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Repeated measurement of the components of attention using two versions of the Attention Network Test (ANT): Stability, isolability, robustness, and reliability

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ABSTRACT

Using orthogonal subtractions of performance in selected conditions the attentional network test (ANT) measures the efficacy of three isolable components of attention: alerting, orienting, and executive control. Ten test sessions, each containing two versions of the ANT (Fan et al., 2002; Callejas et al., 2005), were administered to 10 young adults to examine stability, isolability, robustness, and reliability of the tests. Participants indicated the direction of a target arrow presented either above or below the fixation. The target arrow was accompanied by distracting arrows, either pointing to the same direction (congruent) as or the opposite direction (incongruent) to the target arrow. The arrows were preceded by informative visual cues (central, double, spatial, and no cue) differing in temporal and spatial information (Fan et al.) or by alerting auditory signals (tone and no tone) and uninformative visual cues (valid, invalid, and no cue) (Callejas et al.). All network scores remained highly significant even after nine previous sessions despite some practice effects in the executive and the orienting networks. Some lack of independence among the networks was found. The relatively poor reliability of network scores with one session of data rises to respectable levels as more data is added.

1. Introduction

The original Attention Network Test (which we will refer to it simply as 'ANT') was developed by Fan et al. (2002) to measure three isolable attentional networks: alerting, orienting, and executive attention. These networks are defined jointly in anatomical and functional terms, by finding correspondence between areas of activation in the brain and performance in attention tasks which measure different functions of attention. Alerting involves a change in mental state as well as some changes in physiological state. These changes follow the presentation of a signal that provides information that a task-relevant event will occur soon (Posner, 1978). Right hemisphere and thalamic areas are involved in alerting (e.g., Coull et al., 1996; Sturm and Willmes, 2001). Orienting involves turning one's attention to a source of signals in space (Posner, 1978). Areas of the parietal lobe, the midbrain, and the thalamus have been associated with this function (Posner and Raichle, 1994). Executive attention involves conflict resolution and control over decision-making, error detection, and habitual response inhibition (Norman and Shallice, 1986). The anterior cingulate cortex and the lateral prefrontal cortex have been associated with this function (e.g., Bush et al., 2000; Casey et al., 2000).

The ANT is a simple, yet carefully designed, test of performance in which specific subtraction scores are used to measure the efficiency of three different attention networks (Klein, 2003). On each trial, different types of warning cue precede a central target arrow, pointing either left or right, that is often flanked by distracting arrows (Fig. 1A). The participants' task is to indicate the direction of the target arrow as quickly and accurately as possible. The efficiency of the alerting and orienting networks are measured by comparing performance in the different types of cue condition (central, double, spatial, and no cues); the efficiency of the executive network is measured comparing performance in the different types of target congruency condition (congruent and incongruent) (Table 1). Fan et al. (2002) demonstrated that the ANT provides a reliable measure of each network (alerting, orienting and executive attention). In addition, they suggested that each network was independent of the others by showing no significant correlations among the network scores. However, they also reported an interaction between the cue condition and target congruency (as have others, see e.g., Ishigami and Klein, 2009), suggesting some lack of independence among the networks. It is partly for this reason that we use the weaker term (from Posner, 1978) "isolable" when describing relationships among the three attention networks.

As noted by Callejas et al. (2005) there are limitations of the ANT as described above. First, the alerting and the orienting networks are both defined by cue condition (i.e., alerting = double cue minus no cue conditions, orienting = center cue minus spatial cue conditions). Consequently, we cannot know whether the alerting and

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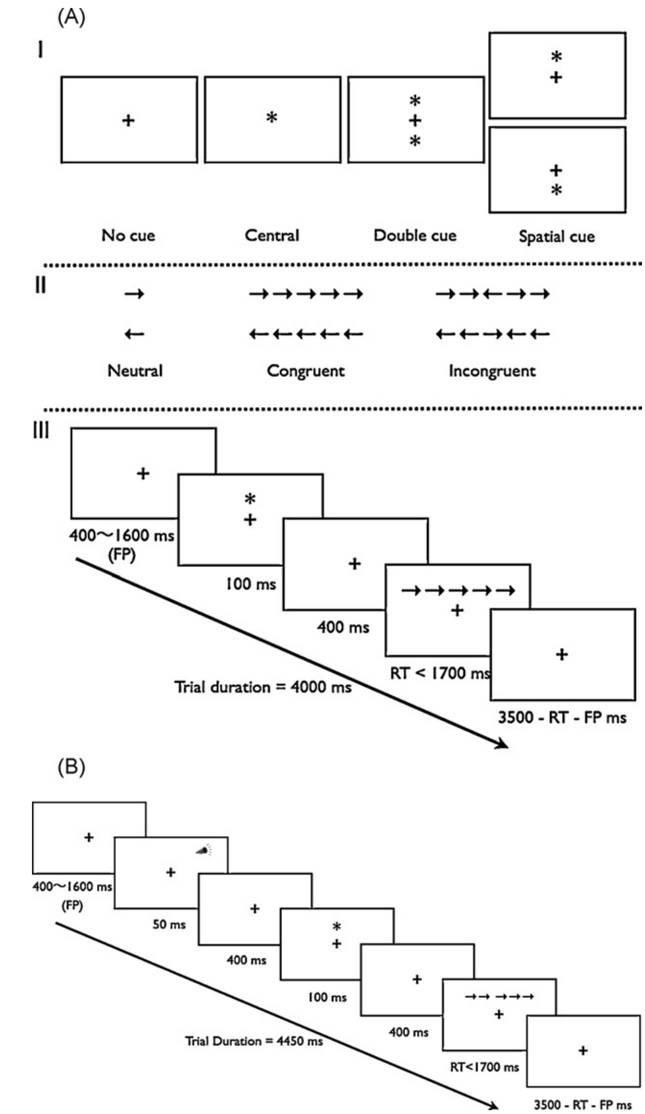

Fig. 1. (A) Experimental procedure of the ANT (Fan et al., 2002). (I) The four cue conditions. (II) The six stimuli used in the present experiment and (III) an example of the procedure; a spatial cue is presented followed by a target (central) arrow. (B) Experimental procedure of the ANT-I (Callejas et al., 2005). An example of the procedure; an auditory tone is presented, followed by a valid cue, and a target (central) arrow flanked by congruent arrows.

Table 1
Conditions and their levels in the ANT and the ANT-I.

	ANT	ANT-I
Auditory signal	NA	Tone No tone
Cue condition (ANT), visual cue (ANT-I)	No cue Central cue Double cue Spatial	No cue Valid Invalid
Target congruency	Neutral Congruent Incongruent	Congruent Incongruent
Subtractions for each network		
Alerting	No cue–double cue	No tone–tone
Orienting	Central cue–spatial cue	Invalid–valid
Executive	Incongruent–congruent	Incongruent–congruent

the orienting networks interact. Relatedly, we cannot separate a potential interaction between the alerting and orienting networks from the significant interaction between cue condition and target congruency, which Fan et al. (2002) reported. Second, their peripheral cue (spatial cue condition), one of the two cue conditions used to define the orienting network, predicts the target location with 100% validity. The combination of information value with peripheral cueing means that the measure of orienting (central minus peripheral cue) has indeterminate contributions from exogenous and endogenous shifts of attention (Klein, 2004). In the model cueing task developed by Posner and colleagues (e.g. Posner, 1980; see Klein, 2005, for a review) orienting is measured as the difference in performance following a peripheral (or central arrow) cue between targets presented at the cued location versus targets presented at the opposite, uncued location. Importantly, in both of these conditions the participant's attention is in the same general state (captured by a peripheral cue or allocated in response to the central arrow cue) regardless of where the target is presented. Mental state is necessarily different with the use of a cue with 100% validity, which is compared to a neutral cue to generate a subtraction score (see Jonides and Mack, 1984, for a discussion of this problem).

Callejas et al. (2005) developed an alternative version of the ANT [we will refer to it as the Attention Network Test-Interactions (ANT-I)] to overcome these limitations (Fig. 1B, Table 1). As with the ANT, the orienting and executive networks are defined by the visual cue (valid and invalid) and target congruency (congruent and incongruent), respectively. However, the alerting network is defined by auditory signals (tone and no tone). The separation of the alerting (auditory) from the orienting (visual) cues permits the researcher using this task to explore performance as a joint function of orienting (valid vs invalid) and alerting (tone vs no tone). A secondary benefit of this change derives from the possibility that auditory signals have greater alerting effects than visual signals (Posner, 1978; Posner et al., 1976). Thus, this design permits the researcher to examine the interaction among the networks with confidence. In addition, uninformative peripheral cues were used to define the orienting network in the ANT-I. The use of uninformative peripheral cues allows the researcher to measure the effect of exogenous orienting while excluding the endogenous component. Callejas et al. reported statistical interactions among all the networks. The executive network is inhibited by the alerting network (see also Posner, 1994), but facilitated by the orienting network (see also Funes et al., 2007). In addition, the orienting network is facilitated by the alerting network especially when stimulus onset asynchrony (SOA) is short (i.e., 100 ms rather than 500 ms, which is used in the current study) (see also Sturm et al., 2006; Thimm et al., 2006). Thus, Callejas et al. concluded that the attentional networks in the ANT operate interactively.

Both versions of the ANT (i.e., the ANT and the ANT-I) provide convenient measures of attentional networks (alerting, orienting, and executive attention). It takes only about 20 min to complete, and it is easily performed by children, older adults, brain damaged patients, and even monkeys (e.g., Beran et al., 2003; Jennings et al., 2007; Rueda et al., 2004). Thus, it can be used in variety of contexts (e.g., clinical, genetic, etc.) to address a wide range questions about attention. Indeed, since the original version of the ANT was introduced by Fan et al. (2002) versions of the test have been used in over 60 publications dealing with a wide range of topics and methods including: development, neuroimaging, pharmacology, genetics, psychiatric disorders, brain damage, individual differences, etc. One class of situation to which the ANT might be applied are those in which repeated testing is required. For example, Tang et al. (2007) examined effects of meditation training on alerting, orienting, and executive function (see also Jha et al., 2007). Eighty university students were randomly assigned to either an experimental or control group. The students in the experimental group received meditation training and the students in the control group simply received information about relaxation of each body part. The ANT was administered before and after five training or information sessions. The students in the experimental group showed more efficient executive function after the training sessions than the students in the control group while there were no differences in alerting and orienting between these two groups after the sessions. Thus, the ANT can be and has been used to evaluate effects of training on the components of attention. Researchers have also been interested in evaluating effects of attention training or rehabilitation on the specific components of attention in clinical populations (e.g., Pero et al., 2006; Robertson et al., 1995; Serino et al., 2007; Sohlberg et al., 2000; Sturm et al., 1997, 2006; Thimm et al., 2006).

Despite the use of the ANT in pre-/post-testing (Jha et al., 2007; Tang et al., 2007) and its potential use in clinical settings (e.g., Robertson et al., 1995), how performance of the three attention networks changes over time with repeated administrations and whether performance in the two versions the ANT (i.e., the ANT and the ANT-I) changes in the same way are not known. Thus, the primary objective of the current study is to examine the stability, robustness and reliability of the attention networks derived from both versions of the ANT over repeated testing. Once we had collected a large corpus of data it was also possible to examine the isolability of the network scores derived from each version. A secondary objective was to compare the two versions of the ANT: to determine if there were any substantial differences in their utility and to determine whether they were tapping the same three components of attention. The temporal stability of the scores was examined by analysis of variances (ANOVAs) with session as a factor to determine whether the magnitude of the score was changing with practice on the task. The robustness of the scores was examined using one-sample *t*-tests to evaluate the significance of each component's score in the different testing sessions. Reliability (or intra-subject stability) was examined by computing for each score the correlation across different combinations of sessions (as will be described in more detail later). Finally, isolability was examined in two ways: By determining whether there were significant interactions among the measures of the networks in the ANOVAs and whether there were significant correlations among the three networks. In the current study, the aforementioned analyses were made possible by having each participant perform both versions of the ANTs on 10 different occasions.

2. Materials and methods

2.1. Participants

Ten participants (eight females and two males) took part in the current experiment. Four participants were research assistants, who volunteered to participate in this experiment. Six participants were students from the Dalhousie University psychology subject pool or students from other institutes and took part for money ($10.00/h). The participants ranged in age from 18 to 39, with a median age of 23. All participants had normal or corrected-to-normal vision. All participants completed an informed consent form and the study was approved by the Dalhousie Social Sciences and Humanities Human Research Ethics Board.

2.2. Apparatus

Attentional Network Test (ANT). We used the program (Java) written by researchers at the Sackler Institute for Developmental Psychobiology (http://sacklerinstitute.org/cornell/assays_and_tools/). A 14-inch iMac controlled stimulus presentation and response collection.

Attentional Network Test-I (ANT-I). We used the program (E-prime) written by Callejas et al. (2005).[1] An AMD Athlon (tm) 64 computer with a 16″ LCD display controlled stimulus presentation and response collection.

2.3. Stimuli, procedure and design

The sequence of events in both tests can be seen in Fig. 1A and B. For more specific details we refer the reader to the original papers by Fan et al. (2002), Callejas et al. (2005), or Ishigami and Klein (2009). The experiment contained four blocks for the ANT and seven blocks for the ANT-I. A practice block (24 trials) was followed by experimental blocks (96 trials/block for the ANT and 48 trials/block for the ANT-I). Cue condition and target congruency conditions for the ANT and auditory signal, visual cue, and target congruency conditions for the ANT-I were orthogonally crossed in the experimental blocks. The 12 possible combinations from each condition were pseudo-randomly presented so that there were eight trials and four trials for each combination in a block for the ANT and the ANT-I, respectively.

2.4. Task administration

The instructions (both verbal and written) emphasized the importance of quick and accurate responding. The participants were told to maintain fixation at the fixation cross all the time. However, they were encouraged to attend when and where indicated by the cues in the ANT. The experimenter was present at the beginning of the experiment in the testing room to start the experiment (i.e., start the program on the computer) and to answer participants' questions regarding the instructions on only earlier sessions. After a couple of the sessions, the participants started the experiment upon arriving the testing room without the presence of the experimenter. In both the ANT and the ANT-I, feedback following errors was given visually only in the practice blocks. Participants performed both versions of the ANT (ANT and ANT-I) in each session, which lasted about an hour and this was repeated 10 times (i.e., 10 days). The ANT and the ANT-I were administered in an alternating order across sessions. In addition, the order of the ANTs was counterbalanced across the participants. Intervals between two consecutive sessions were not fixed and the mean interval was 8.6 days (SD = 15.7).

3. Results

3.1. ANT

For each participant, mean correct RT after eliminating extreme values (less than 200 ms and more than 1200 ms: 1.4% of the total) and mean error rate were computed and subjected to analyses. Table 2 shows mean correct RT and error rate collapsed across session, and Fig. 2A, B shows mean correct RT and error rate for cue condition and target congruency as a function of session.

3.1.1. Stability and isolability of the network scores

In order to allow comparison with the literature (which typically only has one session) analyses were done separately for Session 1 and Sessions 1–10. Stability (do effects change over the 10 sessions?) was examined with ANOVAs and isolability (do conditions interact?) was examined by both ANOVAs and correlation analyses.

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[1] We thank Alicia Callejas for supplying this.

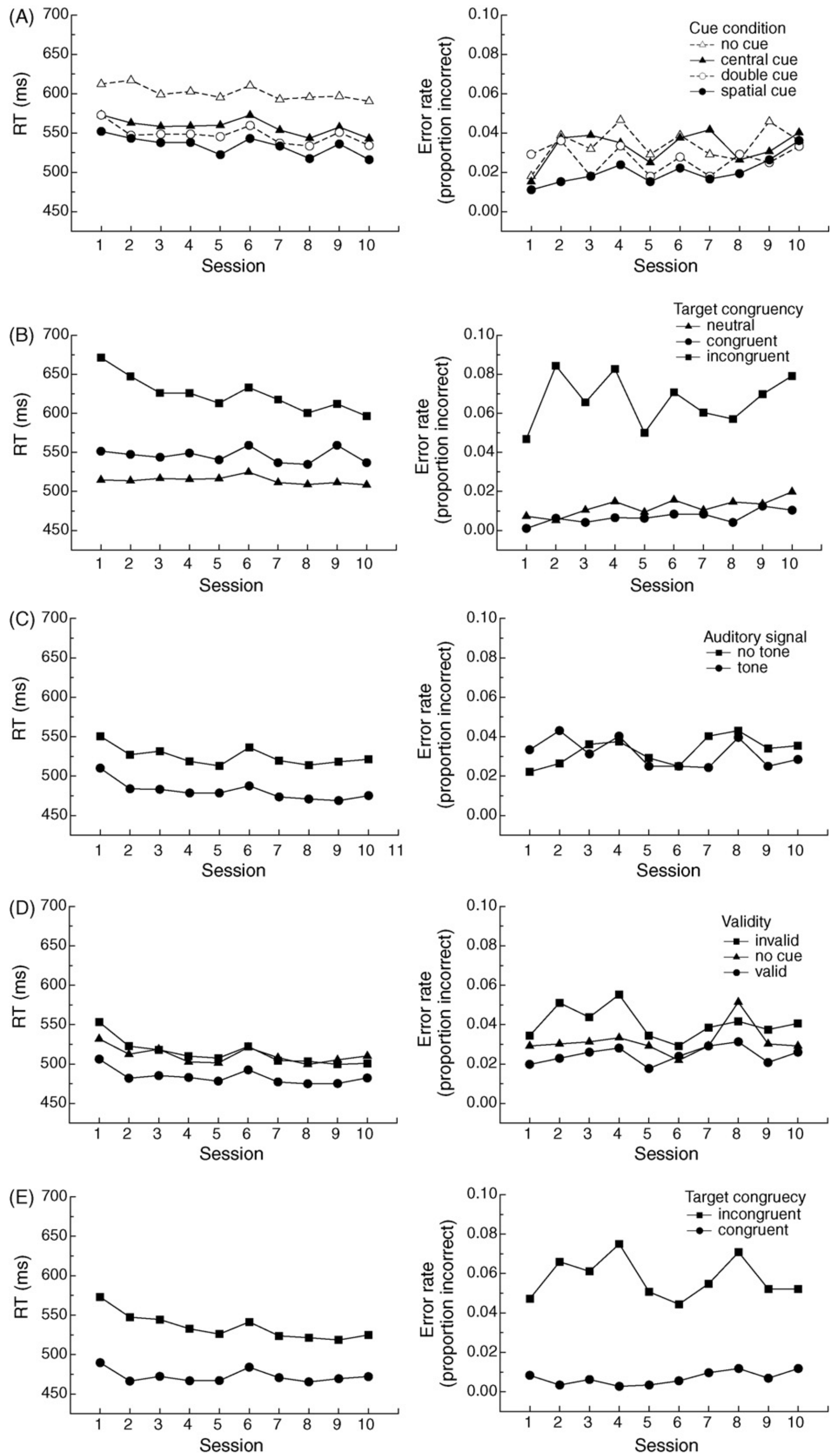

Fig. 2. (A) Mean correct RT and error rate on the ANT as a function of cue condition and session. (B) Mean correct RT and error rate on the ANT as a function of target congruency and session. (C) Mean correct RT and error rate on the ANT-I as a function of auditory signal and session. (D) Mean correct RT and error rate on the ANT-I as a function of visual cue and session.

Table 2
Mean RT (ms) and error rate (proportion incorrect) (between parenthesis) for the ANT and the ANT-I.

ANT	No cue	Center	Double	Spatial
Congruent	582 (.008)	543 (.008)	535 (.004)	524 (.007)
Incongruent	654 (.080)	628 (.075)	620 (.067)	598 (.045)
Neutral	572 (.013)	509 (.016)	495 (.009)	482 (.010)

ANT-I	Tone			No tone		
	Valid	Invalid	No cue	Valid	Invalid	No cue
Congruent	434 (.003)	460 (.009)	444 (.006)	479 (.007)	498 (.009)	519 (.008)
Incongruent	497 (.040)	541 (.070)	516 (.061)	527 (.048)	564 (.075)	569 (.050)

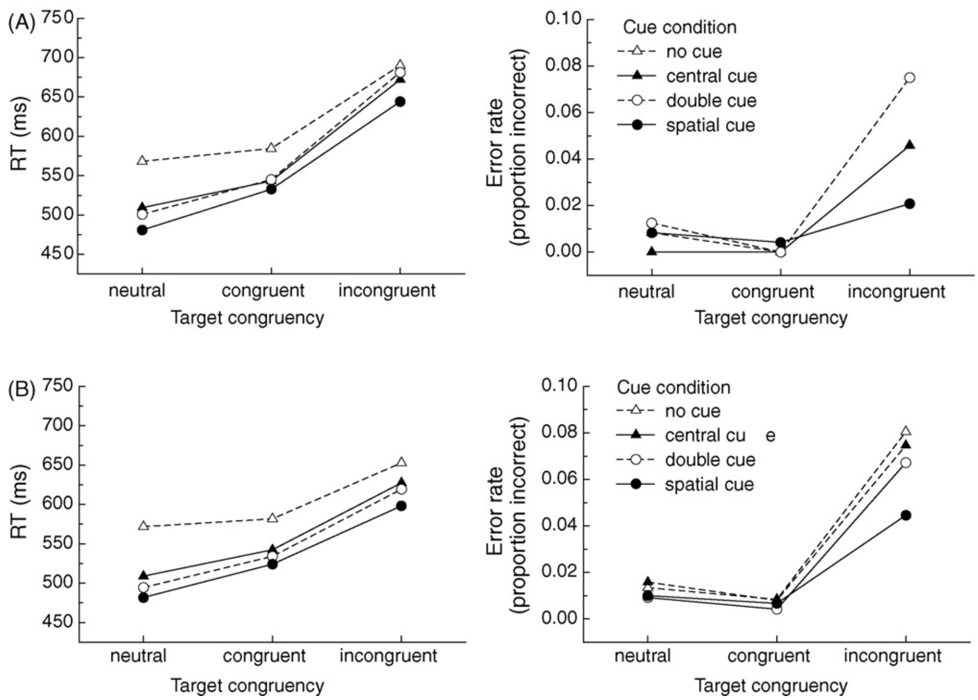

Fig. 3. (A) Mean correct RT and error rate on the ANT for Session 1 as a function of cue condition and target congruency. (B) Mean correct RT and error rate on the ANT for Sessions 1–10 as a function of cue condition and target congruency.

3.1.1.1. ANOVAs. The mean correct RT and the mean error rate were submitted to ANOVAs with cue condition (central, spatial, double, and no cues), and target congruency (neutral, congruent, and incongruent) as repeated-measures factors [and Session (1–10) for the Sessions 1–10 analyses].

Session 1 (Fig. 3A). For RT, the main effects of cue condition, $F(3, 27) = 28.79$, $p < .0001$, and target congruency, $F(2, 18) = 211.05$, $p < .0001$, were significant. The interaction between cue condition and target congruency was significant, $F(6, 54) = 4.45$, $p < .0001$, reflecting some lack of independence among the networks. Here it can be seen that the congruency effect (incongruent-congruent) was greater when participants were alerted by non-spatial cues (double and central cues).

For error rate, the main effect of target congruency was significant, $F(2, 18) = 22.54$, $p < .0001$. The main effect of cue condition was marginally significant, $F(3, 27) = 2.49$, $p = .081$. The interaction between cue condition and target congruency was almost significant, $F(6, 54) = 2.27$, $p = .051$. It can be seen in Fig. 3A that the interaction was similar to and reinforces that seen in RT; the negative impact of distractors was greater in the presence of non-spatial cues.

Sessions 1–10 (Fig. 3B). For RT, the main effect of session was not significant, $F(9, 81) = 1.14$. The main effects of cue condition, $F(3, 27) = 94.87$, $p < .0001$, and target congruency, $F(2, 18) = 152.15$, $p < .0001$, were significant. The interaction between cue condition and target congruency was significant, $F(6, 54) = 22.99$, $p < .0001$, reflecting some lack of independence among the networks. In addition, the interaction between session and target congruency was significant, $F(18, 162) = 7.01$, $p < .0001$, reflecting a learning effect that was due mainly to an improvement in the incongruent condition (see Fig. 2B). The learning effect for the executive network was examined by running a separate ANOVA. The mean executive network scores in RT (mean correct incongruent minus congruent trials) were submitted to an ANOVA with session as a repeated-measures factor to examine the quantitative patterns of performance in executive function across the sessions. The main effect of session was significant, $F(9, 81) = 10.16$, $p < .0001$, reflecting that the executive effects decrease as the sessions progress. No other interactions were significant. In addition, it can be seen by comparing Fig. 3A and B that the negative impact of distractors in the presence of non-spatial cues observed in Session 1 seemed to have attenuated. However, this was not statistically significant.[2]

[2] A separate ANOVA was conducted with session (Session 1 and Sessions 6–10), cue condition [no alert (no cue) and alert (double and center cues)] and target con-

Table 3A
Correlations between attentional networks in the ANT and ANT-I in Session 1.

RT	Alerting	Orienting	Error rate	Alerting	Orienting
ANT					
Orienting	−0.13		Orienting	−0.38	
Executive	0.14	0.11	Executive	0.25	0.54
ANT-I					
Orienting	0.16		Orienting	−0.38	
Executive	−0.19	0.34	Executive	−0.60	0.36

Table 3B
Correlations between attentional networks in the ANT and ANT-I in Sessions 1–10.

RT	Alerting	Orienting	Error rate	Alerting	Orienting
ANT					
Orienting	0.55		Orienting	0.59	
Executive	−0.24	−0.16	Executive	0.58	0.88**
ANT-I					
Orienting	0.03		Orienting	0.68*	
Executive	−0.40	0.34	Executive	0.09	0.41

* $p < .05$.
** $p < .001$.

For error rate, the main effects of cue condition, $F(3, 27) = 8.72$, $p < .001$, and target congruency, $F(2, 18) = 21.52$, $p < .0001$, were significant. The main effect of session was significant, $F(9, 81) = 2.02$, $p < .05$. The interaction between cue condition and target congruency was significant, $F(6, 54) = 5.37$, $p < .001$, reflecting some lack of independence among the networks. The interaction between target congruency and session was marginally significant, $F(18, 162) = 1.53$, $p = .0857$. No other effects were significant.

Correlations analyses

Session 1. Table 3A shows the correlations among the alerting, orienting, and executive networks. Because of the small number of participants contributing only a single session of data to these analyses it is not surprising that there were no significant correlations in the analysis of the RT and error network scores, $ps > .05$

Sessions 1–10. Means of the 10 sessions were entered in the correlation analyses. There were no significant correlations in the analysis of the RT network scores, $ps > .05$ (Table 3B). In the analysis of the error rate the positive correlation between the orienting and the executive network scores was significant; participants with greater congruency effects showed greater orienting effects. Gaining more power when all the sessions were combined, the correlation analyses in error rate[3] suggest that the three networks may operate interactively. However, these results should be interpreted with caution due to the small number of participants in the analyses, the number of relationships examined, and confinement of the significant correlations to error rate.

gruency (congruent and incongruent) as repeated-measures factors. Although the three-way interaction was not significant, $F(1, 9) = 2.69$, we know from our earlier work that with sufficient power the congruency effect is increased in session 1 when the participant is alert (so long as they are not cued to attend the target). And this interaction is clearly not present after the first session in the present study, hence with sufficient power we believe that the 3-way interaction would likely be significant.

[3] Even though errors are not normally distributed, we report the results with untransformed data because the literature on inter-network correlations has more often than not analyzed them untransformed. However, we did transform the errors (arcsine-transformation) and repeat the correlation analyses. Patterns are similar except two correlations; correlation between the orienting and the executive networks with the ANT when all sessions was included, $r(8) = 0.54$, and the correlation between the alerting and the orienting with the ANT-I when all sessions were included, $r(8) = -0.034$, were not significant with the transformed data.

3.1.2. Robustness of the network scores

Fig. 5A summarizes scores of each attentional network for RT and error rate as a function of session.

In order to examine robustness of the network scores, one-sample *t*-tests were conducted on each score for each session. Despite the learning effect described above in the executive network, the tests on the RT data revealed that all the network scores were significantly different from zero in all 10 sessions, $ps < .01$. These results (see Fig. 5A) confirm that the ANT provides a robust index of each network in RT. For error rate, the executive effects were significantly different from zero across all the sessions, $ps < .05$. None of the alerting effects were significantly different from zero. The orienting effects were significantly different from zero only in one session (Session 7, $p < .05$).

3.1.3. Reliability of the network scores

First, reliability was examined by correlating the first two sessions to allow comparison with Fan et al.'s (2002) correlation analysis between Sessions 1 and 2. Then, reliability including different number of consecutive sessions was examined using a modified split-half correlation. In this permutation method,[4] trials were randomly split into two halves 10,000 times, a correlation was computed for each split, and reliability was the mean of the 10,000 correlations.

With RT, the correlation between Sessions 1 and 2 was significant for the executive network, and was not significant for the alerting and the orienting network (Table 4). These results are different from Fan et al. (2002) who reported that the correlations between Sessions 1 and 2 were significant for all the network scores. None of the correlations for error rate were significant in the current study.

Results of the modified split-half reliability analyses as a function of number of consecutive sessions included in the analysis can be seen in Fig. 6A. The executive network was significantly reliable (i.e., correlated) for RT regardless of the number of the sessions included and for error rate so long as more than first three sessions were included. Reliability for the executive network increased with increasing number of sessions and reached an asymptote when more than first five and four sessions were included for RT and error rate, respectively. The alerting network was significantly reliable for RT when more than the first seven sessions were included, but not for error rate regardless of the number of the sessions included. The orienting network was significantly reliable only when all the sessions were included for RT, and was not reliable regardless of the number of the sessions included for error rate.

3.2. ANT-I

For each participant, mean correct RT after eliminating extreme values (less than 200 ms and more than 1200 ms: 1.1% of the total) and mean error rate were computed and subjected to analyses. Table 2 shows mean correct RT and error rate collapsed across session, and Fig. 2C–E shows mean correct RT and error rate for auditory signal, and visual cue, and target congruency as a function of session.

3.2.1. Stability and isolability of the network scores

The mean correct RT and the mean error rate were submitted to ANOVAs with auditory signal (tone and no tone), visual cue (valid, invalid, and no cue), target congruency (congruent and incongruent) as repeated-measures factors [and Session (1–10) for the Sessions 1–10 analyses].

[4] We thank Michael A Lawrence for proving us of R scripts for the modified split-half correlation analysis.

Table 4
Reliability of the three attentional networks from a correlation analysis between Sessions 1 and 2 (Fan et al., 2002 and current study) and from a variation of a split-half correlation analyses including all the sessions (current study).

		Network	Fan et al.	Sessions 1–2	Sessions 1–10
ANT	RT	Alerting	0.52^{**}	−0.02	0.80^{**}
		Orienting	0.61^{**}	0.57	0.65^{*}
		Executive	0.77^{**}	0.86^{**}	0.93^{**}
	Error	Alerting	N/A	0.20	−0.02
		Orienting	N/A	0.42	0.32
		Executive	N/A	0.45	0.93^{**}
ANT-I	RT	Alerting	N/A	0.64^{*}	0.98^{**}
		Orienting	N/A	0.77^{**}	0.81^{**}
		Executive	N/A	0.48	0.89^{**}
	Error	Alerting	N/A	0.28	0.70^{*}
		Orienting	N/A	0.43	0.02
		Executive	N/A	0.63	0.92^{**}

* $p < .05$.
** $p < .01$.

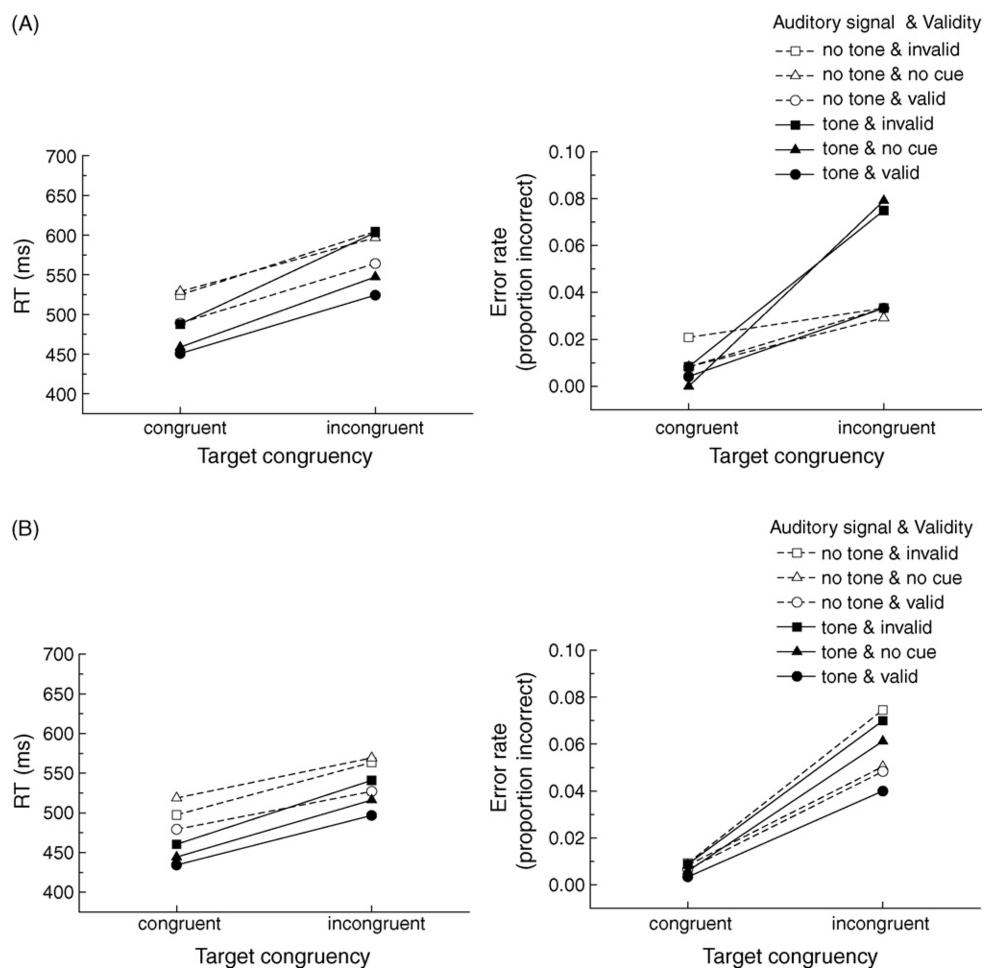

Fig. 4. (A) Mean correct RT and error rate for Session 1 on the ANT-I as a function of target congruency, auditory signal and validity. (B) Mean correct RT and error rate for Sessions 1–10 on the ANT-I as a function of target congruency and auditory signal and validity.

Session 1 (Fig. 4A). For RT, the main effects of auditory signal, $F(1, 9) = 20.69$, $p < .01$, visual cue, $F(2, 18) = 37.31$, $p < .0001$, and target congruency, $F(1, 9) = 214.80$, $p < .0001$, were significant. Here it can be seen that participants were fast to respond to the target in the presence of auditory signals, valid cues, and congruent distractors. Interactions were analyzed excluding data from the no cue trials (visual cue) because the orienting network is measured by subtracting performance in the valid cued condition from that in the invalid cue condition (Callejas et al., 2005). The interaction between auditory signal and target congruency was significant, $F(1, 9) = 13.45$, $p < .01$, reflecting that the congruency effect (incongruent-congruent) was greater in the tone (93.2 ms) than no tone (77.4 ms) conditions.[5] The interaction between auditory signal

[5] A subsequent analysis was carried out excluding the valid and invalid visual cue conditions. This ensures that the alerting effects from auditory signal were not confounded by the alerting effects from visual cue (Callejas et al., 2005). Inconsistent

and visual cue were marginally significant, $F(1, 9) = 4.35$, $p = .067$. The three-way interaction between auditory signal, visual cue, and congruency was significant, $F(1, 9) = 6.24$, $p < .05$, suggesting that the congruency effects were greater in the invalid than in the valid conditions only in the presence of the alerting signal. No other effects were significant. The interactions replicated those reported by Callejas et al. (2005) and Ishigami and Klein (2009) in which the executive network was inhibited by the alerting network (see also Posner, 1994, see Discussion for an alternative interpretation), but facilitated by the orienting network (see also Funes et al., 2007).

For error rate, the main effects of auditory signal, $F(1, 9) = 7.11$, $p < .05$, and target congruency, $F(1, 9) = 25.11$, $p < .001$, were significant. Here it can be seen that participants were more accurate in the absence of auditory signals and presence of congruent distractors. The interaction between auditory signal and congruency was significant, $F(1, 9) = 12.25$, $p < .01$ reflecting that the congruency effect was greater in the tone than no tone conditions.[6] No other effects were significant.

Sessions 1–10 (Fig. 4B). Session (1–10) was included in the analyses as a repeated-measures factor. For RT, the main effect of session was not significant, $F(9, 81) = .89$. The main effects of auditory signal, $F(1, 9) = 17.44$, $p < .01$, visual cue, $F(2, 18) = 47.92$, $p < .0001$, and target congruency, $F(1, 9) = 191.99$, $p < .0001$, were significant. Participants were fast to respond to the target in the presence of auditory signals, valid cues, and congruent distractors. The interaction between visual cue and target congruency was significant, $F(1, 9) = 16.33$, $p < .01$, reflecting that the congruency effect was greater for the invalid (73.2 ms) than for the valid (55.6 ms) conditions. The interaction between auditory signal and target congruency was significant, $F(1, 9) = 10.72$, $p < .01$, reflecting that the congruency effect was greater for the tone (70.9 ms) than no tone (57.2 ms) conditions. It can be seen that the executive network was inhibited by the alerting network, but facilitated by the orienting network. The interaction between visual cue and session, $F(9, 81) = 3.68$, $p < .001$, and between target congruency and session, $F(9, 81) = 7.82$, $p < .0001$, were significant. Consistent with the ANT, it can be seen from Fig. 2E that the learning effect in the executive network was due mainly to an improvement in the incongruent condition. As with the ANT, a different ANOVA was ran to examine the quantitative patterns of performance in executive function across the sessions. The mean executive network scores in RT (mean correct incongruent minus congruent trials) were submitted to an ANOVA with session as a repeated-measures factor. The main effect of session was significant, $F(9, 81) = 6.81$, $p < .0001$, reflecting that the executive effects decrease as the sessions progress. Important, but less obvious was the learning effect in the orienting network, that was due mainly to an improvement in the invalid condition seen in Fig. 2D. As in the executive effects, the mean orienting network scores in RT (mean correct invalid minus valid trials) was submitted to an ANOVA with session as a repeated-measures factor. The main effect of session was significant, $F(9,81) = 3.51$, $p < .01$, reflecting that the orienting effects decrease as the sessions progress. The interaction between auditory signal and visual cue was marginally significant, $F(1, 9) = 3.38$, $p = .099$. No other effects were significant.

For error rate, the main effects of visual cue, $F(2, 18) = 17.65$, $p < .0001$, and target congruency, $F(1, 9) = 32.30$, $p < .001$, were significant. Here it can be seen that participants were more accurate in the presence of valid cues and congruent distractors. The main effect of session was significant, $F(9, 81) = 2.54$, $p < .05$, reflecting that performance fluctuated across the sessions. The interaction between visual cue and congruency was significant, $F(1, 9) = 9.87$, $p < .05$; congruency effects were greater for the invalid than for the valid conditions. The interaction between target congruency and session was significant, $F(9, 81) = 2.26$, $p < 05$. The interaction between auditory signal and session was marginally significant, $F(9,81) = 1.73$, $p = .096$. The four-way interaction between auditory signal, visual cue, target congruency, and session was significant, $F(9, 81) = 2.39$, $p < .05$. No other interactions were significant.

3.2.1.1. Correlations analyses[7].

Sessions 1. There were no significant correlations in the network scores in RT and error rate (Table 3A).

Sessions 1–10. There were no significant correlations in the network scores in RT (Table 3B). In error rate, the positive correlation between the alerting and the orienting network scores was significant; participants with greater orienting effects showed greater alerting effects

3.2.2. Robustness of the network scores

Fig. 5B summarizes scores of each attentional network for RT and error rate as a function of session.

Despite the learning effects described in the orienting and the executive networks, one-sample *t*-tests on the RT data revealed that all the networks were significantly different from zero across all ten sessions, *ps* < .01. For error rate, the executive effects were significantly different from zero across the 10 sessions. These results can be found in Fig. 5B.[8] The alerting effects and the orienting effects were significantly different from zero for two (Sessions 1 and 9, *ps* < .05) and six sessions (Sessions 1, 2, 3,4, 5, and 9, *ps* < .05), respectively.

3.2.3. Reliability of the network scores

With RT, the correlation between Sessions 1 and 2 was significant for the alerting and the orienting networks (Table 4). The correlation was not significant for the executive network. None of the correlations for error rate were significant.

Results of the modified split-half reliability analyses as a function of number of consecutive sessions included in the analysis can be seen in Fig. 6B. The alerting network was significantly reliable for RT regardless of the number of sessions included and for error rate when more than first three sessions were included. The reliabilities seemed to have increased with increasing number of sessions and reached asymptotes when the first seven and three sessions

with Callejas et al., there was no interaction between the auditory signal and target congruency when there was no opportunity for participants to use the visual cue to prepare for the visual target, $F(1, 9) = 1.69$. However, there was a clear interaction between the auditory signal and target congruency when the same analysis was ran including all sessions (i.e., when there was more power), $F(1, 9) = 20.03$, $p < .01$, consistent with Callejas et al.

[6] A subsequent analysis was carried out excluding the valid and invalid visual cue conditions as with the RT analyses. The interaction was significant, $F(1, 9) = 7.88$, $p > 0.01$.

[7] The alerting network scores in the correlation analyses were calculated including all trials. As with the ANOVA analyses above, a subsequent analysis was carried out excluding the valid and invalid visual cue conditions. Significance of the correlations involving the alerting network was similar to those including all trials, except the correlation between the alerting and the orienting network. This correlation was not significant when only the no cue condition was included. Only the results using all trials are reported in Tables 3A and 3B.

[8] An interesting feature seems to be that the alerting effects (in both ANT and the ANT-I, but perhaps more clearly in the ANT-I) reverses with practice in error rate; whereas more error were made in the first session in the condition with greater alertness, fewer error were made in later sessions under alertness [see Ishigami and Klein (2009) for the clear presence of the speed-accuracy tradeoff when the ANT and the ANT-I are tested once with 100 participants each]. Speed-accuracy tradeoffs suggested by Posner et al. (1973) and Posner (1975, 1978) due to alertness (phasic alertness speeds the time when information accumulating about a signal is used to generate a response without affecting the quality of the accumulating information) may be present only early in practice. After one session, the participants may have learned how to make use of warning signals without trading speed for accuracy. It is possible that the participants learned a contingency between the warning signal and the cue with a fixed SOA (Correa et al., 2005; Lawrence et al., 2008), resulting in improvements of the performance.

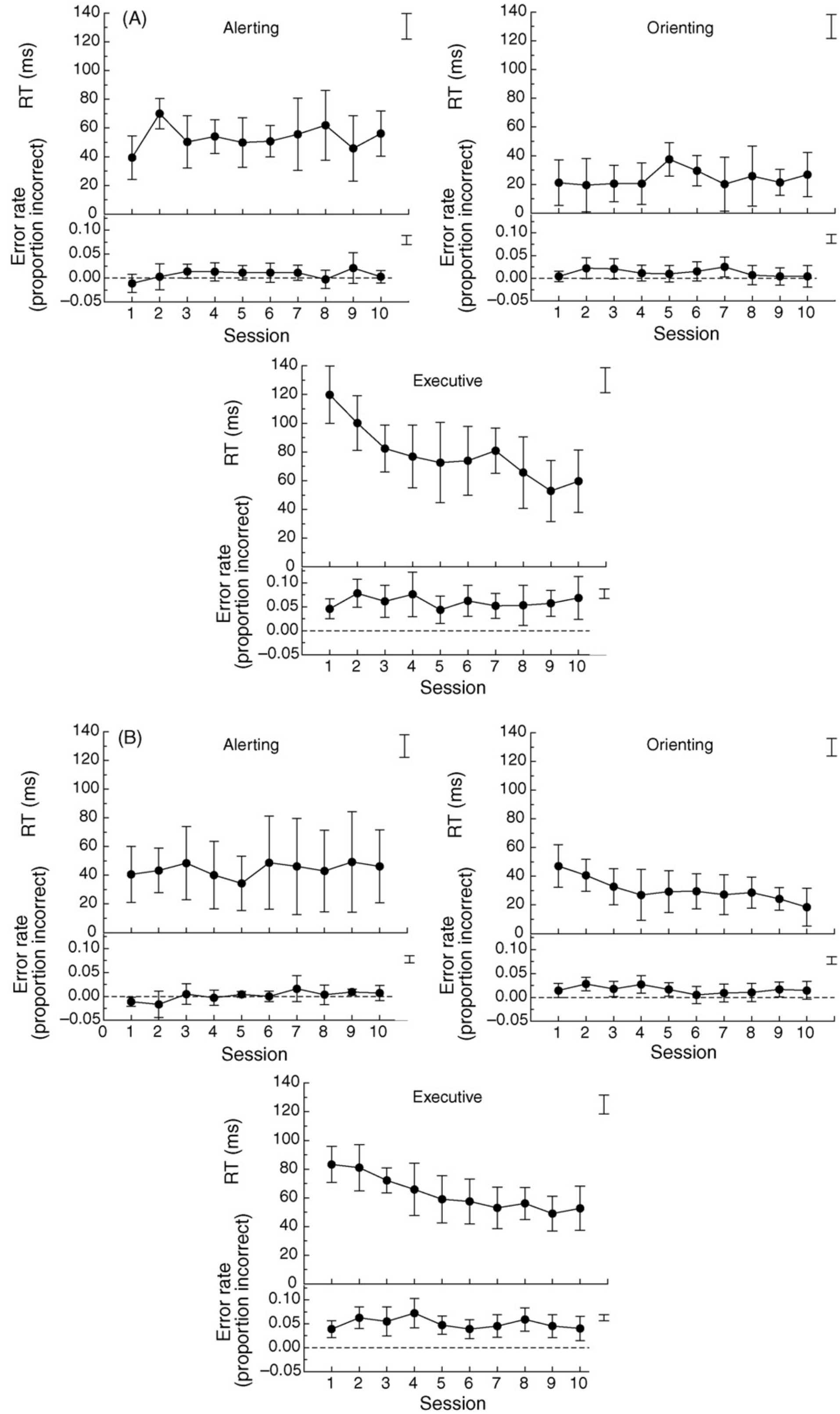

Fig. 5. (A) Mean of each network scores (i.e., difference scores) in RT (top panels) and error rate (bottom panels) for alerting (no cue–double cue), orienting (central cue–spatial cue), and executive (incongruent–congruent) networks in the ANT. The error bars are 95% confidence intervals, which can be used to compare scores against zero. Free standing error bars at the top right of each figure are LSDs to compare scores across the sessions. (B) Mean of each network scores (i.e., difference scores) in RT (top panel) and error rate (bottom panes) for alerting (no tone–tone), orienting (invalid–valid), and executive (incongruent–congruent) networks in the ANT-I. The error bars are 95% confidence intervals, which can be used to compare scores against zero. Free standing error bars at the top right of each figure are LSDs to compare scores across the sessions.

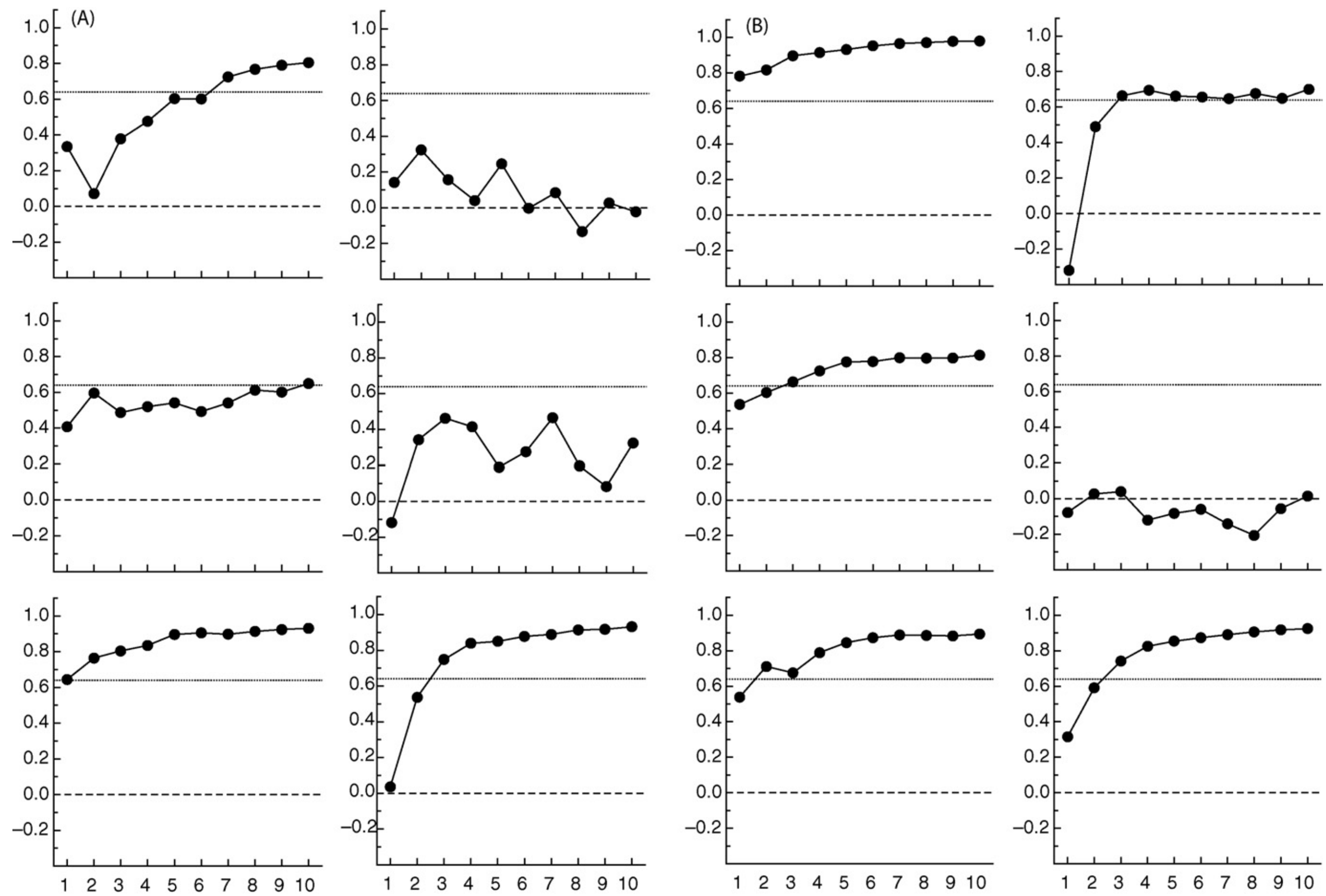

Fig. 6. (A) Reliability of each network scores as a function of number of consecutive sessions included in the analysis (always beginning with Session 1) in the ANT. Reliability was examined using a modified split-half correlation (permutation approach). With a permutation approach, trials were randomly split into two halves 10,000 times, a correlation was computed for each split, and reliability was the mean of the 10,000 correlations. Correlation is significant at the .05 level if $r \geq .64$ and significant at the .01 level if $r \geq .77$ given $N = 10$. (B) Reliability of each network scores as a function of number of consecutive sessions included in the analysis (always beginning with Session 1) in the ANT-I. Reliability was examined using a modified split-half correlation (permutation approach). With a permutation approach, trials were randomly split into two halves 10,000 times, a correlation was computed for each split, and reliability was the mean of the 10,000 correlations. Correlation is significant at the .05 level if $r \geq .64$ and significant at the .01 level if $r \geq .77$ given $N = 10$.

were included for RT and error rate, respectively. The executive network was significantly reliable when more than first two sessions and three sessions were included reaching asymptote with the inclusion of the first seven and four sessions, for RT and error rate, respectively. The orienting network was significantly reliable for RT when more than first three sessions were included, but not for error rate regardless of the number of the sessions included. The reliability of RT seemed to increase with increasing number of sessions and reached an asymptote when the first five sessions were included. In addition, comparing correlations between the first two sessions and reliabilities when all the ten sessions were included suggests better reliability when more data were included (Table 4).

3.3. Correlation between the network scores generated by the two tests

Although the ANT and the ANT-I were written in different programs and ran with different types of computer (see Section 2) and although alerting and orienting are measured somewhat differently (see Section 1) by the two tests, in this section we will compare the magnitudes of the network scores measured by the two tests and we will explore the correlation between corresponding scores (Table 5). For RT, the alerting network scores generated by the ANT and ANT-I were not significantly different. The correlation between these scores was significant. The difference between the orienting networks measured with the two tests was not significant. The correlation between these scores was significant. The executive network measured with the two tests was significantly different. The correlations between these scores were significant. For error rate, the alerting and orienting network scores measured with the two tests were not significantly different. The correlations were not significant for these networks. The difference between the executive networks measured with the two tests was

Table 5
Network scores generated by the ANT and the ANT-I, their difference, and the correlation between the scores from the two different versions of the ANT.

	Network	ANT	ANT-I	$t(9)$	$r(9)$
RT	Alerting	53.1	43.8[a]	1.43	0.86**
	Orienting	24.2	30.6	−2.05	0.69*
	Executive	78.6	63.1	3.58**	0.86**
Error	Alerting	0.007	0.001[b]	1.24	0.11
	Orienting	0.012	0.016	−1.02	0.24
	Executive	0.060	0.050	1.94	0.941**

* $p < .05$.
** $p < .01$.
[a] The alerting network scores were calculated including all trials. When excluding the valid and invalid visual cue conditions, to provide a purer measure of alerting, the alerting score was 64.0 ms. The significance of a t-test and correlation did not change.
[b] The alerting network scores were calculated including all trials. When excluding the valid and invalid visual cue conditions, the alerting score was −0.004 ms. The significance of a t-test and correlation did not change.

not significant. The correlation between these scores was significant.

4. Discussion

The present experiment was conducted to examine the stability, isolability, robustness, and reliability of the measures of attention network (alerting, orienting, and executive) derived from two versions of the ANT over repeated testing. We observed learning effects of executive function both in the ANT and the ANT-I and learning effects of orienting in the ANT-I (Fig. 5A and B). Despite these learning effects, both the ANT and the ANT-I produced a robust index of each attention network even after the 10 sessions of each test. There was some lack of independence among the networks in both tests. Overall, the reliability of the network scores was found to be greater with the ANT-I than the ANT. In addition, examination of the data shows that the participants were: 1) quick to respond and accurate when given peripheral cue (spatial in the ANT and valid in the ANT-I) whether it was 100% informative (ANT) or uninformative (ANT-I) and 2) slow and inaccurate in the presence of distracting incongruent information (Fig. 2B and E) across the 10 sessions.

The learning effects for executive function in RT in the ANT and ANT-I are clearly observed. The executive network is defined by the incongruent and congruent conditions. A close examination of Fig. 2B and E shows that decreased executive effects across the sessions are due mainly to decreased RT in the incongruent condition. Thus, as they practice the task (across sessions) the participants learned how to ignore the irrelevant flanking arrows. In addition, learning effects for orienting in the ANT-I were observed. The orienting effects decreased as the sessions progressed. The orienting network in the ANT-I is defined by the invalid and valid conditions. A close examination of Fig. 2D shows that the learning curve for the invalid condition is steeper than for the valid condition in earlier sessions. The participants seemed to learn to disengage from the uninformative cues more efficiently.

The learning effects with orienting were observed only with the ANT-I. The difference between the ANT and the ANT-I may be due to the different components involved in the orienting network for the two tests. In the ANT, the peripheral cue is 100% valid. Thus, it is in the participants 'advantage to pay attention to this cue. On the other hand, in the ANT-I, the peripheral cue is not informative. Thus, it is of the participants' advantage to ignore the cue. The participants leaned how to ignore irrelevant information in the ANT-I – similar pattern observed in the executive network.

The reliability of the network scores is generally greater with the ANT-I than with the ANT. The reliability of all the network scores measured with the both tests seem to have reached asymptotes after around Session 5, especially with RT.

Lastly, our data largely replicate previous studies (Callejas et al., 2005; Fan et al., 2002) and show that the three attention networks do not operate independently in all situations. The executive network was inhibited by the alerting network (see also Posner, 1994), but facilitated by the orienting network (see also Funes et al., 2007). This causal interpretation is possible because the alerting signal precedes the target. However, it is also possible that phasic alertness speeds the time when information accumulating about a signal is used to generate response affecting the quality of the accumulating information in the presence of congruent information, but not in the presence of the incongruent information (e.g., Fernandez-Duque and Black, 2006; Posner, 1978). Whether the orienting network is facilitated by the alerting network when SOA is long (i.e., 500 ms) was not as clear as previous studies (Callejas et al., 2005), who found the interaction only with short SOA (i.e., 100 ms). It is possible that alerting only facilitates speed of attention and not speed of information processing (Posner, 1975) or orienting (Fernandez-Duque and Posner, 1997).

5. Conclusion

Both ANTs are useful tools to measure attention components, namely alerting, orienting, and executive functions, within one session, which takes less than 30 min. The current study shows that scores of these attention components remain robust even after 10 sessions. This enables either ANT to be used in applications that require repeated testing. It is important to note, however, that executive control scores with both ANTs, and orienting with the ANT-I decrease with practice. Therefore, an untreated control group might be warranted in some designs. While the network scores are robust against practice, their reliability is generally lower than is ideal for many purposes. Importantly, the scores measured with the ANT-I were generally more reliable than with the ANT.

The network scores generated by the two tests were found to be related to each other. As we expected the executive effects, which are measured by the two tests using essentially the same conflicting and congruent arrows, were highly related. Phasic alertness, in contrast, is induced by different modalities in these tests: visual in the ANT and auditory in the ANT-I. The scores from the two tests are highly related even though auditory signals may generate alertness more automatically than visual signals. The orienting component of attention is measured quite differently in the two tests; Whereas the 100% valid peripheral cue used in the ANT allows both endogenous and exogenous control to be operating, with the uninformative peripheral cues of the ANT-I orienting depends on the degree to which the cue captures attention exogenously. Despite this different, the scores from the two tests were significantly correlated. One thing the two tests have in common is the use of peripheral cues. Perhaps, the significant correlation is related to the degree to which a peripheral cue captures attention whether or not it is informative.

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