Measuring attention in the hemispheres: The lateralized attention network test (LANT)

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Abstract

The attention network test (ANT) is a brief computerized battery measuring three independent behavioral components of attention: Conflict resolution (ability to overcome distracting stimuli), spatial Orienting (the benefit of valid spatial pre-cues), and Alerting (the benefit of temporal pre-cues). Imaging, clinical, and behavioral evidence demonstrate hemispheric asymmetries in these attentional networks. We constructed a lateralized version of the ANT (LANT), with brief targets flashed in one or the other visual hemifield. We also modified the tests by including invalid spatial cues in order to measure the cost component of Orienting. In a series of experiments, we investigated the efficiency of the attention networks separately in each hemisphere. Participants exhibited significant estimates of all networks measured by the LANT, comparable to the ANT. The three networks were represented in each hemisphere separately and were largely comparable across the two hemispheres. We suggest that the LANT is an informative extension of the original ANT, allowing for measurement of the three attention networks in each hemisphere separately.
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Keywords: Attention; Conflict; Executive; Orienting; Vigilance; Hemispheric specialization; Hemispheric independence

1. Introduction

Attention is believed to involve a bilaterally distributed network whose components are asymmetrically represented in the two hemispheres. Physiological/imaging correlates of attention show that *sustained attention* (vigilance) tasks yield prefrontal and parietal activation, preferentially in the right hemisphere (RH) (Posner & Petersen, 1990). Stroop and flanker-type *conflict resolution* tasks selectively engage the anterior cingulate cortex and left prefrontal cortex (Fan, Flombaum, McCandliss, Thomas, & Posner, 2003). *Orienting of visuospatial attention* selectively engages right parietal cortex (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000). Clinical and behavioral evidence is largely consistent with the imaging data. Clinical studies confirm that the RH is specialized for alerting, arousal and vigilance (Posner & Petersen, 1990). Hemi-neglect is more often reported and more severe in patients with right than left parietal lesions (for a review, see Mesulam, 1999). Further, normal and split-brain participants demonstrate a gradient of attention from right to left, occurring in diverse tasks of spatial attention, namely covert spatial orienting (Zaidel, 1995), line-bisection (Reuter-Lorenz, Kinsbourne, & Moscovitch, 1990), and visual search (Pollmann, 1996; Pollmann & Zaidel,

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1998). Thus, hemispheric contributions are elementary and should be incorporated to any account of attention in the brain.

Attention has been described as a system comprising at least three separate and independent networks: executive Conflict resolution (C), spatial Orienting (O), and Alerting (A) (Posner & Raichle, 1994). Posner and associates devised a brief computerized battery, the attention network test (ANT), to measure the efficiency of these attentional networks (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Studies using the ANT have proven it to be a reliable measure, capable of indexing the three networks independently of one another (Fan, McCandliss, Flombaum, & Posner, 2001; Fan, Wu, Fossella, & Posner, 2001; Fossella, Posner, Fan, Swanson, & Pfaff, 2002; Fossella et al., 2002). FMRI studies of the ANT confirm that it activates three largely orthogonal networks (Fan et al., 2001; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). The fMRI foci of the Conflict network show anterior cingulate cortex (ACC) and prefrontal cortex (PFC) activation; the Orienting network shows parietal activation; and the Alerting network shows fronto-parietal cortical activation in addition to thalamic activation. Pharmacological studies (Marocco & Davidson, 1998) have related each of the networks predominantly to a specific chemical neuromodulator: ACC and lateral PFC are target areas of the mesocortical dopamine system, involved in C; cholinergic systems arising in the basal forebrain play an important role in O; and the norepinephrine system arising in the locus coeruleus of the midbrain is involved in A.

Roberts, Summerfield, and Hall (2006) directly compared auditory and visual presentations of the ANT, and Callejas, Lupianez, Funes, and Tudela (2005) studied mixed modalities, utilizing auditory cues to index A and visual cues to index O. However, neither of these studies addressed hemispheric differences in attention. Konrad et al. (2005) modified the ANT by presenting the target stimuli to the left and right of fixation in order to resemble typical cueing paradigms. However, the stimuli were not flashed briefly to one visual field, and the authors did not examine visual field as a factor in their analysis.

The goal of this paper is to describe an adaptation of the ANT to lateralized presentations. The lateralized ANT (LANT) is aimed at assessing the attentional capacity of each hemisphere and the hemispheric status of each network. Our goal was to first provide a battery that successfully measures each component of attention (C, O, and A) separately in each hemisphere. Once this was achieved, we modified the LANT to improve the task in a second experiment. In both experiments, we investigated the independence of all the networks, the reliability of the tests, and the attentional capabilities of each hemisphere.

2. Experiment 1

By rotating the ANT stimuli 90° and using tachisto-scopic presentation, we developed a variation of the task to assess the three attentional networks in each hemisphere. In the present experiment, we compared performance of normal participants on the ANT to the LANT and to the data reported by Fan et al. (2002). One issue addressed is the capacity for each hemisphere to support each attentional network. Another is the hemispheric specialization for the component networks. In addition, we further examined the alleged independence of the networks and the reliability of the measures.

2.1. Methods

2.1.1. Participants

Twenty-three right-handed young Israeli adults (11 men and 12 women) volunteered to participate in the experiment. None had a psychiatric or neurological history, learning disability or attention deficit, assessed by self-report. Handedness was evaluated with a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971).

2.1.2. Apparatus

Stimuli were presented via E-Prime on an IBM-compatible Pentium III personal computer, with a 733 MHz CPU, running Windows 98. Stimuli were presented on a 15″ MAG X3770 monitor with a refresh rate of 85 Hz and a resolution of 1024 × 768 pixels. Participants viewed the screen from a distance of 57 cm, and responses were collected unimanually from a computer mouse placed in front of the subject at midline.

2.1.3. Stimuli

Attention Network Test (ANT) targets consisted of a leftward or a rightward arrow centered 1.06° of visual angle above or below the fixation. This target arrow was flanked on each side by two arrows in the same direction (congruent condition), in the opposite direction (incongruent condition), or by lines without arrowheads (neutral condition). The participants' task was to identify the direction of the centrally presented arrow. A single arrow or line subtended 0.55° of visual angle, and the contours of adjacent arrows or lines were separated by 0.06° of visual angle. The stimuli (one central arrow plus four flankers) subtended a total of 2.99° of visual angle.

Targets were preceded by one of four types of cues: no cue, center cue, double cue, or a valid spatial cue. For the no-cue trials, participants saw only a fixation. For the center-cue trials, participants were shown an asterisk at the location of the center fixation cross. For the double-cue trials, there were two asterisks corresponding to the two possible target locations—up and down. For the valid-cue trials, the cue was at the target position.

Performance in the incongruent-flanker condition minus performance in the congruent-flanker condition defined the Conflict (C) or executive component of attention. Alerting (A) was defined as performance in the no-cue condition minus performance in the double-cue condition. Orienting

(O) was defined as performance in the center-cue condition minus performance in the valid-cue condition.

Each trial consisted of five events. First, there was a fixation period for a random variable duration (400–1600 ms). Then, the warning cue was presented for 100 ms. There was a short fixation period for 400 ms after the warning cue and then the target and flankers appeared simultaneously. The target and flankers remained on the screen until the participant responded, but for no longer than 1700 ms. After participants made a response, the target and flankers disappeared immediately and there was a post-target fixation period for a variable duration, which was based on the duration of the first fixation and reaction time (RT) (3500 ms minus duration of the first fixation minus RT). After this interval, the next trial began. Each trial lasted for a total of 4000 ms. The fixation cross was present at the center of the screen during the entire trial.

Fig. 1 displays the experimental procedure for the LANT. This simple variation of the ANT rotates each stimulus display 90° clockwise to present lateralized targets. Thus, targets consisted of an upward or a downward arrow centered 1.15° of visual angle to the right or left of fixation. Each single arrow or line subtended 0.57° of visual angle, and the contours of adjacent arrows or lines were separated by 0.06° of visual angle. The entire stimuli (one central arrow plus four flankers) subtended a total 3.09° of visual angle. Each trial began with a fixation period of 150 ms, followed by the presentation of the warning cue for 100 ms. Then there was a fixation period for 750 ms, after which the target stimulus was flashed for 170 ms in order to isolate the information to one hemisphere. Next, there was a 1500 ms response period that ended once participants responded. Finally, there was another fixation period of 1000 ms. Each trial lasted a variable length ranging from 2235 ms (the fastest response)—3670 ms, depending on response time.

2.1.4. Design

The ANT had a 3 (Flanker type: neutral, congruent, incongruent) × 4 (Cue type: none, center, double, valid) factorial design. The LANT had a 3 (Flanker type: neutral,

congruent, incongruent) × 2 (Target Visual Field: left, right) × 4 (Cue type: none, center, double, valid) factorial design.

2.1.5. Procedure

Participants were first exposed to a 24-trial practice block, in which they received feedback for their speed and accuracy. This was followed by four experimental blocks for each test (ANT and LANT), with 96 trials per block. Trials were presented in a random order within each block. The practice block lasted approximately 2 min, while the experimental blocks lasted approximately 6 min. Between blocks, participants were allowed a short break period to rest their eyes. The order of taking the ANT and LANT was counterbalanced across participants. The total session running both tests lasted approximately 1 h.

Participants were instructed to fixate on the central fixation cross at all times, and to respond to the direction of the target arrow as quickly and accurately as possible. For the ANT, responses were made by pressing the left key for left-pointing targets and the right key for right-pointing targets. Thus, "left" responses were made with the middle finger of the left hand or with the index finger of the right hand. "Right" responses were made with the index finger of the left hand or the middle finger of the right hand. Response hand alternated between blocks in the following order: left hand, right hand, left hand, right hand. For the LANT, responses were made unimanually on a mouse placed at midline on its side, facing the responding hand. Thus, "up" responses were made with index fingers, and "down" responses were made with middle fingers. Response hand alternated between blocks in a counterbalanced order.

2.2. Results

Prior to analysis, trials with a reaction time less than 230 ms and greater than 3 standard deviations from the grand mean for each test (ANT = 887 ms, LANT = 954 ms) were excluded. This procedure excluded 1.2% of trials in the ANT and 1.8% of trials in the LANT.

We performed repeated measures ANOVAs with accuracy and mean latency (ms) as dependent variables for the ANT and LANT. Only correct trials were used for latency analysis. Table 1 summarizes the data for the ANT and the LANT for each condition. Fig. 2 displays the estimates of the three components of attention for latency in each test. The effect of Conflict (C) was calculated by subtracting the mean effect of congruent-flanker trials from the mean effect of incongruent-flanker trials. Orienting (O) was calculated by subtracting the mean effect of valid-cue trials from the mean effect of center-cue trials. Alerting (A) was calculated by subtracting the mean effect of double-cue trials from the mean effect of no-cue trials. Whenever an effect involving Flanker or Cue was significant in the overall ANOVA, we followed it up with more specific ANOVAs involving C, O, and A.
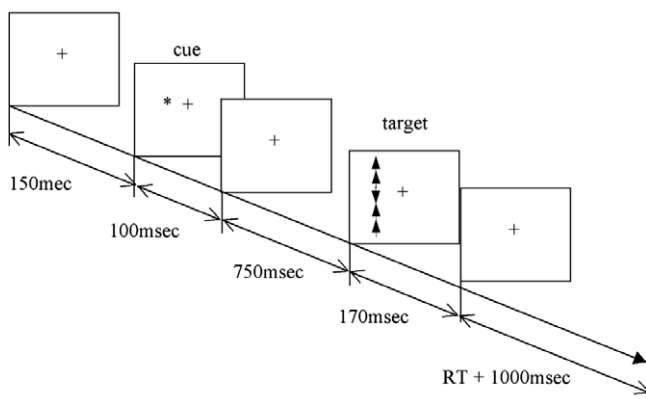

Fig. 1. LANT stimuli and experimental procedure.

Table 1
Mean accuracy and latency for each condition in the ANT and LANT

Congruency	Cue type			
	None	Center	Double	Valid
(a) ANT: mean accuracy				
Congruent	100(0.0)	99.7(1.0)	99.9(0.5)	99.9(0.5)
Incongruent	94.4(4.8)	95.7(7.2)	95.5(6.2)	95.3(6.7)
Neutral	99.5(1.0)	99.7(1.0)	99.7(1.0)	99.9(0.5)
(b) ANT: mean latency				
Congruent	491.1(55.7)	483.6(58.6)	481.7(58.5)	474.2(60.3)
Incongruent	597.3(62.8)	599.1(62.3)	598.7(64.0)	579.3(76.3)
Neutral	478.2(53.2)	477.0(60.0)	477.9(54.0)	466.5(57.1)
(a) LANT LVF: mean accuracy				
Congruent	98.9(2.4)	98.4(3.4)	99.2(2.9)	99.7(1.4)
Incongruent	89.0(14.4)	92.1(13.4)	89.8(12.0)	94.4(10.6)
Neutral	98.4(3.4)	98.4(3.4)	97.3(5.3)	99.4(1.9)
(b) LANT LVF: mean latency				
Congruent	574.1(62.3)	558.4(61.0)	553.4(66.2)	521.4(64.0)
Incongruent	657.1(70.3)	636.2(74.4)	639.3(75.2)	590.3(80.5)
Neutral	563.9(50.9)	550.2(63.8)	555.3(54.8)	516.4(56.2)
(a) LANT RVF: mean accuracy				
Congruent	98.3(4.3)	98.1(3.4)	99.2(1.9)	97.8(4.8)
Incongruent	93.7(10.6)	93.9(12.5)	89.0(18.7)	94.3(9.6)
Neutral	97.6(4.8)	97.3(3.8)	98.2(3.4)	98.7(3.8)
(b) LANT RVF: mean latency				
Congruent	565.1(57.9)	535.8(67.2)	539.6(51.0)	520.3(57.7)
Incongruent	631.4(70.7)	625.6(85.4)	629.8(84.8)	584.1(76.3)
Neutral	556.6(58.9)	536.5(59.9)	535.2(57.0)	509.7(56.4)

Note. Values are listed as "mean (standard deviation)" in % correct for accuracy and ms for latency.

2.2.1. Attention network test (ANT)

We carried out a 3 (Flanker: congruent, incongruent, neutral) × 4 (Cue: none, center, double, valid) ANOVA on mean latency. There was a main effect of Flanker reflecting that performance on incongruent-flanker trials ($M = 593.59$) was significantly slower than congruent-flanker trials ($M = 482.64$), which in turn was significantly slower than neutral-flanker trials ($M = 474.89$), $F(2, 44) = 284.51$, $p < .001$. The main effect of Cue was also

significant $F(3, 66) = 6.44$, $p < .001$. Follow-up ANOVA's investigating O and A showed that valid-cue trials ($M = 506.66$) were significantly faster than center-cue trials ($M = 519.88$), defining O, $F(1, 22) = 8.69$, $p = .007$, but there was no significant difference between double-cue trials and no-cue trials that define A.

The same 3 × 4 ANOVA was carried out on accuracy scores. The main effect of Flanker was significant $F(2, 44) = 18.46$, $p < .001$, revealing higher accuracy for congruent-flanker trials ($M = 99.9\%$) than incongruent-flanker trials ($M = 95.2\%$), defining C. There was no significant difference between neutral flankers and congruent flankers. The effect of Cue was not significant.

2.2.2. Lateralized attention network test (LANT)

To measure the attention networks in each hemisphere, we included Target Visual Field (LVF, RVF) as a factor, resulting in a 3 × 4 × 2 ANOVA. For latency, we found a main effect of Flanker $F(2, 44) = 114.73$, $p < .001$, demonstrating significantly slower performance for incongruent-flanker trials ($M = 624.24$) than for congruent-flanker trials ($M = 546.07$), and somewhat slower performance for congruent-flanker trials than for neutral-flanker trials ($M = 540.49$ ms) ($p = .068$). There was also a main effect of Cue, $F(3, 66) = 53.0$, $p < .001$. Follow-up ANOVAs showed that valid-cue trials ($M = 540.37$) were significantly faster than center-cue trials ($M = 573.81$), $F(1, 22) = 48.7$, $p < .001$, and double-cue trials ($M = 575.50$) were significantly faster than no-cue trials ($M = 591.38$), $F(1, 22) = 20.5$, $p < .001$. The main effect of VF was significant, such that the RVF ($M = 564.15$ ms) was faster than the LVF ($M = 576.38$ ms), $F(1, 22) = 13.81$, $p = .001$. We also found a significant C × O interaction, reflecting a larger O in incongruent-flanker trials ($M = 43.68$ ms) than in congruent ones ($M = 26.25$ ms), $F(1, 22) = 5.38$, $p = .030$. There was a trend towards a significant O × VF interaction reflecting a larger O in the LVF ($M = 41.41$ ms) than in the RVF ($M = 28.52$ ms), $F(1, 22) = 3.72$, $p = .067$. The C × VF × A interaction also almost reached significance, reflecting that in the RVF A was significant for congruent trials but not incongruent trials $F(1, 22) = 4.20$, $p = .053$.
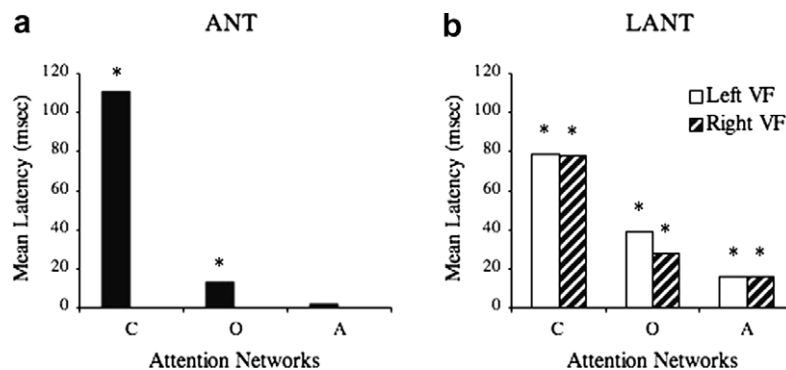

Fig. 2. Latency estimates of the Conflict (C), Orienting (O), and Alerting (A) networks of attention in the (a) ANT and (b) LANT for Experiment 1 ($N = 23$); * = significant.

We conducted separate 3×4 ANOVAs for each visual field. We found significant effects of Flanker in the LVF $F(2, 44) = 102.31$, $p < .001$, and in the RVF $F(2, 44) = 95.88$, $p < .001$. The difference between congruent-flanker trials and incongruent-flanker trials was significant in the LVF $F(1, 22) = 115.53$, $p < .001$, and in the RVF $F(1, 22) = 87.28$, $p < .001$, defining C. In the LVF, there was no significant difference between neutral and congruent flanker trials, but in the RVF, neutral-flanker trials ($M = 534.51$ ms) were somewhat faster than congruent-flanker trials ($M = 540.23$ ms), $F(1, 22) = 3.99$, $p = .058$. The main effect of Cue was also significant in the LVF $F(3, 66) = 46.57$, $p < .001$, and in the RVF, $F(3, 66) = 28.98$, $p < .001$. In both VF's, valid-cue trials (LVF $M = 542.71$, RVF $M = 538.03$) were significantly faster than center-cue trials (LVF $M = 581.61$, RVF $M = 566.0$), and double-cue trials (LVF $M = 582.8$, RVF $M = 568.2$) were significantly faster than no-cue trials (LVF $M = 598.38$, RVF $M = 584.38$), rendering significant effects of O and A. In the RVF, there was a significant C × O interaction, such that O was greater for incongruent-flanker trials ($M = 41.50$ ms) than congruent ones ($M = 15.53$ ms), $F(1, 22) = 5.92$, $p = .024$. There was also a significant C × A interaction, such that A was only significant in congruent-flanker trials ($p = .001$), but not incongruent-flanker trials, $F(1, 22) = 5.87$, $p = .024$. Thus, in the RVF there was a larger O in the incongruent trials, but a larger A in the congruent trials.

The same $3 \times 4 \times 2$ ANOVA was carried out on accuracy scores. The main effect of Flanker reflected that incongruent-flanker trials ($M = 92\%$) were significantly less accurate than congruent-flanker trials ($M = 98.7\%$) and neutral-flanker trials ($M = 98.1\%$), $F(2, 22) = 8.34$, $p = .001$. Neutral-flanker trials were only somewhat less accurate ($M = 98.1\%$) than congruent-flanker trials ($M = 98.7\%$) ($p = .07$). We found a main effect of Cue $F(1, 22) = 4.77$, $p = .04$, revealing that valid-cue trials ($M = 97.4\%$) were significantly more accurate than center-cue trials ($M = 96.4\%$), but no difference between double and no-cue trials.

When examining the visual fields separately, we found significant effects of Flanker in the LVF $F(1, 22) = 10.77$, $p < .001$, and in the RVF $F(1, 22) = 5.2$, $p = .009$. In both VF's, incongruent-flanker trials (LVF $M = 91.3\%$, RVF $M = 92.7\%$) were significantly less accurate than congruent-flanker trials (LVF $M = 99.1\%$, RVF $M = 98.4\%$) and neutral-flanker trials (LVF $M = 98.4\%$, RVF $M = 97.9\%$). The effect of Cue was significant in the LVF, $F(3, 66) = 4.59$, $p = .006$, reflecting higher accuracy in valid-cue trials ($M = 97.9\%$) than in center-cue trials ($M = 96.3\%$) (O), but no difference between double and no-cue trials (A). The effect of Cue was not significant in the RVF.

2.2.3. Split-half reliability
We calculated the Pearson r product moment correlations for the first two blocks of each test with the second

Table 2
Reliability of Conflict (C), Orienting (O), and Alerting (A) measured by correlation of first vs. second half of the tests

	ANT (N = 23)	LANT (N = 23)			ANT (N = 40)
		Overall	LVF	RVF	(Fan et al.)
C	.741***	.786***	.686***	.585**	.770
O	.708***	.330	.115	.521*	.610
A	.145	.194	−.101	.235	.520

Note. Boldface indicates significance; *p ⩽ .05, **p ⩽ .01, and ***p ⩽ .001.

two blocks across subjects. The first and second halves were balanced for stimuli and response hand. Latency estimates were used, as the very high accuracy scores did not provide as robust estimates of the networks. Table 2 displays these correlations for the ANT and LANT. C was reliable in the ANT and both VF's, measured by the LANT. O was reliable in the ANT and LANT-RVF, and A was not reliable in any test.

2.2.4. Intercorrelations among the three component networks
Table 3 displays correlations across attention networks and tests. To examine the mutual independence of the networks, we calculated the correlations among the networks for latency in the ANT and in each VF of the LANT. This yielded no significant correlations between networks in both tests, suggesting network independence. To investigate the independence of the networks between hemispheres, we next examined correlations between the two VF's for each network in the LANT. There were significant correlations between C in the two hemispheres and between O in the two hemispheres, but not for A. Finally, we correlated each network of the ANT with the corresponding networks in the LVF and the RVF of the LANT in order to compare the effects of central and lateralized presentation. This demonstrated that C in the ANT was significantly correlated with C in the LANT overall and with C in each VF. The other networks were not correlated between tests.

2.3. Discussion

This experiment presents a simple variation of the ANT that efficiently measures the Conflict, Orienting, and Alerting attentional networks in each normal cerebral hemisphere. Examining both latency and accuracy measures, we found that latency provided a more sensitive index of performance, especially in view of the high overall accuracy rate (98%).

Our first goal was to determine if each hemisphere can support all three networks of attention. The LANT provided significant measures of all three in latency as well as significant C and O in accuracy, indicating that each hemisphere is capable of supporting the networks. In the ANT, our dataset yielded consistently lower estimates of the networks than the dataset of Fan et al. (2002), and our estimate of A was not significant in either latency or

Table 3
Pearson r cross-correlations among the three attention networks within and across the ANT and the LANT for latency

	ANT			LANT-LVF			LANT-RVF		
	C	O	A	C	O	A	C	O	A
ANT									
C		.028	.339	**.680*****	.049	.061	**.669*****	.089	−.016
O			.225	.078	.222	.321	−.028	.311	.353
A				.130	.156	−.141	.185	−.005	−.295
LANT-LVF									
C					−.379	.237	**.740*****	−.142	.051
O						.369	−.158	**.494***	−.110
A							.196	−.011	.100
LANT-RVF									
C								−.076	−.014
O									.294

Note. Significant correlations are indicated in boldface; $^{*}p \leqslant .05$, $^{**}p \leqslant .01$, and $^{***}p \leqslant .001$.

accuracy. Since there were no methodological differences between this version of the ANT and that of Fan et al., this discrepancy is perplexing. Perhaps the difference is attributable to our smaller sample size ($N = 23$ vs. 40), which was younger (mean age 23 years vs. 30.1 years) and included fewer women (52% vs. 57%). With 23 participants, the power to detect an effect of cue at the .05 level of significance for latency in the ANT exceeds 80% ($\Phi = 1.7$).

We also aimed to investigate the hemispheric specialization of each attentional network. The LANT revealed a trend toward a significant O × VF interaction, showing that O was larger in the right hemisphere (RH) than in the left hemisphere (LH). Though only a trend ($p = .067$), this interaction suggests that the task is ''direct access'', i.e., processed independently in each hemisphere (Zaidel, Clarke, & Suyenobu, 1990). Thus, each target may be processed by the hemisphere it reaches first. We also correlated each network in the LVF with the corresponding network in the RVF. C and O, but not A, were correlated between VF's, demonstrating the similarity between the networks in the two hemispheres.

In our sample, like that of Fan et al., the ANT demonstrated independence of the networks. The LANT, on the other hand, exhibited significant interactions among networks. There was a curious dissociation between A and O in the RVF, such that A was significant only for congruent trials, whereas O was largest for incongruent trials. Regarding reliability, Fan et al. report more reliable estimates of all three networks. In our sample, C was reliable in all tests (ANT, LANT overall and in each VF), and O was reliable in the ANT and LANT overall, but not separately in each VF. A was not reliable in any test.

Direct comparisons between the ANT and LANT are not definitive here, since subtle methodological differences may generate different results. Since the ANT displays the target stimulus until a response is made, while the LANT presents the target briefly for 170 ms, we cannot ascertain whether differences in performance are due to the different stimulus exposure times or to the mode of presentation (central vs. lateralized). Thus, conclusions

regarding the correlations of networks between tests must be interpreted with caution.

Interestingly, neutral flankers did not provide the expected results. The ideal neutral would yield performance between that of incongruent-flanker trials and congruent-flanker trials, demonstrating the facilitatory effect of congruency and inhibitory effect of incongruency on Conflict. Instead, our data demonstrated no difference in performance for neutral-flanker trials and congruent-flanker trials. This result may be the consequence of a perceptual pop-out effect of the target arrow when flanked by lines without arrowheads. This would explain why trials with neutral flankers were no slower than, and even sometimes faster than, trials with congruent flankers. Further experiments that manipulate the number and nature of neutral flankers are necessary to test this hypothesis. On the other hand, if the neutral flankers here are indeed properly neutral, it would follow that Conflict reflects a purely inhibitory process.

Like Conflict, spatial Orienting includes an inhibitory process in addition to its facilitatory component. In the ANT and LANT, we measured the facilitatory effect of valid spatial cues, which give rise to a benefit in performance. However, we did not measure the inhibitory effect of invalid spatial cues, which give rise to a cost in performance. Without invalid cues, we were unable to investigate the relationship between the inhibitory component of Orienting and the other networks. Experiment 2 aims to address this issue, and presents modified versions of both the ANT and LANT.

3. Experiment 2

In this experiment, we first aimed to replicate the general findings of Experiment 1. Our next goal was to investigate the separate benefit and cost components of the Orienting network and to examine whether the two inhibitory networks (Orienting cost and Conflict) are subserved by the same underlying process. Valid spatial pre-target information (a cue in the location that the target will appear) leads

to a benefit in performance, Orienting$_{Benefit}$ (O$_B$), while invalid spatial information (a cue in a different location than where the target will appear) leads to a cost in performance, Orienting$_{Cost}$ (O$_C$) (Posner, 1980). In fact, these benefit and cost components have been associated with distinct ERP components, suggesting different underlying neural mechanisms (Hillyard, Luck, & Mangun, 1994). By including invalid cues in the ANT and LANT, we can separately measure both O$_B$ and O$_C$. The inhibitory effect of O$_C$ may be similar to that involved in Conflict (C) and they may engage the same cortical structures. Further, tasks sharing neural circuitry place demands on similar cognitive resources (Kinsbourne & Hicks, 1978), and therefore, should interfere and correlate with each other. Fan et al. (2003) described and compared three types of conflict: Stroop language conflict, flanker conflict (exactly as we define C), and spatial conflict (similar to O$_C$). Two brain regions, the ACC and left prefrontal cortex, were similarly activated in each type of conflict. However, they did not correlate with each other, indicating that they may tap into separate mechanisms after all. Measuring both C and O$_C$ in each hemisphere, we can further examine whether these are truly independent operations.

Experiment 1 compared the LANT to the ANT as the latter was originally constructed, with the stimuli remaining on the screen. To ensure that the target presentation time is equated between tests, Experiment 2 compares the modified LANT with a modified and fully matched ANT. We further investigated the independence of all the networks, reliability of the task, and the attentional capabilities of each hemisphere.

3.1. Methods

3.1.1. Participants
Twenty-seven right-handed undergraduate psychology students at the University of California Los Angeles (13 men and 14 women) participated in the experiment for course credit. None had a psychiatric or neurological history, learning disability or attention deficit, assessed by self-report. Handedness was assessed with a modified version of the Edinburgh Handedness Inventory (Oldfield, 1971).

3.1.2. Apparatus and stimuli
Apparatus and stimuli were the same as in Experiment 1, with the following modifications. For both the ANT and the LANT, neutral flankers were excluded, invalid cues were included, and the target stimuli were presented briefly. Invalid cues consisted of an asterisk cue appearing opposite to the impending target location, and occurred 1/4 as often as each of the other cues. This allowed for the division of Orienting into benefit and cost components. Orienting$_{Benefit}$ (O$_B$) was defined as performance in the center-cue condition minus performance in the valid-cue condition. Orienting$_{Cost}$ (O$_C$) was defined as performance in the invalid-cue condition minus that of the center-cue condition.

For both tests, the sequence of events began with a fixation period for a random variable duration (400–1600 ms), followed by an asterisk cue presented for 100 ms. Next, there was a short fixation period for 400 ms, after which the target and flankers appeared simultaneously for 170 ms. Finally, there was a post-target fixation period for a variable duration, based on the duration of the first fixation and the participant's RT for that trial (3500 ms minus duration of the first fixation minus RT). Each trial lasted for a total of 4170 ms.

3.1.3. Design
The ANT had a 2 (Flanker type: congruent, incongruent) × 5 (Cue type: none, center, double, valid, invalid) factorial design. The LANT had a 2 (Flanker type: congruent, incongruent) × 2 (Target Visual Field: left, right) × 5 (Cue type: none, center, double, valid, invalid) factorial design.

3.1.4. Procedure
The procedure of the experiment was the same as in Experiment 1, with the following exceptions. For both the ANT and LANT, there were two experimental blocks, each consisting of 136 trials and lasting 9 min. For both tests, response hand alternated in counterbalanced order. All other procedures were as reported in Experiment 1.

3.2. Results

As in Experiment 1, trials with a reaction time less than 230 ms and greater than 3 standard deviations from the grand mean for each test (ANT = 902 ms, LANT = 936 ms) were excluded. This procedure excluded 1.6% of trials in the ANT and 1.4% of trials in the LANT.

We performed repeated measures ANOVAs with mean latency (ms) as the dependent variable for correct trials in the ANT and LANT. Experiment 1 demonstrated latency to be the most meaningful measure, given the overall high accuracy rates. Table 4 summarizes the data for the ANT and the LANT for each condition. Fig. 3 displays the estimates of the components of attention in each test. The effects of the networks were calculated the same as in Experiment 1 with the addition of Orienting cost (O$_C$), calculated by subtracting the mean effect of center-cue trials from the mean effect of invalid-cue trials.

3.2.1. Attention network test (ANT)
We carried out a 2 (Flanker: congruent, incongruent) × 5 (Cue: none, center, double, valid, invalid) ANOVA on mean latency. There was a main effect of Flanker reflecting that performance on incongruent-flanker trials ($M = 568.94$) was significantly slower than congruent-flanker trials ($M = 482.90$), $F(1, 26) = 272.85$, $p < .001$. The main effect of Cue was also significant $F(4, 104) = 33.83$, $p < .001$. Follow-up ANOVAs investigating O$_B$, O$_C$, and A showed that valid-cue trials ($M = 496.86$) were significantly faster than center-cue trials ($M = 520.57$), defining O$_B$ $F(1, 26) = 24.54$, $p < .001$, center-cue trials were signifi-

Table 4
Mean latency for each condition in the ANT and LANT

Congruency	Cue type				
	None	Center	Double	Valid	Invalid
ANT					
Congruent	509.8(59.5)	475.0(61.4)	470.6(63.8)	456.3(61.4)	502.7(65.6)
Incongruent	583.8(74.2)	566.2(76.7)	563.2(73.4)	537.4(78.9)	594.2(72.9)
LANT LVF					
Congruent	561.6(66.1)	516.0(74.0)	501.5(73.2)	494.6(69.5)	539.8(80.9)
Incongruent	608.4(75.2)	580.9(77.1)	571.4(81.4)	540.2(71.3)	612.9(91.3)
(b) LANT RVF					
Congruent	566.3(76.3)	513.0(80.6)	506.7(66.9)	485.1(67.8)	541.1(85.9)
Incongruent	610.1(80.2)	586.0(87.1)	580.9(81.1)	550.8(84.3)	611.6(84.1)

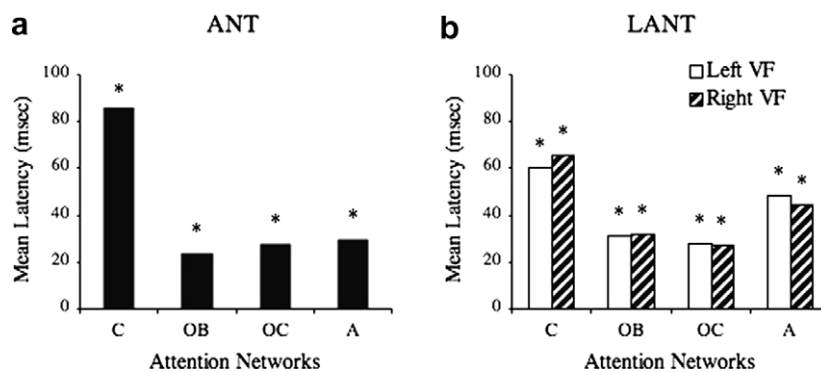*Note.* Values are listed as "mean (standard deviation)" in ms.

Fig. 3. Latency estimates of the Conflict (C), Orienting benefit (OB), Orienting cost (OC), and Alerting (A) networks of attention in the (a) ANT and (b) LANT for Experiment 2 ($N = 27$); ∗ = significant.

cantly faster than invalid-cue trials ($M = 548.48$), defining O_C $F(1,26) = 25.03$, $p < .001$, and double-cue trials ($M = 516.89$) were significantly faster than no-cue trials ($M = 546.82$), defining A $F(1,26) = 66.08$, $p < .001$. There was a trend toward a significant $C \times O_B$ interaction such that O_B was larger for incongruent-flanker trials ($M = 28.8$) than for congruent-flanker trials ($M = 18.62$), $F(1,26) = 3.10$, $p = .09$. There was also a significant $C \times A$ interaction such that A was larger for congruent trials ($M = 39.23$) than incongruent trials ($M = 20.63$), $F(1,26) = 9.12$, $p = .006$.

3.2.2. Lateralized attention network test (LANT)

The LANT included Target Visual Field (LVF, RVF) as a factor, resulting in a $2 \times 5 \times 2$ ANOVA. The significant effect of Flanker revealed slower performance for incongruent-flanker trials ($M = 585.32$) than for congruent-flanker trials ($M = 522.58$), $F(1,26) = 130.44$, $p < .001$. The main effect of Cue, $F(4,104) = 65.39$, $p < .001$, led to follow-up ANOVAs to investigate the distinct networks. These showed that valid-cue trials ($M = 517.67$) were significantly faster than center-cue trials ($M = 548.97$), $F(1,26) = 53.42$, $p < .001$, center-cue trials were significantly faster than invalid-cue trials ($M = 576.36$), $F(1,26) = 37.61$, $p < .001$, and double-cue trials ($M = 540.12$) were significantly faster than no-cue trials

($M = 586.61$), $F(1,26) = 119.68$, $p < .001$. Thus, we efficiently measured O_B, O_C, and A. There was a trend toward a significant $C \times O_B$ interaction, such that O_B was larger for incongruent-flanker trials ($M = 37.94$) than for congruent-flanker trials ($M = 24.65$), $F(1,26) = 3.69$, $p = .066$. There was also a significant $C \times A$ interaction, reflecting a larger A in congruent-flanker trials ($M = 59.85$) than in incongruent-flanker trials ($M = 33.12$), $F(1,26) = 20.72$, $p < .001$. The main effect of VF was not significant.

We conducted separate 2×5 ANOVAs for each visual field to investigate the networks separately in each hemisphere. There were significant effects of Flanker in the LVF $F(1,26) = 156.01$, $p < .001$, and in the RVF $F(1,26) = 77.81$, $p < .001$, and therefore significant estimates of C in both VF's. The main effect of Cue was also significant in the LVF $F(4,104) = 43.18$, $p < .001$, and in the RVF, $F(4,104) = 44.69$, $p < .001$. Valid-cue trials (LVF $M = 517.38$, RVF $M = 517.96$) were significantly faster than center-cue trials (LVF $M = 548.45$, RVF $M = 549.49$), which were significantly faster than invalid-cue trials (LVF $M = 576.35$, RVF $M = 576.37$), resulting in significant measures of O_B and O_C. Also, double-cue trials (LVF $M = 536.41$, RVF $M = 543.833$) were significantly faster than no-cue trials (LVF $M = 585.02$, RVF $M = 588.19$), rendering significant effects of A. In the LVF, there was a significant $C \times O_B$ interaction such that

O_B was larger for incongruent-flanker trials ($M = 40.73$) than congruent-flanker trials ($M = 21.39$), $F(1, 26) = 7.18$, $p = .013$, and a significant C × A interaction reflecting a larger A in congruent-flanker trials ($M = 60.17$) than incongruent-flanker trials ($M = 37.04$), $F(1, 26) = 5.70$, $p = .024$. In the RVF, the C × A interaction was significant, again revealing a larger A in congruent-flanker trials ($M = 59.52$) than incongruent-flanker trials ($M = 29.20$), $F(1, 26) = 16.0$, $p < .001$.

3.2.3. Split-half reliability

We calculated the Pearson r product moment correlations on latency for the first block of each test with the second block across subjects. The first and second blocks were balanced for stimuli and response hand. Table 5 displays these correlations for the ANT and LANT. C was reliable in the ANT, overall LANT (both VF's), and the RVF in the LANT. O_B was reliable in the ANT, overall LANT, and both VF's in the LANT. The other networks did not demonstrate significant reliability.

3.2.4. Intercorrelations among the three component networks

Table 6 displays correlations on latency across attention networks and tests. There was a significant negative correlation between C and O_C in the RVF in the LANT. No other correlations between networks were significant, suggesting mostly network independence. There was a significant correlation between C in the LVF and C in the RVF, but not for the other networks. We also found that C in the ANT was significantly correlated with C in each VF, and A in the ANT was significantly correlated with A in the LVF, but not the RVF. O_B and O_C were not correlated between tests.

3.3. Discussion

This experiment implemented modified versions of the ANT and the LANT in which neutral flankers were excluded, invalid cues were included, and the target stimuli were presented briefly. First, we aimed to replicate the findings from Experiment 1, and in general, our findings were similar. The modified ANT and LANT efficiently measured all networks of attention centrally and separately in each VF. The reliabilities were also similar between the two experiments. Again, interactions showed a dissociation between A and O_B, such that A was larger for congruent-flanker trials and O_B was larger for incongruent-flanker trials. The C × A interaction was more prominent in Experiment 2, as it was significant in the ANT and in both VFs of the LANT. The C × O_B interaction was present in the LVF in this experiment, rather than in the RVF as in Experiment 1, and was close to significant in the ANT. Interestingly, we did not find an O_B × VF interaction, following the trend found in Experiment 1.

We also investigated the cost component of Orienting and examined the relationship between the inhibitory effect of invalid cues and that of incongruent flankers. O_C was efficiently measured by the ANT and by each VF in the LANT. Therefore, like the other networks, it can be supported by both hemispheres. There were no interactions between O_C and C, indicating that the inhibitory processes tapped by each may be driven by distinct neural mecha-

Table 5
Reliability of Conflict (C), Orienting benefit (Ob), Orienting cost (Oc) and Alerting (A) measured by correlation of first vs. second blocks of the tests

	ANT	LANT		
		Overall	LVF	RVF
C	**.830*****	**.647*****	.341	**.677*****
Ob	**.654*****	**.476***	**.391***	**.407***
Oc	.172	.070	−.163	−.131
A	.184	.180	.322	−.100

Note. Boldface indicates significance; *$p \leqslant .05$, **$p \leqslant .01$, and ***$p \leqslant .001$.

Table 6
Pearson r cross-correlations among the attention networks within and across the ANT and LANT for latency

	ANT				LVF				RVF			
	C	OB	OC	A	C	OB	OC	A	C	OB	OC	A
ANT												
C		−.082	−.066	.075	**.661*****	−.066	.013	−.020	**.688*****	**.467***	−.311	.076
OB			.161	.193	.054	.166	−.043	−.047	.015	−.007	.345	.089
OC				.088	−.133	−.250	.169	.263	.209	.096	.100	.038
A					−.136	.221	−.203	**.441***	−.032	.271	.093	−.046
LVF												
C						−.056	−.124	−.041	**.660*****	.125	−.374	.053
OB							.032	−.319	**−.460***	.155	**.411***	−.131
Oc								−.164	−.087	.241	.254	.072
A									.035	−.160	−.214	.320
RVF												
C										.362	**−.397***	−.177
OB											.002	−.127
OC												−.229

Note. Significant correlations are indicated in boldface; *$p \leqslant .05$, **$p \leqslant .01$, and ***$p \leqslant .001$.

nisms. However there was a negative correlation between O_C and C in the RVF.

By controlling for target stimulus presentation time and the experimental procedure of each trial, we were able to directly compare the two tests in Experiment 2. Correlations between the tests demonstrated that C in the ANT was correlated with C in both VFs in the LANT. However, A in the ANT was correlated only with A in the LVF of the LANT. Thus, while each hemisphere is capable of efficiently supporting Alerting, it may be dominated by the right hemisphere.

4. General discussion

The goal of the present study was to utilize a lateralized adaptation of the attention network test by Fan et al. (2002) in order to assess the status of attentional networks within each hemisphere. The first experiment introduced the lateralized ANT (LANT), which provided efficient estimates of the Conflict (C), Orienting benefit (O_B), and Alerting (A) attention networks. The second experiment improved upon the task by excluding uninformative, neutral flankers and including a measure of the cost component of Orienting (O_C). Again, all networks were efficiently measured by both tests.

Experiment 2 showed no interactions between networks and Visual Field (VF) even though the $O_B \times VF$ interaction was nearly significant in Experiment 1. The absence of an interaction is inconsistent with well-known clinical and imaging data that show clear hemispheric asymmetries in attention. Long-standing clinical data on patients with hemi-neglect consistently support the idea that right parietal damage leads to more severe and lasting impairments in visuospatial orienting (for a review, see Mesulam, 1999). In normal participants, imaging data demonstrate right parietal activation on covert spatial orienting tasks (Corbetta et al., 2000; Thiel, Zilles, & Fink, 2004). A common account of the orienting asymmetry posits that the left hemisphere is responsible for shifting attention to the RVF, while the right hemisphere is involved in attentional shifts in both VF's (Heilman, 1995; Kolb & Whishaw, 1990; Zaidel, 1995). However, behavioral data on covert orienting tasks in normal participants do not always yield laterality effects (interactions with visual field) (Losier & Klein, 2004; Nagel-Leiby, Buchtel, & Welch, 1990). Likewise, our task may eschew laterality effects by drawing attention automatically to each hemisphere with quick, discrete trials. By lateralizing the stimuli, we tap the competence of each hemisphere alone rather than measuring performance under central conditions. Thus, the networks can operate independently, though similarly, in each hemisphere when directly probed, but may make only partial and asymmetric contributions to central presentations.

The results from this study question the independence of the attention networks, as both experiments yielded significant $C \times A$ and $C \times O_B$ interactions. This suggests that C shares processing components, albeit different ones, with

O_B and with A. A was consistently larger for congruent-flanker trials, while O_B was consistently larger for incongruent trials. Thus, the more one is engaged in Conflict resolution processing, the less benefit will be gained from a temporally alerting cue (A). In contrast, more engagement in Conflict resolution also leads to an increase in benefit from a spatial cue (O_B). Given that both A and O_B are facilitatory, this result is perplexing. It suggests that O_B and A may use fundamentally different processes with different resources allocated to them, yet they both interact with C. The LANT in Experiment 1 yielded the $C \times O_B$ interaction in the RVF, while the LANT in Experiment 2 exhibited this interaction in the LVF. Thus, the lack of independence of the component networks can occur in either hemisphere. However, it is possible that an interaction may be driven by a third, unrelated factor, so that a more definitive argument for independence can still be made. For example, the absence of an interaction in one dependent variable, even in the presence of an interaction in another dependent variable, suggests independence. Similarly, if it is possible to modulate one network without affecting the other, then they must be independent. Future studies that aim to manipulate the networks selectively could resolve this issue of independence.

The reliability of the networks was generally high for C and O_B, but insignificant for O_C and A. The poor reliability scores may be attributable to the fact that the number of trials included for measuring O_C is much smaller than that for the other networks due to the infrequency of invalid cues. Additionally, when analyzing each VF separately, the number of trials decreased by half, further lowering power. More importantly, unreliability may be due to the fact that networks are defined as difference measures. Consequently, even though each defining trial type (e.g., trials preceded by double cues or trials preceded by no cue) may be highly reliable, the difference (i.e., A) may not be, due to a high cross-correlation between the two trial types. Unfortunately, correlations among the networks are limited by these low reliability coefficients. In principle, it is possible to correct for unreliability when estimating the correlations between networks (Nunnally & Bernstein, 1993). However, in our case correcting for attenuation yields uninterpretable results due to low reliabilities of some of the network estimates. Consequently, we must interpret with caution the correlations among the networks.

The C and O_B networks were both correlated between the two hemispheres, whereas the low reliabilities of the other networks preclude precise computation of the correlation coefficients. However, the presence of a significant correlation does not show that one hemisphere controls the operation of any attentional network in both visual fields ("callosal relay"). Callosal relay would imply exclusive specialization in one hemisphere, and it should exhibit a significant main effect of Target Visual Field, reflecting the time for callosal transfer (Zaidel, 1983). However, no such effect was present in Experiment 2, supporting the conclusion that the LANT is a "direct access" task. A similar inference in

support of "direct access" follows from the nearly significant interaction of $O_B \times$ Target Visual Field in Experiment 1. Taken together, the data suggest that the LANT reflects independent and similar networks in the two hemispheres.

We conclude that the LANT is a useful extension of the ANT, yielding significant estimates of the attentional networks in each hemisphere. The ability to tap the competence of each hemisphere is useful for detecting and interpreting the effects of unilateral lesions or of other pathologies with hemispheric differences in attention. The inclusion of invalid cues yields estimates of the inhibitory component of spatial Orienting in addition to the facilitatory component, and we recommend this modification for future use of the tests. The limited reliabilities of O_C and A suggest that the present version of the test may not serve well to characterize stable individual differences in attention for individual case studies. Further improvements that increase the reliability of the measures are necessary. Nonetheless, the LANT is a powerful measure of group differences in attention. The LANT provides, in a single test, a relatively quick assessment of three components of attention separately in each hemisphere. These components may be selectively and asymmetrically impaired in a particular population, and therefore, an efficient and simple test that can assess all components is highly valuable.

Acknowledgments

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