ATTENTION NETWORK TEST: PSYCHOMETRIC CONSIDERATIONS

PSYCHOMETRIC CONSIDERATIONS OF THE ATTENTION NETWORK TEST

By

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ABSTRACT

It has been suggested that the human attention system is subdivided into three functionally and anatomically independent networks—the alerting network, the orienting network, and the executive control network. The Attention Network Test (ANT) aims to provide a quick, easy and intuitive tool for measuring the efficiency of these three networks. The ANT, first described in 2001, has become popular in the neuropsychological literature, with some form of the task currently appearing in no less than 65 original research papers. Although several general reviews of the ANT exist, an analysis of the psychometric properties of the ANT is lacking. The present study analyzed the reliability, variance structure, distribution shape, and independence of the three attention network measures provided by the ANT using a multi-study approach with a large sample (N=1129). The findings suggest caution is needed in the collection, analysis, and interpretation of ANT data.

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PREFACE

The majority of this thesis has been written in the form of a manuscript to be submitted to the journal *Neuropsychology* for publication. The research project described in the thesis was a collaborative effort between researchers at Dalhousie University and McMaster University. The author of the thesis was responsible for conceptual development of the project, some data collection, some initial data analyses (that do not appear in the thesis), consultation and discussion surrounding the data analyses which appear in the thesis, the writing and development of all sections of the thesis (including the literature review detailed in the introduction), and co-ordinating the edits and multiple revisions of the original thesis documents (with the five co-authors). Michael A. Lawrence (from Dalhousie University) was responsible for helping in the conceptual development of the project, collection of raw Attention Network Test data from various researchers in the scientific community who were not part of the current project, conducting data analyses (in consultation with co-authors), the creation of figures, significant editing of drafts of the manuscript, and writing several paragraphs which appear in the Results and Discussion sections of the thesis (these sections were subsequently edited by the author). Meghan M. McConnell was responsible for helping in the conceptual development of the project, and testing the majority of participants who completed the Attention Network Test at McMaster University. Drs. Gail A. Eskes, Raymond M. Klein, and David I. Shore were responsible for editing drafts of the manuscript, providing guidance in data analysis, and all made significant contributions to the conceptual development of the project.

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INTRODUCTION

On the basis of behavioral and neuroscientific studies Posner & colleagues have suggested that the human attentional system can be subdivided into three functionally and anatomically independent networks (Fan, McCandliss, Sommer, Raz, Posner, 2002; Fan, McCandliss, Fosella, Flombaum, Posner, 2005; Posner & Peterson, 1990; Posner & Rothbart, 2007). 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 in order 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 of the attentional system has redefined the approach cognitive scientists use when examining the function (Fan, McCandliss, Sommer, Raz, Posner, 2002) and development (Rueda, Fan, McCandliss, Halparin, Gruber, Lercari, Posner, 2004) of the attentional system, and has allowed better description of the attention disorders and difficulties associated with neuropsychological (for example, *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 Posner & Rothbart, 2007, or Fan & Posner, 2004, 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 neuropsychological literature, with some form of the task appearing in at least 65 original research papers since 2001. The reliability of each of the three attention network scores provided by the task has not been well established, and whether the ANT assesses the attention networks independently remains unclear. The present report addresses both of these issues using a multi-study approach.

The ANT 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. Figure 1 shows the task timeline, the three arrow conditions, and four cue conditions.

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. Although Fan, Fossella, Sommer, Wu, Posner (2003) set a good example for the field by doing so in their seminal paper, these calculations are usually omitted in the ANT literature (but see: Adolfsdottir, Sorensen, Lundervold, 2008; Costa, Hernandez, Sebastian-Galles, 2008; Jha, Krompinger, Baime, 2007; Fan, Byrne, Worden, Guise, McCandliss, Fossella, et al., 2007; Fossella, Green, & Fan, 2006; Ishigami & Klein, in press). 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 dyslexia (Bednarek, Saldana, Quintero-Gallego, Garcia, Grabowska, Gomez, 2004), schizophrenia (Wang, Fan, Dong, Wang, Lee, Posner, 2005), borderline personality disorder (Rogosch & Cicchetti, 2005), Depression (Murphy & Alexopoulos, 2006), ADHD (Adolfsdottir et.al., 2008), and 22q11 deletion syndrome (Bish et.al., 2005). It has also been used to examine the heritability of attention networks (Fosella, Sommer, Fan, Pfaff, Posner, 2003; Fan, Fosella, Sommer, Wu, Posner, 2003; Fosella, Green, Fan, 2006), and the effectiveness of mindfulness training (Zylowska, Ackerman, Yang, Futrell, Horton, Hale, Pataki, Smalley, 2008; Tang, Ma, Wang, Fan, Feng, Lu et.al. 2007; Jha, Krompinger, Baime, 2007). 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, Rothbart, Vizueta, Levy, Evans, Thomas, Clarkin, 2002), post-traumatic stress disorder (Leskin & White, 2007), attention deficit/hyperactivity disorder (ADHD; Loo, Humphrey, Tapio, Moilanen, McGough, McCracken et.al. 2007), severe obesity (Beutel, Klockenbrink, Wiltink, Dietrich, Thiede, Fan, Posner, 2006), dyslexia (Bednarek et.al., 2004), and 22q11 deletion syndrome (Bish et.al., 2005; Sobin, Kiley-Brabeck, Daniels, Blundell, Anyane-Yeboa, Karayiorgou, 2004). A specific orienting network deficit was reported in individuals who had a concussion (van Donkelaar, Langan, Rodriguez, Drew, Halterman, Osternig, Chou, 2005), and a specific alerting deficit has been observed in older individuals (relative to younger individuals; Jennings, Dagenbach, Engle, Funke, 2007), and 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; Neuhaus, Koehler, Opgen-Rhein, Urbanek, Hahn, Dettling, 2007; Gooding, Braun, Studer, 2006), one study has reported a specific alerting deficit (Nestor, Kubicki, Spencer, Niznikiewicz, McCarley, Shenton, 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 has also 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 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 non-independence 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 published by Rueda et al, 2004). More recently, however, this Cue × Flanker interaction has been replicated (e.g. Ishigami & Klein, in press; Redick & Engle, 2006; Fan, Byrne, Worden, Guise, McCandliss, Fosella, Posner, 2007; Dye, Baril, & Bavelier, 2007; Jennings, Dagenbach, Engle, & Funk, 2007), and small, but significant correlations between alerting and executive control network scores (Fosella, Sommer, Fan, Wu, Swanson, Pfaff, Posner, 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, for example, show an overlap in executive control and orienting). It is questionable, then, whether the weight of currently published evidence supports network independence.

Given the ANT's prevalence in the scientific literature, it would appear that this tool has widely been 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. Also, it has been suggested that performance of the task is associated with the distinct activation of three neural networks within the brain (Fan et. al., 2005). However, 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. Fan, Wu, Fossella, & Posner (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 first-half performance to second-half performance) 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, Barnea, Herzberg, Rassis, Neta, Raz, Zaidel, 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 relationship to statistical power (Williams, Zimmerman & Zumbo, 1995), but one possible relationship is that less reliable measures can decrease statistical power. If this relationship 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 relationships (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 (see Kopriva & Shaw, 1991, for formulae relating reliability and effect size to power in the case of one-way analysis of variance).

To explore whether the observed frequency of 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 the analysis 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, only analyzed ANT data to examine whether network scores were significantly different from zero, used a modified ANT (e.g. Greene, Barnea, Herzberg, Rassis, Neta, Raz, Zaidel, 2008), or used the child ANT (Rueda et.al., 2004). Of the seventy articles considered, thirty-nine 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 are listed in Table 1. While a number of hypotheses can account for this observed pattern of frequencies (e.g. differential true effect sizes, etc), it is concerning to note that the pattern roughly correspond to the reliability estimates provided by Fan et. al. (2001, 2002) and thus is at least consistent with an account attributing the pattern solely to 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 that will help motivate decisions on its use and/or interpretation.

Analysis of the reliability of network scores is an essential part of this assessment, but other issues also need to be considered. Reliability itself is a function of the between-subjects score variance and the within-subjects score variance, and the interplay of these two sources of variance influence statistical power (Williams, Zimmerman & Zumbo, 1995), so 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.

Methods

Data collection

The data collection process was a collaborative effort between researchers at McMaster University and Dalhousie University, with both research groups testing participants. Additionally, the Dalhousie research group requested raw ANT data from the authors of published and unpublished research projects employing the ANT[2,3]. In total, data from 1141 participants from 15 unique studies employing the ANT were gathered (see Table 2 for the demographic information associated with each data set). Of these 1141 participants, 1129 were used in the subsequent analyses (12 failed to meet an overall accuracy criterion of 70% correct). Each data set was initially collected in order to answer a unique set of research questions that, for the most part, were orthogonal to that of the current investigation. Participants ranged in age from 16-65 years (see Table 2 for mean ages of each study).

The Attention Network Test

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 2 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 (400ms – 1600ms). 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 100msec, 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 400msec 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 2). Each Flanker type is equally likely. The target display remains on the screen until a response is made, or 1700 msec 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 et.al. [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 in R (R Development Core Team, 2009) and 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 reaction time (RT) and error rate (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 (or cell). This method was used to calculate the split half reliability estimates for each of the 15 data 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 3 we provide examples of such extrapolation.

Considering RT, the Executive network was most reliable ($r_{weighted} = .65$, $CI_{95\%, weighted} = .61$ to .71) followed by the Orienting network ($r_{weighted} = .32$, $CI_{95\%, weighted} = .26$ to .38); the Alerting network was least reliable ($r_{weighted} = .20$, $CI_{95\%, weighted} = .14$ to .27). Within ER, the Executive network was again most reliable ($r_{weighted} = .71$, $CI_{95\%, weighted} = .67$ to .76) followed by the Alerting network ($r_{weighted} = .14$, $CI_{95\%, weighted} = .07$ to .21); the Orienting network was least reliable ($r_{weighted} = .06$, $CI_{95\%, weighted} = .01$ to .12). See Figure 2 for a 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 re-sampling. These scores were then submitted to paired t-tests comparing each pair of networks across the entire sample of 1129 participants. In RT, all networks manifested different within-Ss variance (all $p<.05$); the within-Ss variance of executive network scores (305ms) was less than that of the the orienting network scores (352ms) which in turn was less than that of the alerting network scores (406ms). In ER, the within-Ss variance of executive network scores (6.9%) was less than that of the orienting network scores (7.3%, $p<.01$) and that of the alerting network scores (7.5%, $p<.01$); the within-Ss variance of alerting and orienting network scores were not significantly different ($p = .09$).

Between-Ss Variance of Attention Network Scores. The between-Ss variance of scores was computed for each network for the entire sample of 1129 participants, along with 95% confidence intervals estimated by bootstrap resampling. In RT, the between-Ss variance of the executive network scores (1655ms, $CI_{95\%}$ = 1447ms to 1898ms) was greater than that of the orienting network scores (818ms, $CI_{95\%}$ = 751ms to 885ms), which in turn was greater than that of the alerting network scores (689ms, $CI_{95\%}$ = 626ms to 750ms). In ER, the between-Ss variance of the executive network scores (47.3%, $CI_{95\%}$ = 40.1% to 55.1%) was greater than that of the orienting network scores (8.9%, $CI_{95\%}$ = 7.9% to 10.0%) and the alerting network scores (10.4%, $CI_{95\%}$ = 9.1% to 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 1129 participants. RT and ER histograms for each attention network are presented in Figure 3. D'agostino-Pearson tests of normality were used to assess normality in both variables for all three attention networks. All tested distributions were non-normal (see Table 4). T-tests of the distribution means were also performed, rejecting the null hypothesis of zero in all tested distributions (see Table 4).

Cue × Flanker ANOVA.

A standard 3 x 4 (3 flanker types x 4 cue types) repeated measures ANOVA was conducted on each of the 15 data sets separately in order to examine the percentage of studies demonstrating a Cue × Flanker interaction. 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[4] 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 ($r_{weighted}$ = .06, $CI_{95\%, weighted}$ = .01 to .11, between Alerting ER and Executive ER ($r_{weighted}$ = -.33, $CI_{95\%, weighted}$ = -.37 to -.28), between Orienting ER and Executive ER ($r_{weighted}$ = .20, $CI_{95\%, weighted}$ = .12 to .28), and between Orienting RT and Executive ER ($r_{weighted}$ = -.11, $CI_{95\%, weighted}$ = -.21 to -.01; this correlation will not be discussed further due to difficulty of interpretation). Significant within-network correlations were found between Alerting ER and Alerting RT ($r_{weighted}$ = -.10, $CI_{95\%, weighted}$ = -.18 to -.01), and between Executive ER and Executive RT ($r_{weighted}$ = .21, $CI_{95\%, weighted}$ = .13 to .28).

Discussion

The present study had three main goals: 1) to analyze the reliability of the ANT measurements; 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 multi-study approach, drawing on a large sample (N=1129) from 15 unique data sets (see Table 2).

Reliability

In 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 3) the current study observes estimates that correspond rather well with the Fan et al results. The present study thus replicates the previously observed pattern of differential reliability of the three network scores in RT. In ER, this pattern is even more dramatic (see Table 3). These 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. To address this concern more directly, we turn to the analysis of the variance structure of the ANT scores.

Variance of Attention Network Scores

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 has the lowest variance, followed by orienting and alerting (which differed in RT, but not in ER), suggesting 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, 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 scores also have the greatest between-Ss variance. This suggests that, in the context of between-Ss designs, the executive network will have the least statistical power even though its reliability is the highest of the three networks.

In light of these results, we reviewed our original tally of published ANT effects (detailed in the introduction), re-categorizing the tally according to whether the experimental design employed within- or between-Ss manipulation. Of the 15 within-Ss analyses, 5 (33%) alerting, 4 (27%) orienting, and 12 (80%) executive effects were significant, and of the 30 between-Ss designs, 11 (37%) alerting, 9 (30%) orienting, and 23 (77%) executive effects were significant. Thus, while the within-Ss tally is generally consistent with the pattern of within-Ss variance observed in the current data, the between-Ss tally is not consistent with the pattern of between-Ss variance observed in the current data. This suggests mixed support for the previously noted concern that the observed frequency of reported results is driven solely by the psychometric properties of the ANT. 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. Since power is 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, 2009) to investigate this approach.

Shape and Location of Attention Network Score Distributions

All network score distributions, using both performance measures, were determined to be non-normal (see Figure 3 and Table 4). These non-normal 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 non-parametric test such as the randomization test, which is known to have superior power in the context of non-normal distributions (Mewhort. 2005; Mewhort, Kelly & Johns, 2009). Additionally, 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 and limiting the usefulness of the ANT for diagnostic purposes and examining individual differences. This is especially true for the alerting and orienting scores calculated using ER as the performance measure (the mean score for these networks was close to zero). The ER distributions suggest that while on average there were non-zero 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 (Redick & Engle, 2006; Fan et.al., 2007; Ishigami & Klein, in press; Costa, Hernandez, Sebastian-Galles, 2008). 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. The presence of this interaction suggests that the three attention networks are not measured independently by the ANT. In this case, executive control (as reflected in conflict resolution, or filtering) is relatively poor when participants are alerted by a cue that does not narrow down the number of locations where a target might appear.

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 which employed a larger sample (Fosella et.al., 2008). An interaction between the alerting and orienting networks has also been demonstrated in studies which 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, Tudela, 2004; Callejas, Lupiáñez, Funes, & Tudela, 2005; 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 presence of significant inter-network correlations and a robust demonstration of a Cue × Flanker interaction together suggest that the attention networks, as assessed by the ANT, are not independent.

The present study found no evidence for inter-network correlations between orienting and executive networks and alerting and executive networks with RT as the performance measure, although interactions between these networks have been reported (Fan et.al., 2007, 2009). Additionally, no evidence was obtained for a correlation between alerting and orienting with ER as the performance measure. However, given that attention network measurement reliabilities were low for two of the three attention networks, this lack of significant inter-network correlations cannot be interpreted as evidence of a lack of true correlation in the cognitive functions that the network scores are designed to assess. That is, strong correlations between attention network measures cannot reasonably be expected when these networks do not correlate well with themselves (Spearman, 1907). Indeed, given the low reliability of the alerting and orienting network measurements with ER as the dependent variable, it is striking that substantial and significant inter-network correlations among these variables were found in the present study[5].

Attention network independence: measurement vs. mind

The observed non-independence between network scores in the current data may be a matter of measurement or of mind. If a matter of measurement, then the non-independence reflects the ANT's failure to isolate the networks. If a matter of mind, then the non-independence is a result of interaction between the attention networks that is a part of normal attention processing. In order to be demonstrate that this interaction is a matter of mind, one would first need to demonstrate that the ANT is assessing all three attention networks in a valid manner. Although this cannot be demonstrated by the current data, the computation of ANT scores has strong face validity that is corroborated by brain imaging data (Fan, McCandliss, Fosella, Flombaum, Posner, 2005). Therefore, it is reasonable to suggest that the evidence of interaction between the attention networks in the current data appears, at least in part, because the networks interact during normal attentional processing. This suggestion does agree with imaging data demonstrating the attention networks are not entirely neuroanatomically separable (Fan et.al., 2005; Corbetta & Shulman, 2002), and with behavioral data from more recent versions of the ANT demonstrating significant network interactions (Fan, Gu, Guise, Liu, Fossella, Wang, Posner, 2009; Callejas et.al. 2005).

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 that the RT scores are not being generated by a 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 numbers suggest that the RT benefit from alerting is accomplished, at least in part, via a tradeoff in accuracy. The pattern of alerting network scores conforms 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). Furthermore, the negative correlation between the RT and ER alerting scores suggests that participants with larger RT benefits from alerting tend to have larger ER costs, providing converging evidence for Posner's suggestion.

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 supports, 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 group differences of manipulation effects. We suggest that researchers seeking confidence in network-specific observations may benefit from repeated administration of the ANT (following demonstration that such repeated administration improves psychometric performance), or from the the administration of alternative, psychometrically equated, tests of each specific network. Indeed, using multiple measurements to assess the attentional system seems well advised regardless of whether the ANT is used. Many studies that have used the ANT to assess attentional function in special populations potentially spent more time gathering diagnosis and disease characteristic information than they did on experimental cognitive assessment (the ANT requires less than 30 minutes; E.g. Posner et.al., 2002; Murphy & Alexopoulos, 2006; Adolfsdottir et.al., 2008). While these relatively long clinical assessments are critical for diagnostic purposes and comprise an essential part of any study of special populations, the current analyses show that more time and data from cognitive assessment with the ANT and other measures also are required for results to be meaningful and reliable. In this spirit, the ANT should be treated as an exploratory measure that provides only a glimpse at the efficiency of the complex processes involved in the function and modulation of attention.

Future work on the ANT should attempt to develop variants of the ANT that allow for more reliable measurement and quantification of the interactions between networks without sacrificing the excellent face validity of the original ANT. Two notable attempts at this have already appeared in the literature—the ANT-i (Callejas et.al. 2005) and the ANT-R (Fan et.al. 2009). If established as reliable measures, these quick and simple tools could prove useful in the initial assessment of patients with neuropsychological disorders and in some populations (such as children) unable to handle the rigors of a more thorough cognitive assessment.

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FOOTNOTES

1. The JAVA version of the ANT provides both raw data and pre-calculated scores. The pre-calculated 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.

2. The data collection process was a collaborative effort between researchers at McMaster University and Dalhousie University. Initially, however, these two research groups were working in isolation. The McMaster research group had collected 681 ANT data sets 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 had also decided to analyze the psychometric properties of the ANT, but largely relied on a different data collection method. In addition to collecting 118 ANT data sets, 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 in order 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 in order 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.

4. 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:

- The correlation between Alerting RT and Executive Error Rate was significant ($r = .10$, $p < .01$) in the analyses ignoring origin (cf. current non-significant results)
- The correlation between Orienting RT and Executive RT was significant ($r = -.06$, $p = .04$) in the analyses ignoring origin (cf. current non-significant results)
- The correlation between Alerting RT and Executive RT was non-significant ($r = .05$, $p = .10$) in the analyses ignoring origin (cf. current significant results)
- The correlation between Orienting RT and Executive Error Rate was slightly stronger ($r=-.18$) in the analyses ignoring origin (cf. current results, where $r=-.11$)

5. Using the formula provided by Spearman (1907) to analyze true correlation given observed correlation and the correcting for reliability of the contributing measurements, the true correlation between alerting ER and executive ER is -.97, and the true correlation between orienting ER and executive ER is .81.

LIST OF TABLES

Table 1. The 39 articles that were considered in order to assess the prevalence of significant effects from each ANT network in the psychological literature.

Authors	Year	Title	Alerting	Orienting	Executive Function
Matchcock, Mordkoff	2009	Chronotype and time of day influences on the alerting, orienting, and executive components of attention	1	0	0
Weaver, Bedard, McAuliffe, Parkkari	2008	Using the Attention Network Test to predict driving test scores	0	0	1
Berman, Jonides, Kaplan	2008	The Cognitive Benefits of Interacting with Nature	0	0	1
AhnAllen, Nestor, Shenton, McCarley, Niznikiewicz	2008	Early nicotine withdrawal and transdermal nicotine effects on neurocognitive performance in Schizophrenia.	0	0	0
Zylowska, Ackerman, Yang, Futrell, Horton, Hale, Pataki, Smalley	2008	Mindfulness meditation training in adults and adolescents with ADHD: a feasibility study	0	0	1
Wan, Friedman, Boutros, Crawford	2008	P50 Sensory gating and attentional performance	1	1	1
Lehtonen	2008	Self-reported inattention and hyperactivity-impulsivity as predictors of attention network efficiency	1	0	1
Gruber, Rathgeber, Braunig, Gauggel	2007	Stability and course of neuropsychological deficits in manic and depressed bipolar patients compared to patients with major depression.	0	1	1
Neuhaus, Koehler, Opgen-Rhein, Urbanek, Hahn, Dettling	2007	Selective anterior cingulate cortex deficit during conflict solution in schizophrenia: An event-related potential study	0	0	1
Tang, Ma, Wang, Fan, Feng, Lu, Yu, Sui, Rothbart, Fan, Posner	2007	Short-term meditation training improves attention and self-regulation.	0	0	1
Dennis, Chen	2007	Neurophysiological mechanisms in the emotional modulation of attention: The interplay between threat sensitivity and attentional control.	0	0	1
Dennis, Chen	2007	Emotional face processing and attention performance in three domains: Neurophysiological mechanisms and moderating effects of trait anxiety	1	1	1
Lampe, Konrad, Kroener, Fast	2007	Neuropsychological and behavioural disinhibition in adult ADHD compared to borderline personality disorder	0	0	1
Dye, Baril, Bavelier	2007	Which aspects of visual attention are changed by deafness? The case of the Attentional Network Test	0	0	0
Leskin, White	2007	Attentional Networks Reveal Executive Function Deficits in Posttraumatic Stress Disorder	0	0	1

Authors	Year	Title	Alerting	Orienting	Executive Function
Jennings, Dagenbach, Engle, Funke	2007	Age-related changes and the attention network task: An examination of alerting, orienting, and executive function.	1	0	0
Jha, Krompinger, Baime	2007	Mindfulness training modifies subsystems of attention.	1	1	1
Loo et. al.	2007	Executive Functioning Among Finnish Adolescents With Attention-Deficit/Hyperactivity Disorder	1	1	1
Reuter, Ott, Vaitl, Hennig	2007	Impaired executive control is associated with a variation in the promoter region of the tryptophan hydroxylase 2 gene.	0	0	1
Nestor, Kubicki, Spencer, Niznikiewicz, McCarley, Shenton	2007	Attentional networks and cingulum bundle in chronic schizophrenia.	1	1	0
Rusch et.al.	2007	Inferior frontal white matter microstructure and patterns of psychopathology in women with borderline personality disorder ...	0	0	1
Blank, Kleykamp, Jennings, Eissenberg	2007	Caffeine's Influence on Nicotine's Effects in Nonsmokers	0	1	0
Gooding, Braun, Studer	2006	Attentional network task performance in patients with schizophrenia-spectrum disorders: Evidence of a specific deficit.	0	0	1
Costa, Hernandez, Sebastian-Galles	2006	Bilingualism aids conflict resolution: Evidence from the ANT task	1	0	1
Beutel, Klockenbrink, Wiltink, Dietrich, Thiede, Fan, Posner	2006	Attention and executive functions in patients with severe obesity. A controlled study using the Attention Network Test.	0	0	1
Fernandez-duque, Black	2006	Attentional Networks in Normal Aging and Alzheimer's Disease	1	0	1
Redick, Engle	2006	Working Memory Capacity and Attention Network Test Performance.	0	0	1
Gardner, Dishion, Posner	2006	Attention and adolescent tobacco use: A potential self-regulatory dynamic underlying nicotine addiction.	0	0	1
Leclerc et.al.	2006	Trouble du contrôle attentionnel et prématurité. / Attentional control disorder and prematurity.	1	1	1
Du, Wang, Dong, Fan	2006	Effects of Venlafaxine for the Attention Networks of Depression Disorder	1	0	1
Halterman et.al.	2006	Tracking the recovery of visuospatial attention deficits in mild traumatic brain injury	0	1	1
Murphy, Alexopoulos	2006	Attention Network Dysfunction and Treatment Response of Geriatric Depression.	0	0	1

Authors	Year	Title	Alerting	Orienting	Executive Function
Wang, Fan, Dong, Wang, Lee, Posner	2005	Selective impairment of attentional networks of orienting and executive control in schizophrenia.	0	1	1
Kleykamp, Jennings, Blank, Eissenberg	2005	The Effects of Nicotine on Attention and Working Memory in Never-Smokers	0	0	0
van Donkelaar et.al.	2005	Attentional deficits in concussion	0	1	0
Oberlin, Alford, Marrocco	2005	Normal attention orienting but abnormal stimulus alerting and conflict effect in combined subtype of ADHD	1	1	1
Posner, Rothbart, Vizueta, Levy, Evans, Thomas, Clarkin	2002	Attentional Mechanisms of Borderline Personality Disorder	0	0	1
Fossella Sommer, Fan, Wu, Swanson, Pfaff, Posner	2002	Assessing the molecular genetics of attention networks	1	0	1
Fan, Wu, Fosella, Posner	2001	Assessing the heritability of attentional networks.	1	0	1
		Total number of effects observed for each network:	15	12	31

Table 2. Authorship, demographic information, and software information for the 15 data sets included in the present analyses.

Dataset Name	Associated Publication	n	Mean Age (years)	Age Range (years)	Sex	Software Platform	Neutral Condition Flanker
AhnAllen	AhnAllen, Nestor, Shenton, McCarle, Niznikiewicz, 2008	17	42	18-60	All male	Eprime	Dash Flankers
Beutel	Beutel, Klockenbrink, Wiltink, Dietrich, Thiede, Fan & Posner, 2006	43	42	18-62	39 Female, 4 Male	Eprime	Dash Flankers
Breau	Unpublished	20	22.9	18-46	All male	Java	No Flankers
Callejas	Unpublished	25	N/K	18-25	20 Female, 5 Male	Eprime	Dash Flankers
Fan (1)	Fan, Wu, Fossella, Posner, 2001	104	N/K	14-42	N/K	Eprime	Dash Flankers
Fan (2)	Fan, McCandliss, Sommer, Raz, Posner, 2002	40	30.1	20-44	23 Female, 17 Male	Eprime	Dash Flankers
Ishigami	Unpublished	98	20.87	17-37	64 Female, 34 Male	Java	No Flankers
MacLeod (1)	Unpublished	49	19.1	18-26	29 Female, 20 Male	Matlab	Dash Flankers
MacLeod (2)	Unpublished	60	18.6	18-24	35 Female, 25 Male	Matlab	Dash Flankers
McConnell (1)	Unpublished	64	19.3	17-26	48 Female, 16 Male	Matlab	Dash Flankers
McConnell (2)	Unpublished	271	19.1	17-42	219 Female, 52 Male	Matlab	Dash Flankers
McConnell (3)	Unpublished	237	19.2	16-29	170 Female, 67 Male	Matlab	Dash Flankers
Neuhaus	Neuhaus, Koehler, Opgen-Rhein, Urbanek, Hahn, Dettling, 2007	16	36.63	18-65	8 Female, 8 Male	Experimental Run Time System in Windows 98	Dash Flankers
Oberlin	Oberlin, Alford, Marrocco, 2005	33	N/K	18-30	17 Female, 16 Male	Eprime	No Flankers
Redick	Redick, Engle, 2006	52	N/K	18-35	N/K	Eprime	Dash Flankers

Table 3. 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	0.20	.14 to .27	0.38
	Orienting	0.32	.26 to .38	0.55
	Executive	0.66	.61 to .71	0.81
Error Rate	Alerting	0.14	.07 to .21	0.25
	Orienting	0.06	.01 to .12	0.15
	Executive	0.72	.67 to .76	0.85

Table 4. Results of the normality tests for each frequency distribution.

	Reaction Time				
	Omnibus	*Skewness*	*Kurtosis*	*Mean*	*T-test*
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				
	Omnibus	*Skewness*	*Kurtosis*	*Mean*	*T-test*
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 CAPTIONS

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.

Figure 2 Split-half reliability analyses. In each of these panels, 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 (see dataset key below). The split-half reliability r-value resulting from the analysis of each individual data set is indicated with a datapoint on each graph, and size of this datapoint is scaled to correspond to size of the data set.. The gray shaded areas are centered on the weighted mean split half reliability, and width of the shaded area is determined by the 95% confidence interval around the weighted mean. Reaction Time (RT) reliabilities are depicted in left column, and error rate (ER) reliabilities in the right column. A vertical gray line marks the point where r=0. 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.

Figure 4. A line graph depicting mean reaction times (RT) and error rates (ER) for each of the twelve trial types (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 1129 participants.

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 non-significant correlation. RT=Reaction Time, ER=Error Rate.

FIGURE 1

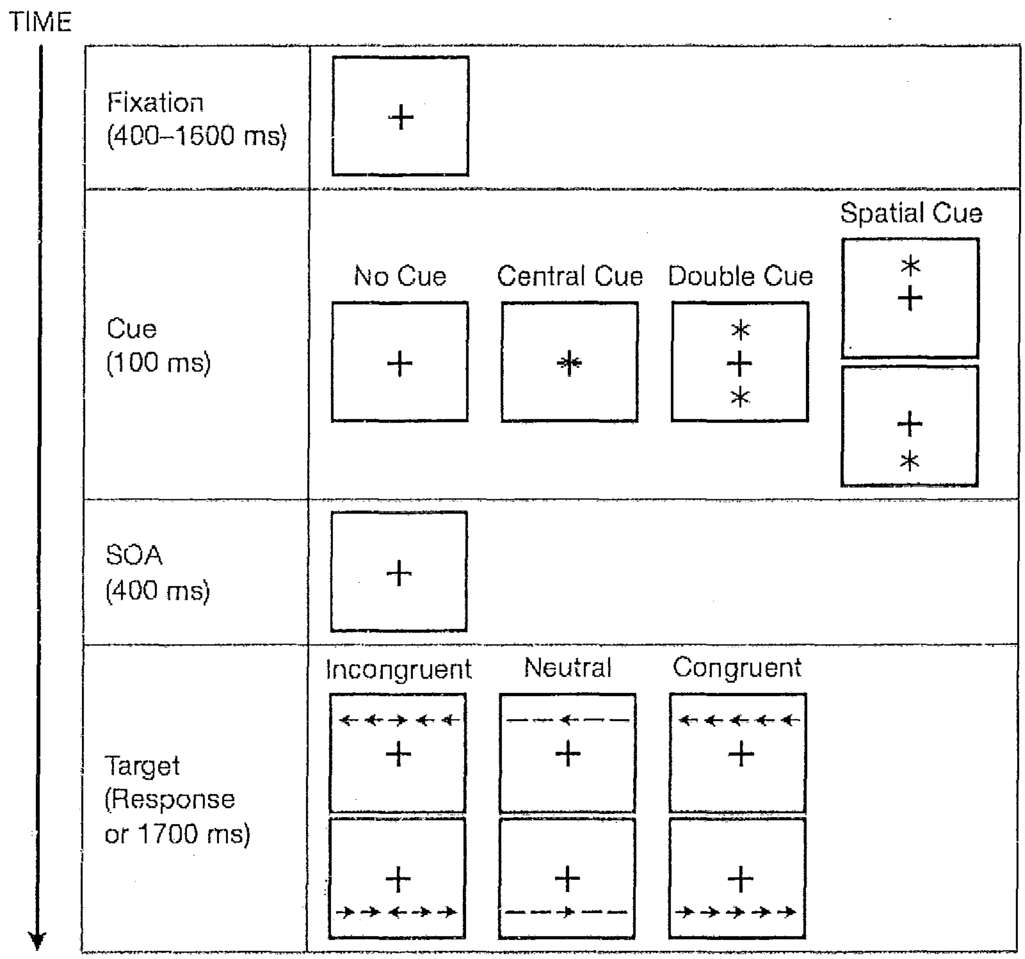

TIME
Fixation
(400–1600 ms)
Cue
(100 ms)
No Cue
Central Cue
Double Cue
Spatial Cue
SOA
(400 ms)
Target
(Response
or 1700 ms)
Incongruent
Neutral
Congruent

FIGURE 2

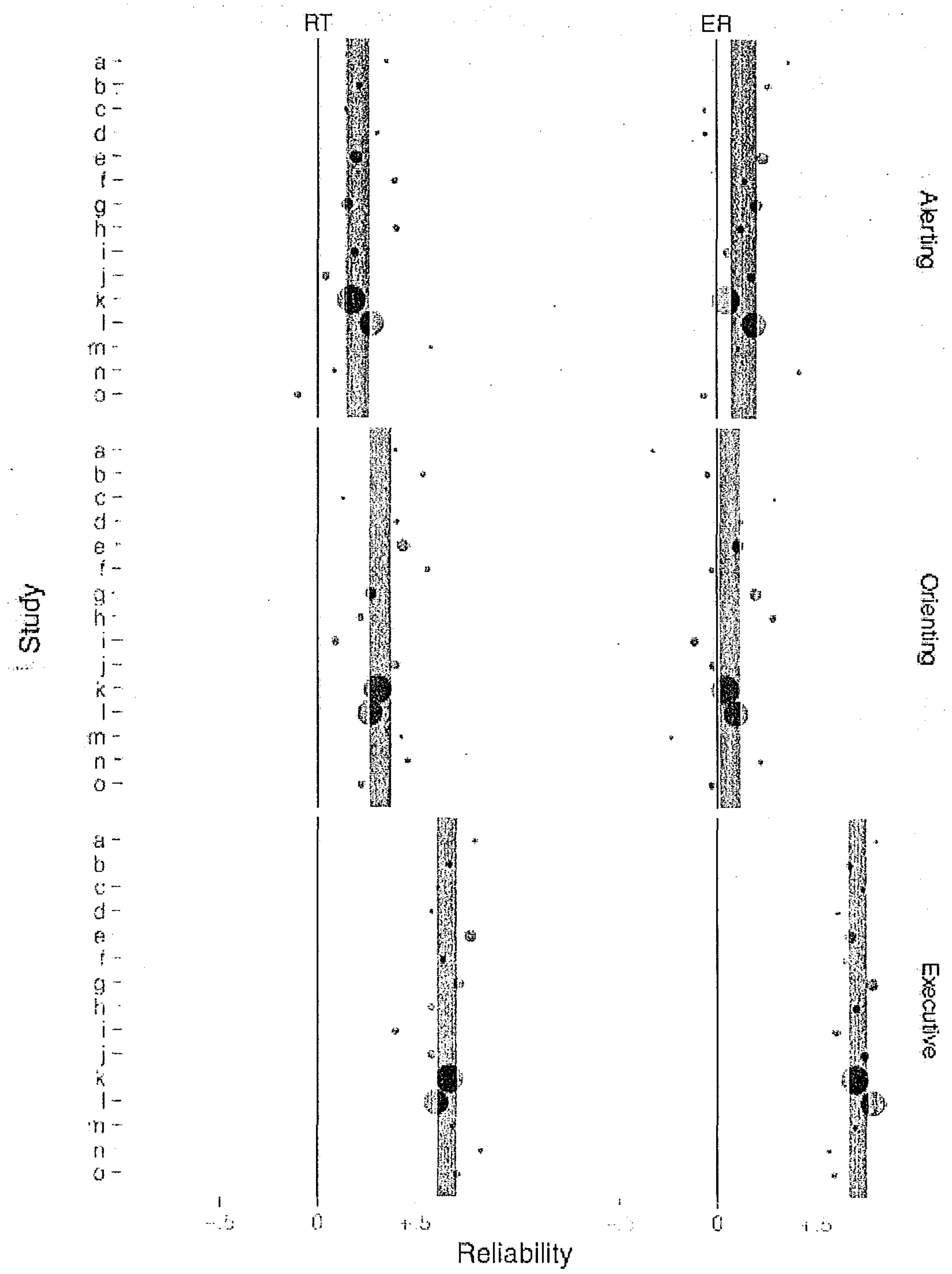
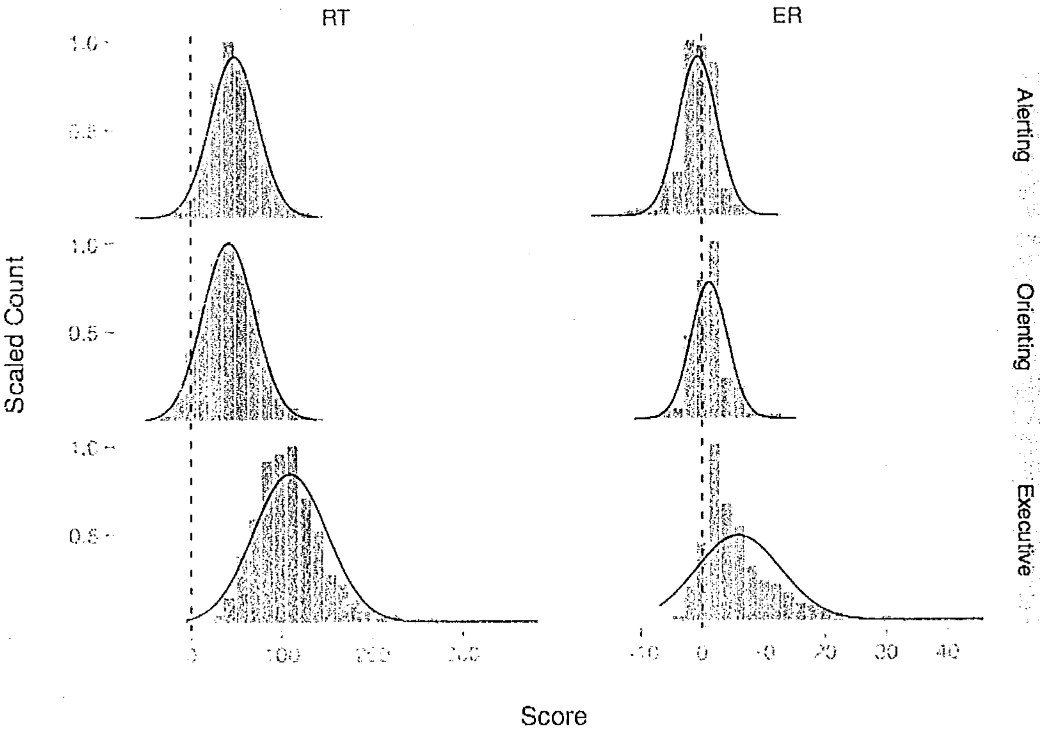
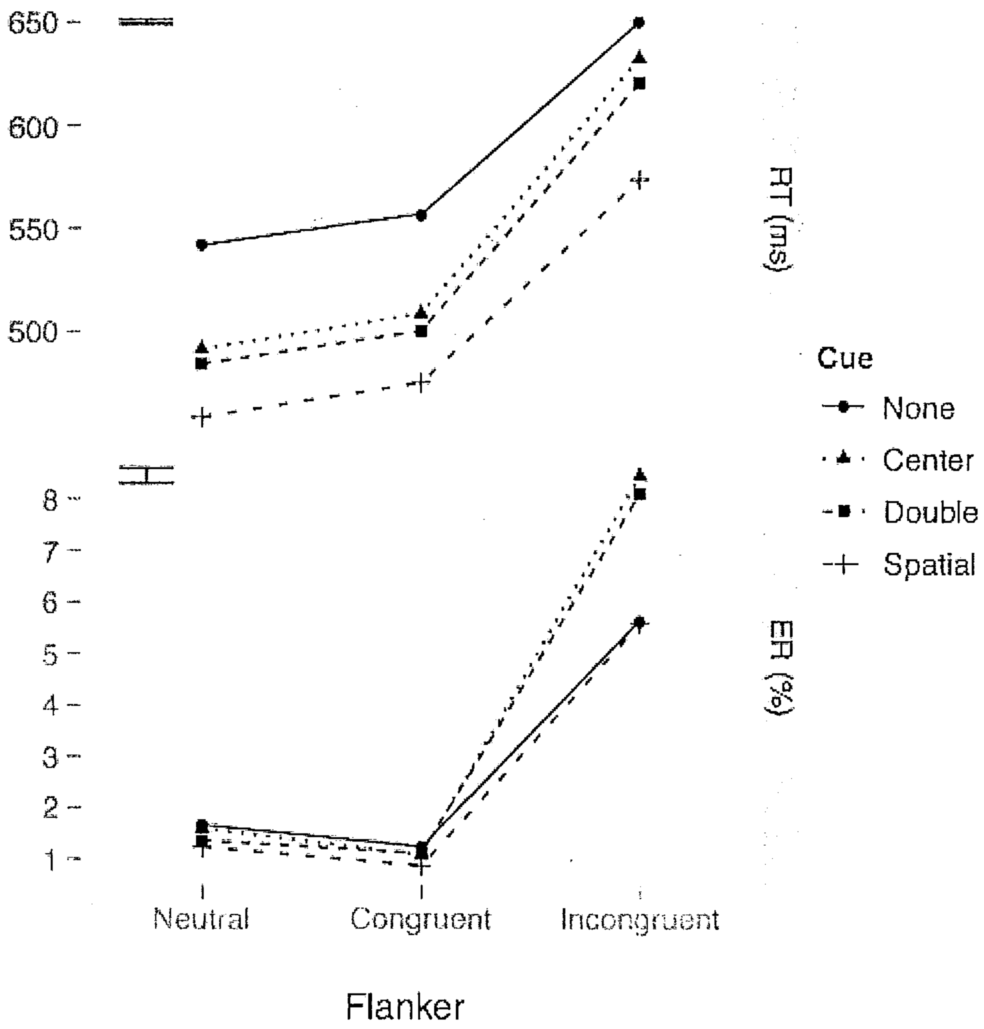

RT
ER
Alerting
Orienting
Executive
Study
a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
0
+.5
Reliability

FIGURE 3



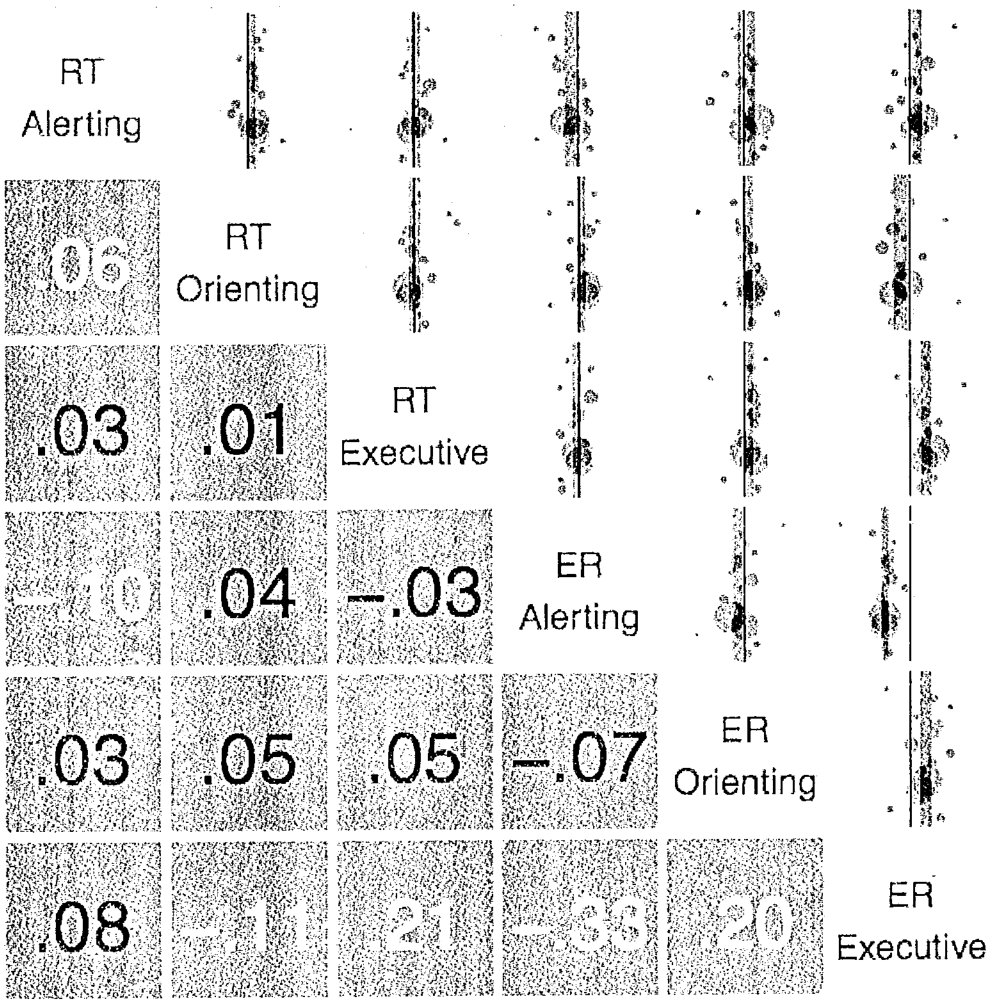
RT
ER
Alerting
Orienting
Executive
Scaled Count
1.0
0.5
1.0
0.5
1.0
0.5
0
100
0
10
20
30
40
Score

FIGURE 4



650
600
550
500
8
7
6
5
4
3
2
1
RT (ms)
ER (%)
Cue
None
Center
Double
Spatial
Neutral
Congruent
Incongruent
Flanker

FIGURE 5



RT
Alerting
.06
RT
Orienting
.03
.01
RT
Executive
−.10
.04
−.03
ER
Alerting
.03
.05
.05
−.07
ER
Orienting
.08
−.11
.21
−.33
.20
ER
Executive