F(1,29) = 5.97$ ,  $p < 0.05$ . Higher order interactions were analyzed but not reported here.

3.2.3. The flanker congruency by location congruency interaction

The flanker congruency by location congruency interaction was tested in the ANOVAs of alerting and orienting effects, which was significant in the analysis of orienting effects, but not in the analysis of alerting effects. This interaction (see Fig. 6) was also tested based on combined trials conditions of the cue-target interval and cue conditions. The flanker by location congruency interaction ( $-13 \pm 14$  ms) was significant on RT ( $t(29) = -5.06$ ,  $p < 0.01$ ) but

not on accuracy ( $0 \pm 3\%$ ,  $t(29) = -0.57$ , n.s.) under merged cue conditions. This indicates that the flanker conflict effect is greater under congruent location condition than under the incongruent location condition.

3.3. The correlations between the network measurements

The correlation coefficients between the attentional effects, and the means and standard deviations of each effect on RT, are shown in Table 4. The alerting score was positively correlated with the disengaging score ( $r = 0.38$ ). This correlation might be due to the common reference condition of the double-cue and a common driving factor affecting the response speed. Almost all of the measures of the orienting network were highly correlated. For example, the validity effect was significantly correlated with the measures of disengaging ( $r = 0.77$ ) and moving + engaging ( $r = 0.69$ ). These significant correlations, however, are possibly due to the common reference conditions. However, the correlation

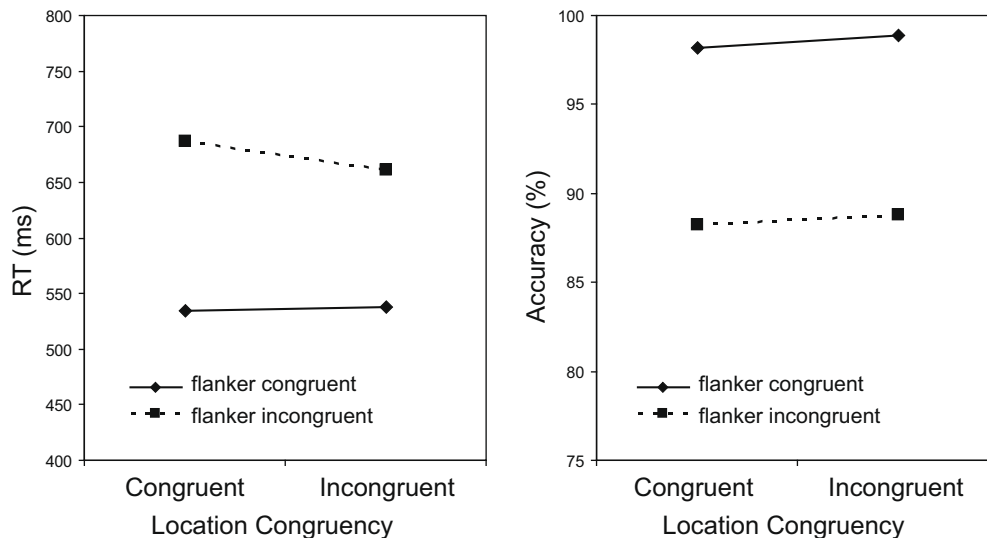


Fig. 6. Flanker congruency by location congruency interaction in terms of RT (ms) and accuracy (%) differences.

**Table 4**  
Correlation coefficients between attentional network effects.

	Alerting	Validity	Moving + Engaging	Disengaging	IOR	Orienting time	Flanker conflict	Location conflict
Alerting								
Validity	.18							
Moving + Engaging	-.16	.69 <sup>b</sup>						
Disengaging	.38 <sup>a</sup>	.77 <sup>b</sup>	.07					
IOR	-.02	-.38 <sup>a</sup>	-.34	-.22				
Orienting time	.35	.68 <sup>b</sup>	.62 <sup>b</sup>	.39 <sup>a</sup>	-.46 <sup>a</sup>			
Flanker conflict	.09	.16	-.01	.23	-.17	.08		
Location conflict	.05	-.02	.01	-.03	-.09	.14	-.23	
Mean RT	.19	-.01	-.09	.07	-.34	.08	.43 <sup>a</sup>	.07

<sup>a</sup> Correlation is significant at the 0.05 level (2-tailed).

<sup>b</sup> Correlation is significant at the 0.01 level (2-tailed).

between disengaging and moving + engaging was not significant ( $r = 0.07$ ). The flanker conflict effect was only significantly correlated with the mean RT ( $r = 0.43$ ) but not other network scores. Finally, the location conflict effect was not correlated with any network scores.

#### 4. Discussion

The most intriguing finding of the current study is that alerting improves overall response speed while it exerts negative influence on executive control under certain conditions. The small but negative alerting by flanker congruency interaction is consistent with what we found previously. Although the alerting cue conditions improved overall RT compared to no-cue conditions, the conflict effect was greater under the alerting cue, especially under the 400 ms cue-target interval condition. We found this effect in our previous papers (Fan et al., 2002; Fossella et al., 2002), and proposed that resolving the conflict might proceed in parallel with the extra time taken to deal with the lack of a cue. In other studies, an effect of auditory cueing on visual orienting and conflict processes has been observed (Callejas et al., 2004; Fuentes & Campoy, 2008). Alerting improved the overall response speed, yet elicited a larger conflict effect. Their finding is similar to what we found in the current study under the 400 ms cue-target interval. However, in another study with a longer cue to target interval, we did not find the interaction between response anticipation and response conflict (Fan, Kolster, et al., 2007). The interaction between alerting and executive control may indicate that there is competition for limited attentional resources under the 400 ms cue-target interval condition. The interval effect might be more consistent with the resource competition explanation. The competition for resources between alerting and conflict processes from their shared brain networks, e.g., the ACC and the fronto-parietal network (Fan, Kolster, et al., 2007), may underlie this behavioral interaction. In a previous ERP study, we found that the alerting related alpha suppression occurs at around 400 ms post alerting cue onset while conflict led to a more complex pattern that involved alpha suppression and a later enhancement (Fan, Byrne, et al., 2007). Future neuroimaging studies that utilize ANT-R might be able to further demonstrate the neural mechanisms underlying such competition.

Valid orienting facilitates and invalid orienting inhibits conflict processing. In this study, the orienting by flanker congruency interaction was greatly enhanced by the validity manipulation in the present study. Orienting to the target location in advance enhanced target processing speed and reduced conflict. The strong validity by flanker congruency interaction resulted from a greater flanker interference under the invalid cue condition involving

reorienting of attention. The finding that valid cues facilitated and invalid cues interfered with executive control may also indicate the competition of overlapping or shared attentional resources for the orienting and executive control functions. The orienting function involves the fronto-parietal network including the FEF and the areas near/along the intraparietal sulcus (IPS). The executive control network also needs support from these regions to keep focused on the center target and filter out or suppress the incongruent flankers. Given the common reliance on the overlapping brain network to perform the orienting and executive control functions, conditions that require both functions at work to perform the task will result in division of the processing resources and brain network power. For example, detecting an incongruent target following an invalid cue requires both (re-)orienting and executive control function, whereas detecting a congruent target following an invalid cue requires only (re-)orienting, and detecting an incongruent target following a valid cue requires only executive control. In addition, fMRI studies have consistently shown that ACC is involved in dealing with uncertainty (Behrens, Woolrich, Walton, & Rushworth, 2007; Critchley, Mathias, & Dolan, 2001; Pochon, Riis, Sanfey, Nystrom, & Cohen, 2008; Ullsperger & von Cramon, 2004; Walton, Devlin, & Rushworth, 2004; Zysset et al., 2006). Such common reliance on the ACC for uncertainty processing and conflict processing also causes resource competition under conditions that require both functions (e.g., the incongruent target following an invalid cue) and results in a negative impact on task performance.

A key manipulation in the ANT-R was to include both valid and invalid spatial-cues (75% and 25%, respectively). This is different from the original ANT where all spatial-cues were valid. In the original design of the ANT (Fan et al., 2002, 2005), we did not include validity manipulation in order to avoid the potential interaction between orienting and conflict processing. While the validity effect we found is not surprising, the reliable orienting effect is interesting. Recall that the orienting effect is derived by subtracting RT in the valid cue condition from that in the double-cue condition. Clearly, while a double-cue provided no information where the target was to appear, a spatial-cue here only provided partial information due to the manipulation of validity. A significant orienting effect indicates that this partial information was learned and utilized to improve performance.

The patterns of interactions we report in this study highlight important functional interplay among anatomically separable neural substrates supporting attention. We think that this interplay is common rather than incidental in real-world situations where different aspects of attention work tightly together. One approach to generate hypotheses to further test this intriguing relationship is to

develop computational models so that different responses of the attentional networks to environmental variables can be simulated, both individually and jointly. Because the architecture of the computational models is nothing like a real brain, the modeling results cannot be taken as a test of how the human brain functions. However, computational modeling can help us in developing hypotheses. We have recently developed a connectionist model based on the original ANT (Wang & Fan, 2007). By simultaneously incorporating all three attentional networks in a single system, we were able to simulate how computations carried out in different networks might (or might not) interact, mainly based on how networks are connected and how information is represented and transformed. For example, our model revealed a significant negative correlation between alerting and orienting scores ( $r = -0.47$ ). An examination of the model showed that this was partially because both alerting and orienting affected computations in the “where” spatial pathway. Without changing any parameters, we were able to use the same ANT model to simulate the validity effect in the current ANT-R. It showed that the model responded about three cycles (roughly 36.3 ms based on regression) more slowly to the invalid cue condition compared to the valid cue condition. We plan to see how we can extend the model to simulate and explain the results in the current study.

One limitation of the design is that we were not able to set all cue (and target) conditions to have equal frequency in order to manipulate validity (at least 75% vs. 25% for valid and invalid cues). Therefore the performance differences between valid cue and invalid cue conditions may not be purely related to the validity manipulation (orienting) but perhaps also related to the probability difference. Interpretation of the comparisons should be made with caution because of this. The location conflict manipulation was introduced to enhance the flanker conflict; however, the effect turned out to be in the direction opposite of what we predicted. For the flanker congruency by location congruency interaction, the flanker conflict effect was reduced under the incongruent location. This is opposite to what we found in a previous study with a moderate tendency for increased interference in RT for the double conflict of flanker and location condition (Fan, Flombaum, et al., 2003). This inconsistency needs to be further investigated.

In summary, this study, adopting additional experimental manipulations, finds evidence for interactions among different attentional networks. In particular, alerting improves the overall response speed but interferes with executive control under certain cue-target interval conditions. Valid orienting improves performance on executive control whereas invalid cues interfere with executive control. The interaction among these attentional processes corroborates the neuroimaging findings that showed recruitment of overlapping brain networks by these processes. Together they support the notion that attention is a complex cognitive function that is subserved by distinct yet interactive mental processes and brain networks.

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