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Appraising the ANT: Psychometric and Theoretical Considerations of the Attention Network Test

Jeffrey W. MacLeod
McMaster University

Michael A. Lawrence
Dalhousie University

Meghan M. McConnell
McMaster University

Gail A. Eskes and Raymond M. Klein
Dalhousie University

David I. Shore
McMaster University

Objective: The Attention Network Test (ANT) is a tool used to assess the efficiency of the 3 attention networks—alerting, orienting, and executive control. The ANT has become popular in the neuropsychological literature since its first description in 2002, with some form of the task currently appearing in no less than 65 original research papers. Although several general reviews of the ANT exist, none provide an analysis of its psychometric properties. ***Method:*** Data from 15 unique studies were collected, resulting in a large sample ($N = 1{,}129$) of healthy individuals. Split-half reliability, variance structure, distribution shape, and independence of measurement of the 3 attention network scores were analyzed, considering both reaction time and accuracy as dependent variables. ***Results:*** Split-half reliabilities of reaction time based attention network scores were low for alerting ($r_{\text{weighted}} = .20$, CI $95\%_{\text{weighted}}$ [.14, .27], Spearman–Brown $r = .38$) and orienting ($r_{\text{weighted}} = .32$, CI $95\%_{\text{weighted}}$ [.26, .38], Spearman–Brown $r = .55$), and moderate high for executive control ($r_{\text{weighted}} = .65$, CI $95\%_{\text{weighted}}$ [.61, .71], Spearman–Brown $r = .81$). Analysis of the variance structure of the ANT indicated that power to find significant effects was variable across networks and dependent on the statistical analysis being used. Both analysis of variance (significant interaction observed in 100% of 15 studies) and correlational analyses (multiple-significant inter-network correlations observed) suggest that the networks measured by the ANT are not independent. ***Conclusions:*** In the collection, analysis and interpretation of any test data, psychometric properties, such as those reported here for the ANT, must be carefully considered.

Keywords: Attention Network Test, ANT, attention networks, reliability

On the basis of behavioral and neuroscientific studies, Posner and colleagues (Fan, McCandliss, Fossella, Flombaum, Posner, 2005; Fan, McCandliss, Sommer, Raz, Posner, 2002; Posner & Petersen, 1990; Posner & Rothbart, 2007) suggested that the human attentional system can be subdivided into three functionally and anatomically independent networks. In this framework, the alerting network allows maintenance of a vigilant and alert state, the orienting network is responsible for the movement of attention through space to attend to sensory events, and the executive control network allows for the monitoring and resolution of conflict between expectation, stimulus, and response. This three-system definition has redefined the approach cognitive scientists use when examining the function (Fan et al., 2002) and development (Rueda et al., 2004) of the attentional system, and has allowed a better description of the attention disorders and difficulties associated with neuropsychological (e.g., Borderline Personality Disorder; Rogosch & Cicchetti, 2005; see review by Fernandez-Duque & Posner, 2001) and genetic disorders (Bish, Ferrante, McDonald-McGinn, Simon, 2005; 22q11 deletion syndrome; see Fan & Posner, 2004; Posner & Rothbart, 2007, for a review of attention network research).

The Attention Network Test (ANT) was developed as a measure that would allow independent assessment of the efficiency of the three attention networks within the context of a quick and simple computerized task (Fan et al., 2002; see Figure 1 for a diagram of the task). The ANT rapidly became popular in the neuropsycho-

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Jeffrey W. MacLeod, Meghan M. McConnell, and David I. Shore, Department of Psychology, Neuroscience and Behaviour, McMaster University; Michael A. Lawrence and Raymond M. Klein, Department of Psychology, Dalhousie University; Gail A. Eskes, Department of Psychiatry, Dalhousie University.

Jeffrey W. MacLeod is now at Department of Psychology, Dalhousie University.

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Correspondence concerning this article should be addressed to Jeffrey W. MacLeod, Department of Psychology, Dalhousie University, Life Sciences Centre, Halifax, Nova Scotia, B3H 4J1, Canada. Email: jeffmacleod@dal.ca

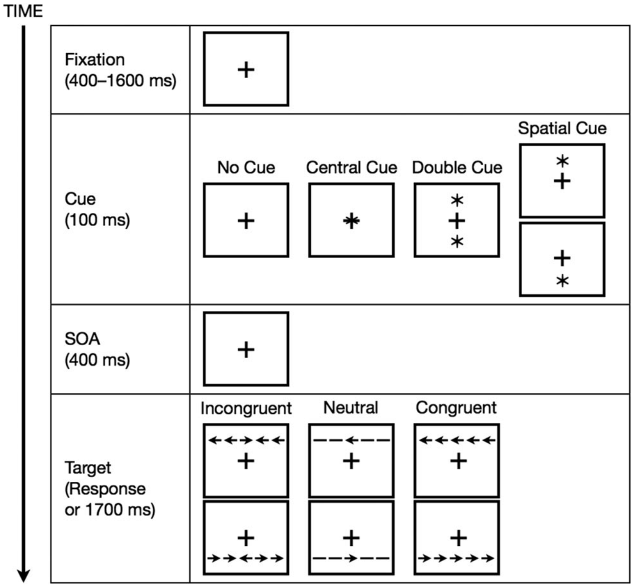

Figure 1. The typical Attention Network Test (ANT) experimental procedure. The sequence of events in one trial is conveyed in the left column, and all possible stimuli associated with each event are presented in the right column. All four cue types are equally probable in the task, as are all three flanker conditions. Targets appear above and below fixation with equal probability.

logical literature, with some form of the task appearing in at least 65 original research papers since 2001.

The ANT (see Figure 1) is a combination of a flanker task (with arrows; Eriksen & Eriksen, 1974) and a cued reaction time task (Posner, 1980). Participants indicate the direction of a central arrow that is flanked by four arrows (two per side) pointing in the same direction as the central arrow (congruent condition) or in the opposite direction (incongruent condition); in the neutral condition, either straight lines flank the central arrow or the central arrow is presented alone, depending on the study. The arrows are preceded by one of three types of cues (center cue, double cue, spatially informative cue; all of which are temporally informative) or no cue (a temporally uninformative condition). The center and double cues indicate that the arrow stimulus will occur soon, and the spatially informative cue is 100% predictive of target location.

As a speeded choice task, the ANT provides two measures of performance, response time (RT) and error rate (ER), and the three network scores are calculable within each of these measures. In the case of RT, the measures of efficiency provided by the ANT for each attention network are calculated using three subtractions using RT data from accurate trials only.[1] To calculate the alerting network score, RT in the temporally informative double cue condition is subtracted from RT in the temporally uninformative no cue condition (averaging across all flanker conditions). For the orienting network score, RT in the spatially informative cue condition is subtracted from RT in the spatially uninformative central cue condition (averaging across all flanker conditions). Finally, the executive control network score is calculated by subtracting RT in the congruent flanker condition from RT in the incongruent flanker condition (averaging across all cue conditions). Analogous subtractions can also be used to compute attention network scores based on ER data, however such scores are usually omitted in the ANT literature, despite the good example set by Fan, Fossella, Sommer, Wu, and Posner's (2003) seminal paper (see also Adolfsdottir, Sorensen, Lundervold, 2008; Costa, Hernández, Sebastián-Gallés, 2008; Fan et al., 2007; Fossella, Green, & Fan, 2006; Ishigami & Klein, 2009a; Jha, Krompinger, Baime, 2007). Pursuant to the recommendations by Wickelgren (1977) on the importance of considering both speed and accuracy data from speeded choice tasks, the present study will consider both ER and RT as performance measures.

Since the initial description of the ANT (Fan et al., 2002), attention network function of many special populations has been examined using this task, including individuals with dyslexia (Bednarek et al., 2004), schizophrenia (Wang et al., 2005), borderline personality disorder (Rogosch & Cicchetti, 2005), depression (Murphy & Alexopoulos, 2006), attention-deficit hyperactivity disorder (ADHD; Adolfsdottir et al., 2008), and 22q11 deletion syndrome (Bish et al., 2005). It also has been used to examine the heritability of attention networks (Fan et al., 2003; Fossella et al., 2006; Fossella, Sommer, Fan, Pfaff, & Posner, 2003), and the effectiveness of mindfulness training (Jha et al., 2007; Tang et al., 2007; Zylowska et al., 2008). Many studies have used ANT results to claim that a clinical population demonstrates an attentional deficit in a specific attentional subsystem, rather than a general attention deficit. For example, specific executive control deficits have been reported in individuals with borderline personality disorder (Posner et al., 2002), posttraumatic stress disorder (Leskin & White, 2007), ADHD (Loo et al., 2007), severe obesity (Beutel et al., 2006), dyslexia (Bednarek et al., 2004), and 22q11 deletion syndrome (Bish et al., 2005; Sobin et al., 2004). A specific orienting network deficit was reported in individuals who had a concussion (van Donkelaar et al., 2005), and a specific alerting deficit has been observed in older individuals (relative to younger individuals; Jennings, Dagenbach, Engle, & Funke, 2007), and alerting network scores have been used to differentiate ADHD subtypes (Booth, Carlson, & Tucker, 2007). Combinations of attention network strengths and deficits within one population have also been reported. For example, in the case of schizophrenia, several studies have reported a specific executive control deficit (but no alerting or orienting deficit; Gooding, Braun, & Studer, 2006; Neuhaus, Koehler, Opgen-Rhein, Urbanek, Hahn, & Dettling, 2007), one study has reported a specific alerting deficit (Nestor et al., 2007), and another study has reported both orienting and executive control deficits (Wang et al., 2005). These reports of specific attention network deficits rely on the ANT's ability to reliably and separately assess the three attention networks.

The ANT also has been used to assess theoretical questions on the operation of the healthy mind, including testing of the original description of the attention networks as comprising independent systems. In the original report on the ANT, Fan et al. (2002) observed no significant correlations between any of the attention

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[1] The JAVA version of the ANT provides both raw data and precalculated scores. The precalculated scores are achieved by first obtaining the median per cell, then computing the subtraction across the means of medians of the appropriate cells. All analyses reported in the present manuscript are based on cell means and not cell medians.

network scores (with $N = 40$). On the other hand, in their analysis of variance, Fan et al. (2002) observed a small, but significant Cue × Flanker interaction. Both the no cue and spatial cue conditions reduced the impact of the incongruent flanker on reaction time (as compared to performance following other cue conditions), suggesting nonindependence between orienting and executive control and between alerting and executive control. Although Fan et al. (2002) recognized this possibility, they also reported that they had discovered no Cue × Flanker interaction in a replication of the study using children (presumably the same data set subsequently published by Rueda et al., 2004). More recently, however, this Cue × Flanker interaction has been replicated (e.g., Dye, Baril, & Bavelier, 2007; Fan et al., 2007; Ishigami & Klein, 2009a; Jennings et al., 2007; Redick & Engle, 2006), and small but significant correlations between alerting and executive control network scores (Fossella et al., 2002) and alerting and orienting scores (Lehtonen, 2008) have been observed. Additionally, some neuroimaging evidence suggests that the networks are not entirely anatomically independent (Corbetta & Shulman, 2002, e.g., show an overlap in executive control and orienting). It is questionable, then, whether the weight of currently published evidence supports network independence.

Validity of the ANT

Given the ANT's prevalence in the scientific literature, it appears that this tool has been widely accepted as a useful, accurate and reliable measure of the functioning of the three attentional subsystems. Is this assumption justified? The face validity of the tool is quite good, as the two subcomponents of the measure—the flanker task (Eriksen & Eriksen, 1974) and the cued RT task (Posner, 1980)—are very well established within the psychological literature, and their combination provides an intuitive way of assessing attentional systems. Behavioral studies have consistently reported nonzero attention network subtraction scores, suggesting that the cue and flanker manipulations are successfully manipulating performance in the expected manner (Fan et al., 2005; Fan, Wu, Fossella, & Posner, 2001; Ishigami & Klein, 2009b). Neuroimaging research using the ANT has demonstrated that the three network scores isolate three largely distinct anatomical and neurochemical circuits that are quite similar to those outlined in previous attention network research (Fan et al., 2005). Neuroimaging studies using the ANT have linked the orienting network to activation of the parietal lobe and frontal eye fields (Fan et al., 2005). The alerting response has been associated with activity in the frontal and parietal regions (Coull, Nobre, & Frith, 2001; Fan et al., 2005), and several genes (i.e., MAOA, DβH) have been linked to the efficiency of the alerting network (Fan et al., 2005; Fossella et al., 2002). Finally, executive control has been found to rely on the activation of the anterior cingulate cortex (ACC) as well as the lateral prefrontal cortex. (Bush, Luu, & Posner, 2000; Fan et al., 2005), and two genes have been associated with executive network ANT scores (DRD4 and COMT; Fossella et al., 2002).

Reliability of the ANT

Although the validity of the ANT is promising, the reliability of the network scores obtained from the ANT (calculated using RT data) for the three networks has been low to moderate in the few studies that have examined it in healthy populations. Fan et al. (2001), using an N of 104, reported test–retest reliability scores for the alerting, orienting, and conflict measures of .36, .41, and .81, respectively. Fan et al. (2002), using an N of 40, reported test–retest reliabilities for the alerting, orienting, and conflict measures of .52, .61, and .77, respectively. Finally, split-half reliability correlations (comparing network scores from the first two blocks with those of the final two blocks) in a small sample of 23 young adults were reported to be .15 for alerting scores, .70 for orienting scores, and .74 for executive control scores (Greene et al., 2008).

The best estimates of the reliability of the ANT provided to date (studies with the largest samples; Fan et al., 2001, 2002) suggest that the executive control measure is the most reliable measure, followed by orienting, and that alerting is the least reliable measure. It is known that reliability bears a complex relation to statistical power (Williams, Zimmerman & Zumbo, 1995), but one possible relation is that low reliability can decrease statistical power. If this relation holds in the case of the ANT, based on the observed reliabilities of the ANT network scores, one would expect to observe statistically significant differences or relations (between two variables or experimental groups) more often using the executive control network score than using either of the other network scores, independently of the true strengths or deficits in the various populations tested. That is, even if alerting or orienting were the most diagnostic concepts differentiating two populations, one could potentially fail to find a difference between those populations simply because of the low reliability of these measures.

Tally of Attention Network Effects in the Literature

To explore whether the observed frequency of network effects in the literature is consistent with this account, a review of all available published original research using the ANT was conducted. The number of articles reporting statistically significant effects using each network measure was tallied. Studies included in this analysis of the literature were those that examined the difference in attention network scores between groups or testing periods, or examined the correlation between attention network scores and another measure. Excluded were studies that did not examine all three network scores (e.g., Opgen-Rhein Neuhaus, Urbanek, Hahn, Sander, & Dettling, 2008), only analyzed ANT data to examine whether network scores were significantly different from zero (e.g., Fan et al., 2002), used a modified ANT (e.g., the LANT, used by Greene et al., 2008), or used the child ANT (Rueda et al., 2004). Of the 70 articles considered, 39 articles met the inclusion criteria. Executive control network effects were observed in 31 articles (79.5%), orienting network effects were observed in 12 articles (30.8%), and alerting effects were observed in 15 articles (38.5%). All articles included in this analysis of the literature are listed in the Appendix. Although a number of hypotheses can account for this observed pattern of frequencies (e.g., true differential effect sizes, etc.), it is concerning to note that the pattern roughly correspond to the reliability estimates provided by Fan et al. (2001, 2002), which may indicate that the pattern of effects stems solely from the psychometric properties of the ANT.

Given these concerns, in this report we seek to provide the research community with a psychometric assessment of the ANT (using data drawn only from healthy participants) that will help motivate decisions on its use and/or interpretation. Analysis of the reliability of the network scores is an essential part of this assessment, but other issues are also considered in this paper. Reliability itself is a function of both between-subjects score variance and within-subjects score variance; the interplay of these two sources of variance influences statistical power (Williams et al., 1995). Therefore, it is critical to assess the variance structure of ANT scores. The shape of the distribution of attention network scores is another psychometric property of interest to those concerned about violating assumptions of many parametric statistical tests. Finally, given the availability of a large, high power data set, we address the theoretical question of the degree of independence between the attention network scores by examining the correlations between network scores and the Cue × Flanker interaction.

Method

Data Collection

Data from 1,141 participants in 15 unique studies of healthy individuals employing the ANT were gathered (see Table 1 for the demographic information associated with each data set). The data collection process was a collaborative effort[2] between researchers at McMaster University and Dalhousie University, including both original data collection and successful data sharing requests sent to authors who had published research employing the ANT. Original data collection by the McMaster and Dalhousie authors accounts for six of the 15 studies listed in Table 1 (Ishigami & Klein 2009a, MacLeod 1–2, McConnell 1–3). The Dalhousie research group identified and requested raw trial-by-trial data from 13 published studies and two unpublished studies that had tested healthy individuals using the ANT. Of the 14 emailed requests, eight authors were willing and able to share their data (From Table 1: AhnAllen, Beutel, Breau, Callejas, Fan1–2, Neuhaus, Oberlin, Redick).[3] As a result, 15 datasets (a total of 1,141 participants) were available for analyses of psychometric properties (seven original and eight obtained). Each of the 15 data sets gathered was initially collected to answer a unique set of research questions that, for the most part, were orthogonal to that of the current investigation.

Of the total 1,141 participants, 1,129 were used in the subsequent analyses (12 failed to meet an overall accuracy criterion of 70% correct). Participants ranged in age from 16 to 65 years (see Table 1 for mean ages of each study).

The ANT

All ANT data sets were collected using a version of the ANT similar to that first presented by Fan et al. (2002; see Figure 1 for a diagram of the task and Table 1 for a list of deviations from the Fan et al. version of the ANT). In this task, each trial begins with a central fixation point of variable duration (400 ms to 1,600 ms). The fixation point is followed by one of four cue conditions: a center cue, a double cue, a spatial cue, or no cue (see Figure 1). Cues are presented for 100 ms, and consist of asterisks that are equally likely to appear at fixation (center cue), both above and below fixation (double cue), in the same location as the upcoming target (spatial cue), or not at all. A target display appears 400 ms after the offset of the cue. The target display is equally likely to appear above or below fixation. Each target display contains a central arrow to which participants respond by using the keyboard to indicate the direction the arrow is pointing. The target display also contains one of three types of flankers on either side of the central arrow (two flankers per side). On congruent trials, the flankers are arrows pointing in the same direction as the central arrow; on incongruent trails the flankers are arrows pointing in the direction opposite that of the central arrow; and, on neutral trials the flankers are either dashes or entirely absent (depending on the study—see Table 1). Each flanker type is equally likely. The target display remains on the screen until a response is made, or 1,700 ms elapses.

All participants first completed a practice block with 24 full-feedback trials (except those from the Redick & Engle, 2006, data set, who completed only 12 practice trials). The test phase consisted of 288 trials, split into three blocks of 96 (with the exception of the AhnAllen, Nestor, Shenton, McCarley, & Niznikiewicz, 2008, who employed three different test sessions with 96 trials each). Participants responded only to the direction of the central arrow in the target display, using one of two keys to indicate arrow direction. Participants were instructed to respond as quickly and accurately as possible.

Results

All analyses were performed by M. Lawrence in R (R Development Core Team, 2009) using supercomputing resources provided by the Shared Hierarchical Academic Research Computing Network (www.sharcnet.ca) for computationally intensive analyses. Each of the analyses below was conducted on both ANT performance measures—mean correct RT and ER.

Reliability of the Attention Network Scores

Estimates of split-half reliability were calculated using a permutation approach whereby the reliability estimate for a given network was obtained from the mean of 10,000 split-half estimates, each computed using a unique random split of the data to halves at the level of trial type (“cell”). This method was used to calculate the split-half reliability estimates for each of the 15 data

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[2] Initially the McMaster and Dalhousie research groups were working in isolation. The McMaster research group had collected ANT data from 681 participants by testing undergraduate students. Realizing the potential to analyze the psychometric properties of the ANT using this large data set, the McMaster group set out to analyze the reliability of the measures and independence of network measurement. During this time, the group at Dalhousie also had decided to analyze the psychometric properties of the ANT, but largely relied on a different data collection method. In addition to collecting ANT data from 118 participants, the Dalhousie group contacted authors of published and unpublished studies that had employed the ANT, and asked that these authors share their data. As part of this process, the Dalhousie group contacted the McMaster group to request data. It was determined that both groups were pursuing, in essence, the same research goals. At that point, the two research groups agreed to collaborate to produce the most meaningful contribution to the scientific literature.

[3] We thank these authors for their willingness and cooperation in making their raw data available to us.

Table 1
Authorship, Demographic Information, and Software Information for the 15 Datasets Included in the Present Analyses

Dataset name	Associated publication	*n*	*M* age (years)	Age range (years)	Gender	Software platform	Type of flanker in neutral condition
AhnAllen	AhnAllen, Nestor, Shenton, McCarle, & Niznikiewicz, 2008	17	42	18–60	All men	E-prime	Dashes
Beutel	Beutel et al., 2006	43	42	18–62	39 women, 4 men	E-prime	Dashes
Breau	Breau & Eskes, unpublished raw data	20	22.9	18–46	All men	Java	None
Callejas	Callejas & Lupiáñez, unpublished raw data	25	N/K	18–25	20 women, 5 men	E-prime	Dashes
Fan (1)	Fan, Wu, Fossella, & Posner, 2001	104	N/K	14–42	N/K	E-prime	Dashes
Fan (2)	Fan, McCandliss, Sommer, Raz, & Posner, 2002	40	30.1	20–44	23 women, 17 men	E-prime	Dashes
Ishigami	Ishigami & Klein, 2009a	98	20.87	17–37	64 women, 34 men	Java	None
MacLeod (1)	MacLeod & McConnell, unpublished raw data a	49	19.1	18–26	29 women, 20 men	Matlab	Dashes
MacLeod (2)	MacLeod & McConnell, unpublished raw data b	60	18.6	18–24	35 women, 25 men	Matlab	Dashes
McConnell (1)	McConnell & Shore, submitted	64	19.3	17–26	48 women, 16 men	Matlab	Dashes
McConnell (2)	McConnell & Shore, unpublished manuscript a	271	19.1	17–42	219 women, 52 men	Matlab	Dashes
McConnell (3)	McConnell & Shore, unpublished manuscript b	237	19.2	16–29	170 female, 67 male	Matlab	Dashes
Neuhaus	Neuhaus et al., 2007	16	36.63	18–65	8 women, 8 men	Experimental Run Time System in Windows 98	Dashes
Oberlin	Oberlin, Alford, & Marrocco, 2005	33	N/K	18–30	17 women, 16 men	E-prime	None
Redick	Redick & Engle, 2006	52	N/K	18–35	N/K	E-prime	Dashes

Note. N/K = not known.

sets individually,[4] allowing the further calculation of a weighted mean. Readers interested in extrapolating from split-half reliability to test–retest reliability may employ the Spearman–Brown prophesy formula (Spearman, 1910), and in Table 2 we provide examples of such extrapolation.

Considering RT, the executive network was most reliable ($r_{\text{weighted}} = .65$, CI 95%$_{\text{weighted}}$ [.61, .71]) followed by the orienting network ($r_{\text{weighted}} = .32$, CI 95%$_{\text{weighted}}$ [.26, .38]); the alerting network was least reliable ($r_{\text{weighted}} = .20$, CI 95%$_{\text{weighted}}$ [.14, .27]). Within ER, the executive network was again most reliable ($r_{\text{weighted}} = .71$, CI 95%$_{\text{weighted}}$ [.67, .76]) followed by the alerting network ($r_{\text{weighted}} = .14$, CI 95%$_{\text{weighted}}$ [.07, .21]); the orienting network was least reliable ($r_{\text{weighted}} = .06$, CI 95%$_{\text{weighted}}$ [.01, .12]). See Figure 2 for graphic detailing network reliabilities.

Variance of Attention Network Scores

Within-Ss variance of attention network scores. The within-Ss variance of scores was estimated for each participant and network by bootstrap resampling. These scores were then submitted to paired *t* tests comparing each pair of networks across the entire sample of 1,129 participants. For RT, all networks manifested different within-Ss variance (all $p < .05$); the within-Ss variance of executive network scores (305 ms) was less than that of the orienting network scores (352 ms), which in turn was less than that of the alerting network scores (406 ms). For ER, the within-Ss variance of executive network scores (6.9%) was less than that of the orienting (7.3%, $p < .01$) and alerting (7.5%, $p < .01$) network scores, which did not differ significantly ($p = .09$).

Between-Ss variance of attention network scores. The between-Ss variance of scores was computed for each network for the entire sample of 1,129 participants, along with 95% confidence intervals estimated by bootstrap resampling. For RT, the between-Ss variance of the executive network scores (1,655 ms, CI 95% [1,447 ms, 1,898 ms]) was greater than that of the orienting network scores (818 ms, CI 95% [751 ms, 885 ms]), which in turn was greater than that of the alerting network scores (689 ms, CI 95% [626 ms, 750 ms]). For ER, the between-Ss variance of the executive network scores (47.3%, CI 95% [40.1%, 55.1%]) was greater than that of the orienting network scores (8.9%, CI 95% [7.9%, 10.0%]) and the alerting network scores (10.4%, CI 95% [9.1%, 11.7%]); the between-Ss variance of alerting and orienting network scores were not significantly different.

Shape and Location of Distribution of the Attention Network Scores

The distributions of network scores based on RT and ER were examined across the entire sample of 1,129 participants (see Figure 3). D'Agostino–Pearson tests were used to assess normality in both variables for all three attention networks. All tested distributions were nonnormal (see Table 3). *T* tests of the distribution means were also performed, rejecting the null hypothesis of zero in

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[4] These reliability analyses were also performed on the full $N = 1{,}129$ data set ignoring origin experiment and results were not discernibly different.

Table 2
Results of the Reliability Analyses

Performance measure	Attention network	Weighted mean split-half reliability	95% confidence interval around weighted mean	Spearman–Brown prophecy formula reliability
Reaction time	Alerting	.20	.14 to .27	.38
	Orienting	.32	.26 to .38	.55
	Executive	.66	.61 to .71	.81
Error rate	Alerting	.14	.07 to .21	.25
	Orienting	.06	.01 to .12	.15
	Executive	.72	.67 to .76	.85

all tested distributions (all were greater than zero except for the alerting ER distribution mean; see Table 3).

Cue × Flanker ANOVA

A standard 3 × 4 (3 flanker types × 4 cue types) repeated-measures analysis of variance (ANOVA) was conducted on each of the 15 data sets separately to examine the percentage of studies demonstrating a Cue × Flanker interaction.[5] When RT was the measure of performance 100% of the data sets had a significant main effect of cue, 100% had a significant main effect of flanker, and 100% had a significant Cue × Flanker interaction. When ER was the measure of performance, 60% of the data sets had a main effect of cue, 100% of the data sets had a main effect of flanker, and 60% of the data sets had a significant Cue × Flanker interaction (see Figure 4).

Inter-network Correlations

Standard correlation analyses were used to examine the inter-network correlations in each data set individually[6] for both dependent variables (RT and ER). See Figure 5 for a depiction of the r values resulting from each data set and the weighted mean r values for each correlation. Significant inter-network correlations were found between alerting RT and orienting RT ($r_{\text{weighted}} = .06$, CI $95\%_{\text{weighted}}$ [.01, .11]), between alerting ER and executive ER ($r_{\text{weighted}} = -.33$, CI $95\%_{\text{weighted}}$ [−.37, −.28]), between orienting ER and executive ER ($r_{\text{weighted}} = .20$, CI $95\%_{\text{weighted}}$ [.12, .28]), and between orienting RT and executive ER ($r_{\text{weighted}} = -.11$, CI $95\%_{\text{weighted}}$ [−.21, −.01]). Significant within-network correlations were found between alerting ER and alerting RT ($r_{\text{weighted}} = -.10$, CI $95\%_{\text{weighted}}$ [−.18, −.01]), and between executive ER and executive RT ($r_{\text{weighted}} = .21$, CI $95\%_{\text{weighted}}$ [.13, .28]).

Discussion

The present study had four main goals: (1) to analyze the reliability of measurements from the ANT, (2) to describe the variance structure of the ANT, (3) to describe the distribution of attention network scores, and 4) to examine the statistical independence of the ANT's three attention network measurements using ANOVA and inter-network correlation. These analyses were conducted using a multistudy approach, drawing on a large sample (N = 1,129) from 15 unique data sets (see Table 1).

Reliability

Using RT, Fan et al. (2001) observed reliabilities of .36 for alerting, .41 for orienting, and .81 for executive. After applying the Spearman–Brown prophesy formula to the current estimates of reliability (to equate test length of the current split-half estimates to that of Fan et al.'s test–retest estimates, see Table 2) the current study observes estimates that correspond rather well with the Fan et al. (2001) results. The present study thus replicates the previously observed pattern of differential reliability of the three network scores in RT. For ER–ANT scores, this pattern is even more marked (see Table 2). The low and moderate reliabilities associated with ANT network scores are potentially a result of the subtractions used in calculating ANT network scores. Difference scores can have low levels of reliability, at least partially as a result of the inverse relation between difference score reliability and the correlation between the two variables used in creation of the difference score (e.g., see Salthouse & Hedden, 2002). Furthermore, raw RT by itself can be expected to have high intraindividual variability and overall between-Ss effects (slowed RTs in older and patient groups, etc.; Salthouse & Berish, 2005). However, meaningful assessment of attention network efficiency in the ANT requires the calculation of RT difference scores, as neither single trial types nor overall RT provide useful data when considered in isolation. Therefore, even though these RT difference scores may be less than optimal in terms of reliability, they do represent the best measures of attention network efficiency available within the

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[5] The demonstration of nonnormal attention network score distributions does not preclude the use of repeated measures ANOVA in this context. The repeated measures ANOVA described here was conducted at the level of the cell (in the 4 [cue] × 3 [flanker] data structure), so only the normality of the cells and, more critically, the sphericity of the covariance matrix were assumptions of the test.

[6] These correlation analyses were also performed on the full $N = 1129$ data set ignoring origin experiment and results were largely similar. For the sake of brevity we omit these results but here note four discrepancies: (1) the correlation between alerting RT and executive ER was significant ($r = .10$, $p < .01$) in the analyses ignoring origin (cf. current nonsignificant results); (2) the correlation between orienting RT and executive RT was significant ($r = -.06$, $p = .04$) in the analyses ignoring origin (cf. current nonsignificant results); (3) the correlation between alerting RT and executive RT was nonsignificant ($r = .05$, $p = .10$) in the analyses ignoring origin (cf. current significant results); (4) the correlation between orienting RT and executive ER was slightly stronger ($r = -.18$) in the analyses ignoring origin (cf. current results, where $r = -.11$).

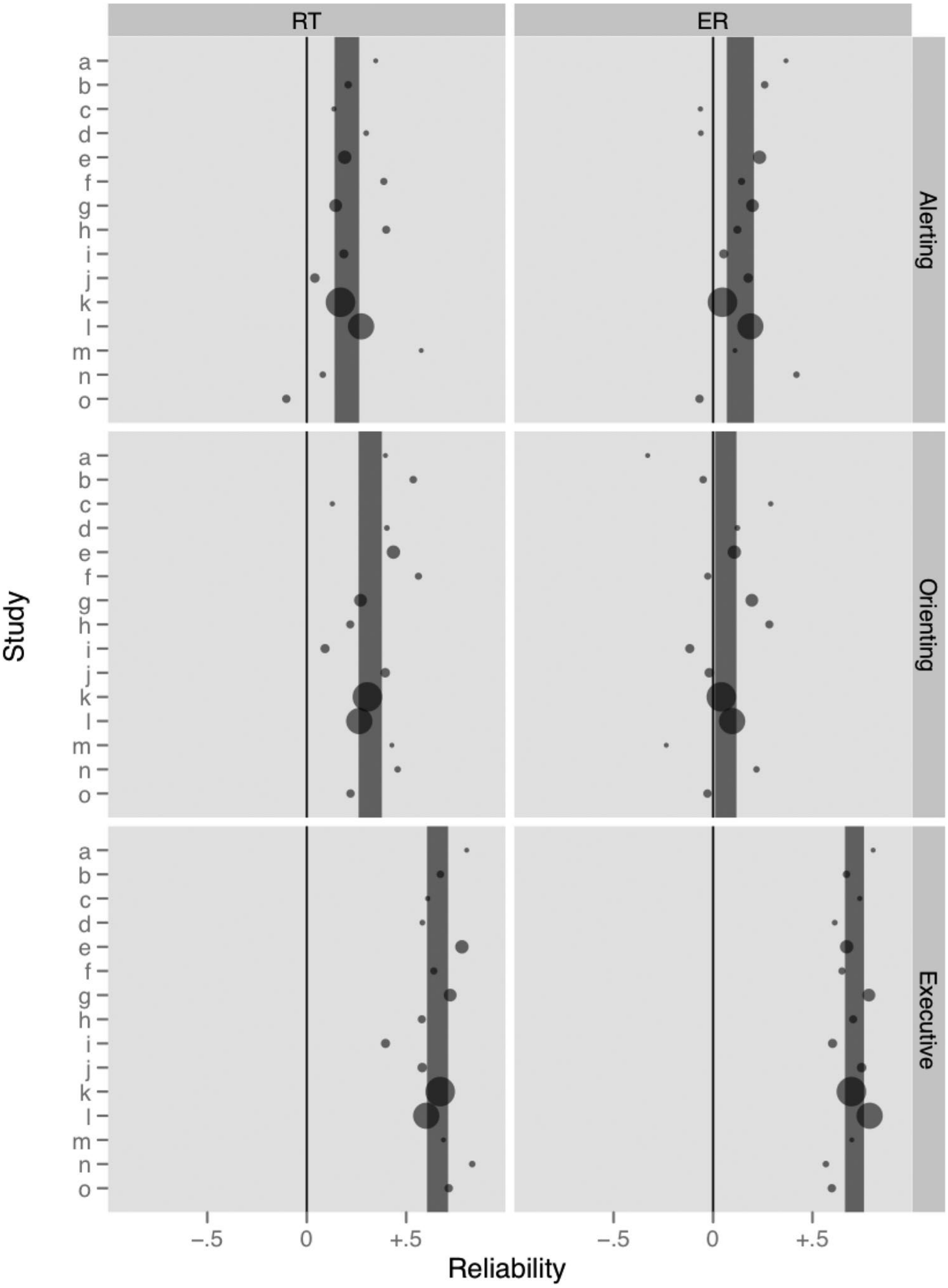

Figure 2. Split-half reliability analyses. In each of these panels, the estimate of split-half reliability is mapped to the *x*-axis, bounded on the left and right by values of −1 and 1, respectively, with zero marked by a black vertical line at center. Data from each study are depicted separately across the *y*-axis (see data set key below). The reliability estimate resulting from the analysis of each individual data set is indicated with a data point on each graph, and size of this data point is scaled to correspond to size of the data set. The gray shaded areas depict the 95% confidence interval around the weighted mean of the reliability estimates. Reaction time (RT) reliabilities are depicted in left column, and error rate (ER) reliabilities in the right column. a = AhnAllen, b = Beutel, c = Breau, d = Callejas, e = Fan(1), f = Fan(2), g = Ishigami, h = MacLeod(1), i = MacLeod(2), j = McConnell(1), k = McConnell(2), l = McConnell(3), m = Neuhaus, n = Oberlin, o = Redick.

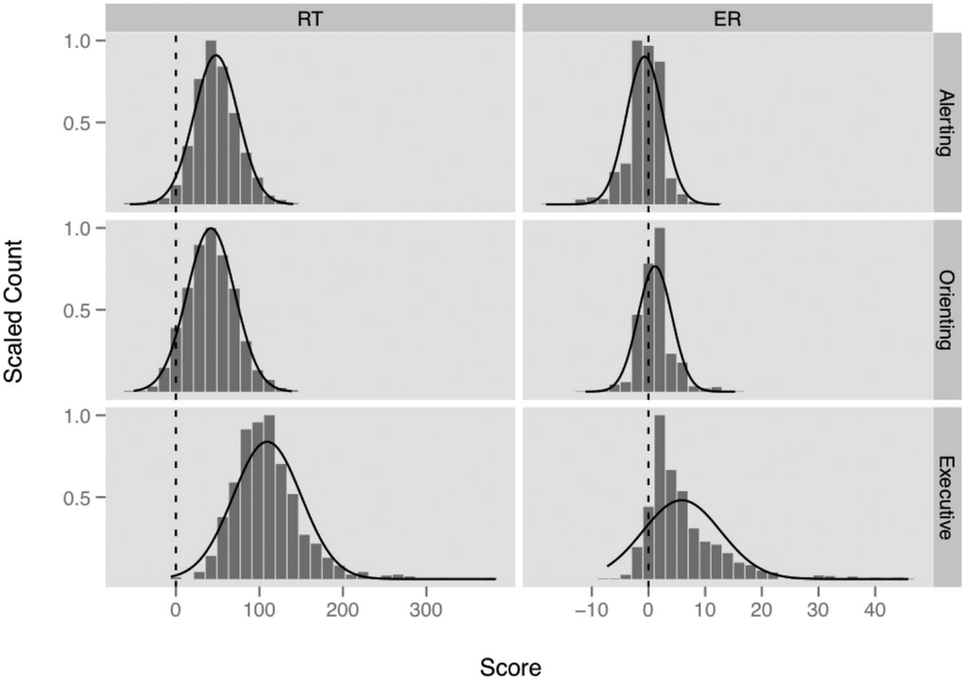

Figure 3. Distribution of attention network scores for each of the three networks using correct mean reaction time (RT) in the left column and error rate (ER) in the right column. Frequencies are scaled with the highest frequency equal to one. A dashed vertical line indicating a score of zero is superimposed on the data, as are curves representing the expected Gaussian density given each distribution's mean and variance.

context of the ANT. The reliability results reinforce the original concern outlined in the introduction that the psychometric properties of the scores provided by the ANT for the three networks are not equivalent, and that these differences might have influenced the frequency with which network specific effects are obtained in the literature of research employing the ANT (see the Tally of Attention Network Effects in the Literature sections). To address this concern more directly, we turn to the analysis of the variance structure of the ANT scores.

Variance of Attention Network Scores, Reliability, and Power

As noted by Williams et al. (1995), reliability alone cannot be used to deduce the relative statistical power of a measure because reliability is a function of both within-Ss variability and the variability of true scores between-Ss. In short, if measure *X* is more reliable than measure *Y*, it could be that this difference is driven by a reduced within-Ss variance in measure *X*, in which case experiments measuring *X* and *Y* will more frequently find significant effects involving *X*. On the other hand, the difference in reliability between *X* and *Y* could be driven by an increased between-Ss variance of the true scores in measure *X*, in which case experiments measuring *X* and *Y* will more frequently find significant effects involving *Y*. A further complication is that this pattern holds for between-Ss experimental designs only; in the case of within-Ss experimental designs, changes in the between-Ss variance of true scores has no bearing on statistical power.

In the present study, we find that the within-Ss variance of network scores is such that executive control has the lowest

Table 3
Results of the Normality Tests for Each Frequency Distribution

	Omnibus	Skewness	Kurtosis	*M*	*t* test
Reaction time					
Alerting	$p < .01$	0.10, $p = .19$	0.74, $p < .01$	48 ms	$p < .01$
Orienting	$p = .05$	0.18, $p = .02$	–0.01, $p = .94$	42 ms	$p < .01$
Executive	$p < .01$	1.21, $p < .01$	3.80, $p < .01$	109 ms	$p < .01$
Error rate					
Alerting	$p < .01$	–0.81, $p < .01$	2.95, $p < .01$	–0.68%	$p < .01$
Orienting	$p < .01$	0.42, $p < .01$	2.28, $p < .01$	1.15%	$p < .01$
Executive	$p < .01$	2.02, $p < .01$	5.72, $p < .01$	5.87%	$p < .01$

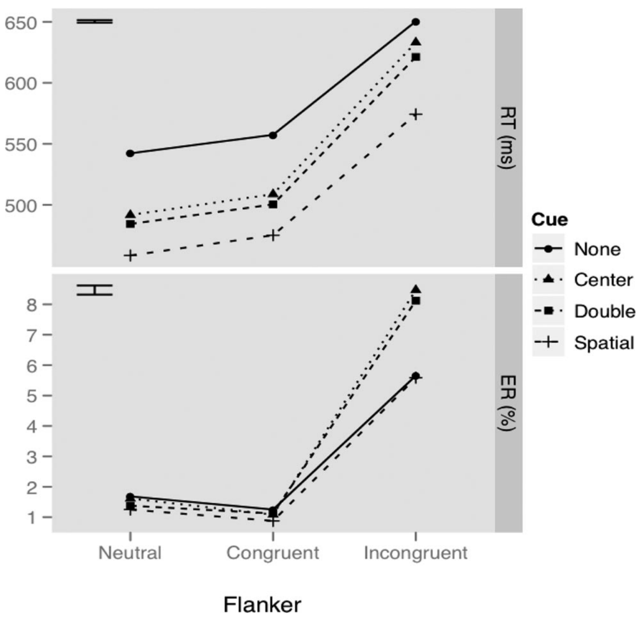

Figure 4. A line graph depicting mean reaction times (RT) and error rates (ER) for each of the 12 cells (every combination of cue and flanker type). Mean RT displayed on the upper graph and mean ER on the lower graph. Error bars in the upper left corners of the graphs indicate Fisher's least significant difference for the interaction in an analysis of variance computed across all 1,129 participants.

variance, followed by orienting and alerting (which differed in RT, but not in ER). This suggests that in the context of within-Ss experimental designs, tests employing the executive scores will have greater statistical power than tests of the other networks. However, this pattern appears to be offset by a stronger opposite pattern in between-Ss true score variance, as examination of the observed between-Ss variance of true network scores (expressed analytically as the sum of within-Ss variance and between-Ss variance of true scores) reveals that executive control scores have the greatest between-Ss variance. This suggests that, in the context of between-Ss designs, the executive control network will have the least statistical power even though its reliability is the highest of the three networks.

In light of these results, we revisited the tally of published ANT effects detailed in the Tally of Attention Network Effects in the Literature section. Examining the same 39 published studies listed in the Appendix, we recategorized the tally according to whether the experimental design employed within- or between-Ss manipulation. Of the 15 within-Ss analyses, five (33%) alerting, four (27%) orienting, and 12 (80%) executive effects were significant, and of the 30 between-Ss designs, 11 (37%) alerting, nine (30%) orienting, and 23 (77%) executive effects were significant. Some studies conducted more than one type of analysis, so the number of analyses tallied is greater than the number of studies considered. Thus, although the within-Ss tally (executive $>$ orienting $\sim$ alerting) is generally consistent with the pattern predicted from the analysis of within-Ss variance (executive $>$ orienting $>$ alerting) observed in the current data, the between-Ss tally (executive $>$ alerting $>$ orienting) is not consistent with the pattern predicted from the analysis of between-Ss variance (executive $<$ orienting $<$ alerting) observed in the current data. These patterns suggest mixed support for the previously noted concern that the observed frequency of significant attention network effects might be driven solely by the psychometric properties (reliability and resulting power) of the ANT. That is, there appear to be more significant between-Ss effects in the executive network than predicted by psychometrics alone. If there is enough power to detect significant between-Ss effects in the executive network (which requires the most power because of high between-Ss variance), and if true between-Ss differences of a similar magnitude in the other networks also existed, significant effects should have been found on all networks. The failure to find such differences supports selective between-Ss differences in the executive network only. However, where the frequency of within-Ss effects is consistent with the pattern predicted from the analysis of within-Ss effects, it is possible that studies that obtained selective within-Ss differences in the executive network may have simply failed to achieve sufficient power to find coexisting true within-Ss differences in the orienting and alerting networks. Thus, the discovery of network specific effects should be considered with caution.

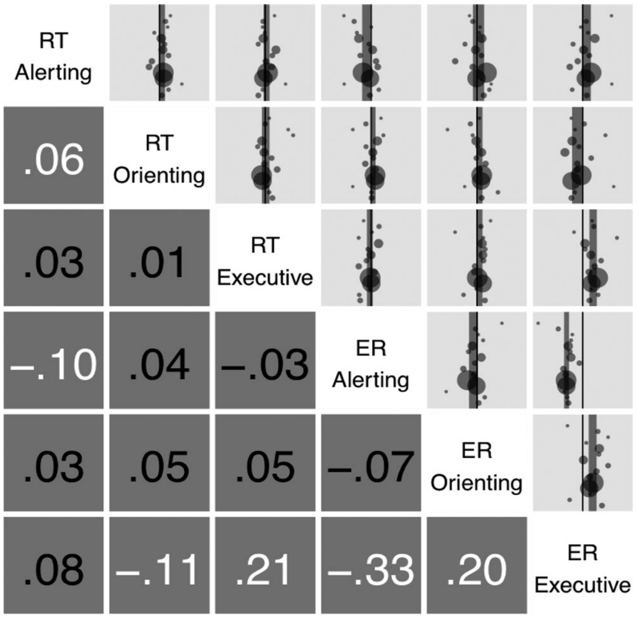

Figure 5. Inter-network correlation matrix. In each of the panels above the diagonal (upper right), the correlation estimate is mapped to the x-axis, bounded on the left and right by values of -1 and 1, respectively, with zero marked by a black vertical line at center. Data from each study are depicted separately across the y-axis where studies appear in descending alphabetical order from the top of each panel (as in Figure 2). Dot sizes are proportional to the N of each study. The shaded areas are centered on the inter-network correlations' weighted mean r values, and width of the shaded areas is determined by the 95% confidence interval around the weighted mean. In each of the panels below the diagonal (lower left) appears the weighted mean inter-network correlation value, calculated across all 15 data sets. These values correspond to those depicted by the shaded areas in the graphics above the diagonal (upper right). Color of the values is determined by the statistical significance of the correlation, with white values indicating the correlation was statistically significant ($p < .05$) and black values indicating a nonsignificant correlation. RT = reaction time; ER = error rate.

To avoid further ambiguity in the future, researchers employing the ANT should take these differences into account when designing studies, ensuring that power is sufficiently high (and roughly equivalent) across networks to minimize the influence of these differences on the likelihood of obtaining significant results. Because power is positively and asymptotically related to test length in this context, a seemingly simple means of minimizing power differences is to repeat administration of the ANT. However, very little research has been conducted on the psychometric consequences of such extension, and it is possible that time-dependent effects such as practice or fatigue may undermine this strategy. Research is underway (Ishigami & Klein, 2009b) to investigate this approach.

Shape and Location of Attention Network Score Distributions

The distributions of all network scores, using both performance measures, were nonnormal (see Figure 3 and Table 3). These nonnormal distributions should be taken into consideration when conducting statistical analyses using parametric tests at the level of the network scores; researchers may benefit from employing a nonparametric test such as the randomization test, which is known to have superior power in the context of nonnormal distributions (Mewhort, 2005; but see Mewhort, Kelly & Johns, 2009, for a more nuanced perspective). In addition, many individual network scores in both RT and ER distributions fall below zero. The meaning of these negative scores is unclear, making interpretation of some individuals' ANT performance difficult, thus limiting the usefulness of the ANT for examining individual differences and providing diagnostic evaluations. This is especially true for the alerting and orienting scores calculated using ER as the performance measure. The ER distributions suggest that although, on average, there were nonzero effects of the cues on ER, these effects may not accurately predict the performance of many individuals, and that the effect of cues manifest more strikingly and consistently in RT.

Attention Network Independence

ANOVA. The presence of a Cue × Flanker interaction in 100% of the 15 data sets is in general agreement with the results of Fan et al. (2002), and more recent studies (Costa et al., 2008; Fan et al., 2007; Ishigami & Klein, 2009a; Redick & Engle, 2006). Similar to Fan et al.'s (2002) data, interactions in the current data sets were largely the result of more efficient conflict resolution following the spatial cue and no cue conditions. This interaction indicates that the attention networks, as measured by the ANT, do not operate independently. In this case, executive control (as reflected in conflict resolution or filtering) was relatively poor when participants were alerted by a cue that did not provide spatial certainty.

Inter-network correlations. Using RT as the performance measure, a small but significant correlation was demonstrated between the alerting and orienting network scores. Though this correlation was not demonstrated in the original reports on the ANT (Fan et al., 2001, 2002), it was reported in a subsequent study that employed a larger sample (Fossella et al., 2002). An interaction between the alerting and orienting networks also has been demonstrated in studies that employed a modified version of the ANT in which a tone serves as a warning signal and cues are uninformative with respect to target location. In this modified ANT, the alerting tone has been demonstrated to improve orienting efficiency (Callejas, Lupiáñez, Funes, & Tudela, 2005; Callejas, Lupiáñez, & Tudela, 2004; Fuentes & Campoy, 2008).

When ER was the performance measure, executive control was significantly related to both orienting and alerting network scores (see Figure 4). The directions of these correlations suggest that the efficiency of conflict resolution (when measured using ER) is improved (smaller congruent–incongruent difference) in individuals whose accuracy benefits most from a spatial cue, and reduced (larger congruent–incongruent difference) in individuals who show greater negative effects on accuracy when they are alerted in the double cue condition. This interpretation of the correlation results agrees with the ANOVA results in both RT and accuracy, as the Cue × Flanker interactions appears to largely result from enhanced conflict resolution following spatial and no cue conditions (see Figure 5).

The magnitude of the relations discovered in the correlation analyses may be even stronger than the data immediately suggest. It is a long established phenomenon (Spearman, 1904) that correlations between measures with imperfect reliability tend to underestimate the strength of the true correlation between the quantities measured. Although this does not affect the null-hypothesis test of a correlation against zero (Lawrence, 2008), it does affect the estimate of the strength of correlations that are significantly different from zero. Spearman provided a correction for this attenuation, and as inspection of Table 4 demonstrates, the estimates for the true values of correlations detect in this study reflect substantial relations, and further evidence that the attention networks do not operate independently in the context of the ANT.

Measurement versus mind. An important consideration in the critique of psychometric tools is whether the observed characteristics of measurement are truly features of the tool under consideration or features of the quantity being measured. That is, a measure may be unreliable either because the tool used to make the measurement is unreliable, or because the mind's natural variability is such that the quantity of interest cannot be measured reliably. Similarly, two measures may correlate because the quantities they reflect are truly associated, or because the tools used for measurement cause systematic yet spurious correlation. We have worded

Table 4

Raw and Corrected Estimates of Significant Correlations Obtained in This Study

Correlation	Raw estimate	Corrected estimate
Alerting RT and orienting RT	.06	0.13
Alerting ER and executive ER	–.33	–.72
Orienting ER and executive ER	.20	.56
Orienting RT and executive ER	–.11	–.16
Alerting ER and alerting RT	–.10	–.32
Executive ER and executive RT	.21	.25

Note. Spearman (1904)'s correction consists of dividing the observed correlation by the square root of the product of the reliabilities of the measures being correlated. Reliabilities for this computation were drawn from applying the Spearman–Brown prophesy formula to the split-half reliabilities observed in the current study.

this report in a manner that thus far implicitly assumes that reliability is attributable to the ANT whereas the associations between networks are attributable to the mind. Although further work is necessary to support the former assumption, a case can be made with respect to the latter insofar as the computation of ANT scores has strong face validity for achieving mathematical independence. Observations from neuroimaging (Corbetta & Shulman, 2002; Fan et al., 2005) and behavioral data (Callejas et al., 2005; Fan et al., 2009) further support the interpretation of the associations observed in the current report as pertaining to mind rather than measurement.

Speed–Accuracy Tradeoffs

In addition to inter-network correlations, within-network (across performance measure) correlations were found in the current data. These correlations can be used, in conjunction with the means of the network score distributions, to examine network performance for the presence of a speed–accuracy tradeoff (SAT). The RT and ER network scores for orienting and executive control had positive means and were positively correlated (although the orienting network correlation was not significant), suggesting an absence of SAT for these networks. However, for the alerting network a positive mean RT score was accompanied by a negative mean ER score, and a small but significant negative correlation (–.09) between the performance measures was observed. These patterns suggest that the RT benefit from alerting is accomplished, at least in part, via a tradeoff in accuracy. These patterns conform to Posner's suggestion that alerting does not affect the quality of information about a signal but does speed responding to it (Posner, 1975; Posner, Klein, Summers, & Buggie, 1973).

Conclusions

The ANT is an easily accessible, intuitive tool that can be completed in a short time period by individuals of almost any age and ability. Partially as a result of these characteristics, the ANT has become a popular tool in the neuropsychological literature. ANT performance has been used to provide evidence of specific attention network deficits in special populations, as evidence of remediative benefits to specific attention networks, and as evidence of developmental differences in attention networks between subgroups of the normal population. Yet as the present study demonstrates, there is growing evidence that the networks of attention do not operate independently from one another, and the psychometric properties of the scores obtained by the ANT complicate interpretation of results that seemingly suggest network-specific phenomena.

The idea of interaction among the networks was suggested in Fan et al., 2002, who presented the following conclusion: "Overall, it appears that there are some interactions between the networks suggesting that they may not prove to be independent in all behavioral studies even though they use different anatomy and chemical modulators" (p. 344). Such a caveat was preceded by Posner's (1978) development of the concept of "isolable" subsystems of attention. Housed in one brain and implemented by distributed and somewhat overlapping neural networks, strong independence between the networks of attention is unlikely. Nevertheless, their isolability means that they can be separately influenced by experimental manipulations and separately impacted by brain damage and psychiatric disorders. The significant correlations we have uncovered here and the significant statistical interaction between cue condition and flanker condition that was present in all the studies we analyzed provide important evidence about how these isolable subsystems influence each other. Although these results show that the network measurements provided by the ANT are not entirely independent, the correlations and interactions among the networks do not preclude the possibility of demonstrating network-specific effects. Experimental manipulations, for example, might isolate attentional networks by showing effects on some network scores but not on others. Because conclusions about isolability from any such pattern will require reliance on some null findings it is imperative that scholars carefully consider whether such null results might be due to insufficient power.

Researchers and clinicians interested in using the ANT to examine individual differences and network-specific effects will be disappointed by the relatively low reliability of the network scores for orienting and alerting. In the current study, we cannot ascertain from the data analyzed here whether the low reliability of these measures is due to a weakness in the measuring tool (ANT) or to relatively high intra-individual variability. Evidence described in the introduction supporting the validity of the ANT supports the individual variability account. In this regard, it is interesting to consider the difference between neuropsychological states and neuropsychological traits. To the extent that a component of attention is a trait, it will tend to be stable across multiple-measurement occasions and its reliability will be relatively high. In contrast, to the extent that a component of attention is a state, it will be freer to vary across multiple measurements and its reliability will be relatively low. The reliability difference between executive control on the one hand, and alerting and orienting on the other, may simply reflect that control is more trait-like while alerting and orienting are more state-like.[7] Indeed, this distinction between state- and trait-like attention networks is borne out in the variance structure of the ANT scores, with executive networks appearing more trait like (low within-subject variance and high between-subjects variance), and the alerting and orienting networks appearing more state like (high within-subject variance and low between-subjects variance). This notion is also commensurate with genetic studies of attention networks that have reported evidence of high heritability in executive network efficiency, but have failed to find similar evidence for the alerting and orienting networks (Fan et al., 2001; see Posner, Rothbart, & Sheese, 2007, for a review).

Putting aside differences in reliability of the network scores and the possible sources of these differences, there is one concrete recommendation we can offer to researchers seeking to increase confidence in their network-specific observations: collect more data. There are two strategies that could be useful to employ. One is to simply increase the number of trials collected using the ANT (e.g., use a greater number of testing sessions). Barring changes in network efficiency due to practice, fatigue, and so forth, such an increase is guaranteed to increase reliability. The other, as suggested by Klein (2003), is to add tasks designed to provide a

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[7] We thank an anonymous reviewer for suggesting we heed this distinction.

more refined measurement of the components of attention. Converging evidence from such tasks should increase confidence and understanding (for examples of this strategy in examination of the executive control network, see Gruber, Rathberger, Braunig, & Gauggel, 2007; Loo et al., 2007). Precisely how these strategies might be accomplished will depend on the questions being posed by the authors.

References

References marked with an asterisk indicate studies included in the mega-analysis.

Adolfsdottir, S., Sorensen, L., & Lundervold, A. (2008). The attention network test: A characteristic pattern of deficits in children with ADHD. *Behavioral and Brain Functions, 4*(1), 9.

*AhnAllen, C. G., Nestor, P. G., Shenton, M. E., McCarley, R. W., & Niznikiewicz, M. A. (2008). Early nicotine withdrawal and transdermal nicotine effects on neurocognitive performance in schizophrenia. *Schizophrenia Research, 100,* 261–269.

Bednarek, D. B., Saldaña, D., Quintero-Gallego, E., García, I., Grabowska, A., & Gómez, C. M. (2004). Attentional deficit in dyslexia: A general or specific impairment? *Neuroreport: For Rapid Communication of Neuroscience Research, 15,* 1787–1790.

*Beutel, M. E., Klockenbrink, P., Wiltink, J., Dietrich, S., Thiede, R., Fan, J., . . . Posner, M. I. (2006). Aufmerksamkeit und exekutive funktionen bei patienten mit adipositas per magna. eine kontrollierte studie mit dem aufmerksamkeitsnetzwerktest [Attention and executive functions in patients with severe obesity. A controlled study using the attention network test]. *Nervenarzt, 77,* 1323–1331.

Bish, J. P., Ferrante, S. M., McDonald-McGinn, D., & Simon, T. J. (2005). Maladaptive conflict monitoring as evidence for executive dysfunction in children with chromosome 22q11.2 deletion syndrome. *Developmental Science, 8*(1), 36–43.

Booth, J. E., Carlson, C. L., & Tucker, D. M. (2007). Performance on a neurocognitive measure of alerting differentiates ADHD combined and inattentive subtypes: A preliminary report. *Archives of Clinical Neuropsychology, 22,* 423–432.

Breau, S., & Eskes, G. A. [The effects of caffeine on attention networks in habitual caffeine consumers]. Unpublished raw data.

Bush, G., Luu, P., & Posner, M. I. (2000). Cognitive and emotional influences in anterior cingulate cortex. *Trends in Cognitive Sciences, 4*(6), 215–222.

Callejas, A., & Lupiáñez, J. [Untitled study]. Unpublished raw data.

Callejas, A., Lupiáñez, J., Funes, M. J., & Tudela, P. (2005). Modulations among the alerting, orienting and executive control networks. *Experimental Brain Research, 167*(1), 27–37.

Callejas, A., Lupiáñez, J., & Tudela, P. (2004). The three attentional networks: On their independence and interactions. *Brain and Cognition, 54,* 225–227.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3,* 201–215.

*Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition, 106,* 59–86.

Coull, J. T., Nobre, A. C., & Frith, C. D. (2001). The noradrenergic α2 agonist clonidine modulates behavioural and neuronanatomical correlates of human attentional orienting and alerting. *Cerebral Cortex, 11,* 73–84.

*Dye, M. W. G., Baril, D. E., & Bavelier, D. (2007). Which aspects of visual attention are changed by deafness? the case of the attentional network test. *Neuropsychologia, 45,* 1801–1811.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149.

Fan, J., Byrne, J., Worden, M. S., Guise, K. G., McCandliss, B. D., Fossella, J., . . . Posner, M. I. (2007). The relation of brain oscillations to attentional networks. *Journal of Neuroscience, 27,* 6197–6206.

Fan, J., Fossella, J., Sommer, T., Wu, Y., & Posner, M. I. (2003). Mapping the genetic variation of executive attention onto brain activity. *Proceedings of the National Academy of Sciences, USA, 100,* 7406.

Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., . . . Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition, 70,* 209–220.

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage, 26,* 471–479.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14,* 340–347.

Fan, J., & Posner, M. (2004). Human attentional networks. *Psychiatrische Praxis, 31*(Suppl. 2), S210–S214.

*Fan, J., Wu, Y., Fossella, J., & Posner, M. (2001). Assessing the heritability of attentional networks. *BMC Neuroscience, 2,* 14.

*Fernandez-Duque, D., & Posner, M. I. (2001). Brain imaging of attentional networks in normal and pathological states. *Journal of Clinical and Experimental Neuropsychology, 23,* 74–93.

Fossella, J., Green, A. E., & Fan, J. (2006). Evaluation of a structural polymorphism in the ankyrin repeat and kinases domain containing 1 (ANKK1) gene and the activation of executive attention networks. *Cognitive, Affective & Behavioral Neuroscience, 6,* 71–78.

Fossella, J. A., Sommer, T., Fan, J., Pfaff, D., & Posner, M. I. (2003). Synaptogenesis and heritable aspects of executive attention. *Mental Retardation and Developmental Disabilities Research Reviews, 9,* 178–183.

*Fossella, J. A., Sommer, T., Fan, J., Wu, Y., Swanson, J. M., Pfaff, D. W., & Posner, M. I. (2002). Assessing the molecular genetics of attention networks. *BMC Neuroscience, 3,* 14.

Fuentes, L. J., & Campoy, G. (2008). The time course of alerting effect over orienting in the attention network test. *Experimental Brain Research, 185,* 667–672.

*Gooding, D. C., Braun, J. G., & Studer, J. A. (2006). Attentional network task performance in patients with schizophrenia–spectrum disorders: Evidence of a specific deficit. *Schizophrenia Research, 88,* 169–178.

Greene, D. J., Barnea, A., Herzberg, K., Rassis, A., Neta, M., Raz, A., . . . Zaidel, E. (2008). Measuring attention in the hemispheres: The lateralized attention network test (LANT). *Brain and Cognition, 66*(1), 21–31.

Gruber, S., Rathgeber, K., Bräunig, P., & Gauggel, S. (2007). Stability and course of neuropsychological deficits in manic and depressed bipolar patients compared to patients with major depression. *Journal of Affective Disorders, 104,* 61–71.

Ishigami, Y., & Klein, R. M. (2009a). Are individual differences in absentmindedness correlated with individual differences in attention? *Journal of Individual Differences, 20,* 220–237.

Ishigami, Y., & Klein, R. M. (2009b, June). *Measuring the components of attention across the lifespan using the Attention Network Test (ANT).* Paper presented at the 19th annual meeting (joint meeting with Experimental Psychology Society) Canadian Society for Brain, Behaviour and Cognitive Science, York, England.

*Jennings, J. M., Dagenbach, D., Engle, C. M., & Funke, L. J. (2007). Age-related changes and the attention network task: An examination of alerting, orienting, and executive function. *Aging, Neuropsychology, and Cognition, 14,* 353–369.

*Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective & Behavioral Neuroscience, 7,* 109–119.

Klein, R. M. (2003). Chronometric explorations of disordered minds. *Trends in Cognitive Sciences, 7,* 190–192.

Lawrence, M. A. (2008). Disattenuation by simulation: An estimation and inferential tool for correlation amidst estimable measurement error. *Canadian Journal of Experimental Psychology, 62,* 279.

*Lehtonen, S. E. (2008). Self-reported inattention and hyperactivity-impulsivity as predictors of attention network efficiency. *Dissertation Abstracts International: Section B: The Sciences and Engineering, 68*(12–B), 8402.

*Leskin, L. P., & White, P. M. (2007). Attentional networks reveal executive function deficits in posttraumatic stress disorder. *Neuropsychology, 2,* 275–284.

*Loo, S. K., Humphrey, L. A., Tapio, T., Moilanen, I. K., McGough, J. J., McCracken, J. T., . . . Smalley, S. L. (2007). Executive functioning among Finnish adolescents with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 46,* 1594–1604.

MacLeod, J. W., & McConnell, M. M. [Examining the relationship between attention networks and executive functions]. Unpublished raw data a.

MacLeod, J. W., & McConnell, M. M. [Examining the relationship between attention networks and the attentional blink]. Unpublished raw data b.

McConnell, M. M., & Shore, D. I. A time to work and a time to play: Temporal variations in measures of attention. Unpublished manuscript a.

McConnell, M. M., & Shore, D. I. The effects of shifts to and from daylight savings time on attentional network. Unpublished manuscript b.

McConnell, M. M., & Shore, D. I. *Upbeat and happy: Arousal as an important factor in studying attention.* Manuscript submitted for publication.

Mewhort, D. J. K. (2005). A comparison of the randomization test with the F test when error is skewed. *Behavioral Research Methods, 37,* 426–435.

Mewhort, D. J. K., Kelly, M., & Johns, B. T. (2009). Randomization tests and the unequal-N/unequal-variance problem. *Behavior Research Methods, 41,* 664–667.

*Murphy, C. F., & Alexopoulos, G. S. (2006). Attention network dysfunction and treatment response of geriatric depression. *Journal of Clinical and Experimental Neuropsychology, 28,* 96–100.

*Nestor, P. G., Kubicki, M., Spencer, K. M., Niznikiewicz, M., McCarley, R. W., & Shenton, M. E. (2007). Attentional networks and cingulum bundle in chronic schizophrenia. *Schizophrenia Research, 90,* 308–315.

*Neuhaus, A. H., Koehler, S., Opgen-Rhein, C., Urbanek, C., Hahn, E., & Dettling, M. (2007). Selective anterior cingulate cortex deficit during conflict solution in schizophrenia: An event-related potential study. *Journal of Psychiatric Research, 41,* 635–644.

Oberlin, B. G., Alford, J. L., & Marrocco, R. T. (2005). Normal attention orienting but abnormal stimulus alerting and conflict effect in combined subtype of ADHD. *Behavioural Brain Research, 165,* 1–11.

Opgen-Rhein, C., Neuhaus, A. H., Urbanek, C., Hahn, E., Sander, T., & Dettling, M. (2008). Executive attention in schizophrenic males and the impact of COMT Val $^{108/158}$Met genotype on performance on the attention network test. *Schizophrenia Bulletin, 34*(6), 1231–1239.

Posner, M. I. (1975). Psychobiology of attention. In M. Gazzaniga & C. Blakemore, (Eds.), *Handbook of psychobiology* (pp. 441–480). New York, NY: Academic Press.

Posner, M. I. (1978). *Chronometric explorations of mind.* Hillsdale, NJ: Wiley.

Posner, M. I. (1980). Orienting of attention. *The Quarterly Journal of Experimental Psychology, 32,* 3–25.

Posner, M. I., Klein, R. M., Summers, J., & Buggie, S. (1973). On the selection of signals. *Memory & Cognition, 1,* 2–12.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13,* 25–42.

Posner, M. I., & Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annual Review of Psychology, 58,* 1–23.

Posner, M. I., Rothbart, M. K., & Sheese, B. E. (2007). Attention genes. *Developmental Science, 10,* 24–29.

*Posner, M. I., Rothbart, M. K., Vizueta, N., Levy, K. N., Evans, D. E., Thomas, K. M., . . . Clarkin, J. F. (2002). Attentional mechanisms of borderline personality disorder. *Proceedings of the National Academy of Sciences, USA, 99,* 16366–16370.

R Development Core Team. (2009). R: A Language and Environment for Statistical Computing [Computer software]. . . . : Author. Retrieved from http://www.R-project.org

*Redick, T. S., & Engle, R. W. (2006). Working memory capacity and attention network test performance. *Applied Cognitive Psychology, 20,* 713–721.

Rogosch, F. A., & Cicchetti, D. (2005). Child maltreatment, attention networks, and potential precursors to borderline personality disorder. *Development and Psychopathology, 17,* 1071–1089.

Rueda, M. R., Fan, J., McCandliss, B. D., Halparin, J. D., Gruber, D. B., Lercari, L. P., . . . Posner, M. I. (2004). Development of attentional networks in childhood. *Neuropsychologia, 42,* 1029–1040.

Salthouse, T. A., & Berish, D. E. (2005). Correlates of within-person (across-occasion) variability in reaction time. *Neuropsychology, 19,* 77–87.

Salthouse, T. A., & Hedden, T. (2002). Interpreting reaction time measures in between-group comparisons. *Journal of Clinical and Experimental Neuropsychology, 24,* 858–872.

Sobin, C., Kiley-Brabeck, K., Daniels, S., Blundell, M., Anyane-Yeboa, K., & Karayiorgou, M. (2004). Networks of attention in children with the 22q11 deletion syndrome. *Developmental Neuropsychology, 26,* 611–626.

Spearman, C. (1904). The proof and measurement of association between two things. *American Journal of Psychology, 15,* 72–101.

Spearman, C. (1910). Correlation calculated from faulty data. *British Journal of Psychiatry, 3,* 271–295.

*Tang, Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., . . . Posner, M. I. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences, USA, 104,* 17152–17156.

*van Donkelaar, P., Langan, J., Rodriguez, E., Drew, A., Halterman, C., Osternig, L. R., . . . Chou, L. S. (2005). Attentional deficits in concussion. *Brain Injury, 19,* 1031–1039.

*Wang, K., Fan, J., Dong, Y., Wang, C., Lee, T. M. C., & Posner, M. I. (2005). Selective impairment of attentional networks of orienting and executive control in schizophrenia. *Schizophrenia Research, 78,* 235–241.

Wickelgren, W. A. (1977). Speed-accuracy tradeoff and information processing dynamics. *Acta Psychologica, 41*(11), 67–85.

Williams, R. H., Zimmerman, D. W., & Zumbo, B. D. (1995). Impact of measurement error on statistical power: Review of an old paradox. *Journal of Experimental Education, 63,* 363–370.

*Zylowska, L., Ackerman, D. L., Yang, M. H., Futrell, J. L., Horton, N. L., Hale, T. S., . . . Smalley, S. L. (2008). Mindfulness meditation training in adults and adolescents with ADHD: A feasibility study. *Journal of Attention Disorders, 11,* 737–746.

(*Appendix follows*)

Appendix

The 39 Articles That Were Considered to Assess the Prevalence of Significant Effects From Each ANT Network in the Psychological Literature

Title	Alerting	Orienting	Executive function
AhnAllen, C. G., Nestor, P. G., Shenton, M. E., McCarley, R. W., & Niznikiewicz, M. A. (2008). Early nicotine withdrawal and transdermal nicotine effects on neurocognitive performance in schizophrenia. *Schizophrenia Research, 100,* 261–269.	0	0	0
Berman, M. G., Jonides, J., & Kaplan, S. (2008). The cognitive benefits of interacting with nature. *Psychological Science, 19,* 1207–1212.	0	0	1
Beutel, M. E., Klockenbrink, P., Wiltink, J., Dietrich, S., Thiede, R., Fan, J. . . . Posner, M. I. (2006). Aufmerksamkeit und exekutive funktionen bei patienten mit adipositas per magna. eine kontrollierte studie mit dem aufmerksamkeitsnetzwerktest [Attention and executive functions in patients with severe obesity. A controlled study using the attention network test]. *Nervenarzt, 77,* 1323–1331.	0	0	1
Blank, M. D., Kleykamp, B. A., Jennings, J. M., & Eissenberg, T. (2007). Caffeine's influence on nicotine's effects in nonsmokers. *American Journal of Health Behavior, 31,* 473–483.	0	1	0
Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition, 106,* 59–86.	1	0	1
Dennis, T. A., & Chen, C. (2007a). Emotional face processing and attention performance in three domains: Neurophysiological mechanisms and moderating effects of trait anxiety. *International Journal of Psychophysiology, 65*(1), 10–19.	1	1	1
Dennis, T. A., & Chen, C. (2007b). Neurophysiological mechanisms in the emotional modulation of attention: The interplay between threat sensitivity and attentional control. *Biological Psychology, 76*(1–2), 1–10.	0	0	1
Du, J, Wang, K, Dong, Y, & Fan, J. (2006). Effects of Venlafaxine for the attention networks of depression disorder. *Acta Psychologica Sinica, 38,* 247–253.	1	0	1
Dye, M. W. G., Baril, D. E., & Bavelier, D. (2007). Which aspects of visual attention are changed by deafness? The case of the attentional network test. *Neuropsychologia, 45,* 1801–1811.	0	0	0
Fan, J., Wu, Y., Fossella, J., & Posner, M. (2001). Assessing the heritability of attentional networks. *BMC Neuroscience, 2*(1), 14.	1	0	1
Fernandez-Duque, D., & Black, S. E. (2006). Attentional networks in normal aging and Alzheimer's disease. *Neuropsychology, 20,* 133–143.	1	0	1
Fossella, J., Sommer, T., Fan, J., Wu, Y., Swanson, J., Pfaff, D. . . . Posner, M. I. (2002). Assessing the molecular genetics of attention networks. *BMC Neuroscience, 3*(1), 14.	1	0	1
Gardner, T. W., Dishion, T. J., & Posner, M. I. (2006). Attention and adolescent tobacco use: A potential self-regulatory dynamic underlying nicotine addiction. *Addictive Behaviors, 31,* 531–536.	0	0	1
Gooding, D. C., Braun, J. G., & Studer, J. A. (2006). Attentional network task performance in patients with schizophrenia–spectrum disorders: Evidence of a specific deficit. *Schizophrenia Research, 88,* 169–178.	0	0	1
Gruber, S., Rathgeber, K., Brãunig, P., & Gauggel, S. (2007). Stability and course of neuropsychological deficits in manic and depressed bipolar patients compared to patients with major depression. *Journal of Affective Disorders, 104*(1–3), 61–71.	0	1	1
Halterman, C. I., Langan, J., Drew, A., Rodriguez, E., Osternig, L. R., Chou, L. . . . van Dankelaar, P. (2006). Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury. *Brain, 129,* 747–753.	0	1	1
Jennings, J. M., Dagenbach, D., Engle, C. M., & Funke, L. J. (2007). Age-related changes and the attention network task: An examination of alerting, orienting, and executive function. *Aging, Neuropsychology, and Cognition, 14,* 353–369.	1	0	0
Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. Cognitive, Affective & *Behavioral Neuroscience, 7,* 109–119.	1	1	1
Kleykamp, B. A., Jennings, J. M., Blank, M. D., & Eissenberg, T. (2005). The effects of nicotine on attention and working memory in never-smokers. *Psychology of Addictive Behaviors, 19,* 433–438.	0	0	0
Lampe, K., Konrad, K., Kroener, S., Fast, K., Kunert, H. J. & Herpertz, S. C. (2007). Neuropsychological and behavioural disinhibition in adult ADHD compared to borderline personality disorder. *Psychological Medicine, 37,* 1717–1729.	0	0	1
Leclercq, V., Jambaqué, I., Picard, A., Bricout, L., & Siéroff, É. (2006). Trouble du contrôle attentionnel et prématurité [Attentional control disorder and prematurity]. *Revue De Neuropsychologie, 16*(1), 41–64.	1	1	1
Lehtonen, S. E. (2008). Self-reported inattention and hyperactivity-impulsivity as predictors of attention network efficiency. *Dissertation Abstracts International: Section B: The Sciences and Engineering, 68*(12–B), 8402.	1	0	1

(*Appendix continues*)

Appendix (*continued*)

Title	Alerting	Orienting	Executive function
Leskin, L. P., & White, P. M. (2007). Attentional networks reveal executive function deficits in posttraumatic stress disorder. *Neuropsychology, 21,* 275–284.	0	0	1
Loo, S. K., Humphrey, L. A., Tapio, T., Moilanen, I. K., McGough, J. J., McCracken, J. T. . . . Smalley, S. L. (2007). Executive functioning among Finnish adolescents with attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 46,* 1594–1604.	1	1	1
Murphy, C. F., & Alexopoulos, G. S. (2006). Attention network dysfunction and treatment response of geriatric depression. *Journal of Clinical and Experimental Neuropsychology, 28,* 96–100.	0	0	1
Nestor, P. G., Kubicki, M., Spencer, K. M., Niznikiewicz, M., McCarley, R. W., & Shenton, M. E. (2007). Attentional networks and cingulum bundle in chronic schizophrenia. *Schizophrenia Research, 90,* 308–315.	1	1	0
Neuhaus, A. H., Koehler, S., Opgen-Rhein, C., Urbanek, C., Hahn, E., & Dettling, M. (2007). Selective anterior cingulate cortex deficit during conflict solution in schizophrenia: An event-related potential study. *Journal of Psychiatric Research, 41,* 635–644.	0	0	1
Oberlin, B. G., Alford, J. L., & Marrocco, R. T. (2005). Normal attention orienting but abnormal stimulus alerting and conflict effect in combined subtype of ADHD. *Behavioural Brain Research, 165*(1), 1–11.	1	1	1
Posner, M. I., Rothbart, M. K., Vizueta, N., Levy, K. N., Evans, D. E., Thomas, K. M. . . . Clarkin, J. F. (2002). Attentional mechanisms of borderline personality disorder. *Proceedings of the National Academy of Sciences of the United States of America, 99,* 16366–16370.	0	0	1
Redick, T. S., & Engle, R. W. (2006). Working memory capacity and attention network test performance. *Applied Cognitive Psychology, 20,* 713–721.	0	0	1
Reuter, M., Ott, U., Vaitl, D., & Hennig, J. (2007). Impaired executive control is associated with a variation in the promoter region of the tryptophan hydroxylase 2 gene. *Journal of Cognitive Neuroscience, 19,* 401–408.	0	0	1
Rüsch, N., Weber, M., Il'yasov, K. A., Lieb, K., Ebert, D., Hennig, J. & van Elst, L. T. (2007). Inferior frontal white matter microstructure and patterns of psychopathology in women with borderline personality disorder and comorbid attention-deficit hyperactivity disorder. *NeuroImage, 35,* 738–747.	0	0	1
Tang, Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q. . . . Posner, M. I. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences of the USA, 104,* 17152–17156.	0	0	1
Van Donkelaar, P., Langan, J., Rodriguez, E., Drew, A., Halterman, C., Osternig, L. R. . . . Chou, L. S. (2005). Attentional deficits in concussion. *Brain Injury, 19,* 1031–1039.	0	1	0
Wan, L., Friedman, B. H., Boutros, N. N., & Crawford, H. J. (2008). P50 sensory gating and attentional performance. International *Journal of Psychophysiology, 67*(2), 91–100.	1	1	1
Wang, K., Fan, J., Dong, Y., Wang, C., Lee, T. M. C., & Posner, M. I. (2005). Selective impairment of attentional networks of orienting and executive control in schizophrenia. *Schizophrenia Research, 78,* 235–241.	0	1	1
Weaver, B., Bédard, M., McAuliffe, J., & Parkkari, M. (2009). Using the attention network test to predict driving test scores. Accident Analysis & Prevention, 41(1), 76–83.	0	0	1
Zylowska, L., Ackerman, D. L., Yang, M. H., Futrell, J. L., Horton, N. L., Hale, T. S. . . . Smalley, S. L. (2008). Mindfulness meditation training in adults and adolescents with ADHD: A feasibility study. *Journal of Attention Disorders, 11,* 737–746.	0	0	1
Total number of effects observed for each network	15	12	31

Note. Articles excluded include those that used the Child Attention Network Test (ANT; or some other alternate form of the ANT), articles that did not report the results from all three networks, and those that did not use ANT data to examine a difference or relation between two groups or conditions.

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