

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)**ScienceDirect**Journal homepage: [www.elsevier.com/locate/cortex](http://www.elsevier.com/locate/cortex)**Research Report****Adaptive modes of attention: Evidence from attentional networks**

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**ABSTRACT**

Posner and Petersen (1990) suggested that the attention system is composed of three networks: alerting, orienting, and executive functioning or control. Drawing on this theory, the Attentional Networks Test (ANT) was designed to quantify the functionality of the three attention networks. The ANT is used extensively in psychology, neuroscience, and medicine. Later adjustments of the ANT have demonstrated that the three attention networks do not operate independently and can interact.

The current study examined whether such interactions are constant or result from task demands. In three experiments ( $N = 147$ ) we measured alerting, orienting, executive control and their interactions while manipulating task demands. The interactions between the three networks differed between experiments, with no interactions detected in the third experiment. We conclude that the interactions between executive functioning and alertness, and between executive functioning and orienting depend on spatial processes and are not an innate feature of attention. Our results suggest that the three attention networks can function independently, depending on task demands. Our findings offer experimental support for Posner and Petersen's theory (1990) and suggest a novel way to optimize attention measurements.

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## 1. Introduction

Our daily lives feature an ever-growing number of stimuli attracting our attention. A seminal cognitive taxonomy of attention suggests that our attention system consists of three attentional networks—alertness, orienting, and the executive function, also called executive control (Petersen & Posner, 2012; Posner & Petersen, 1990). Posner and Petersen's taxonomy has guided studies regarding the neural correlates of attention, its computational architecture, and research aspiring to understand attentional deficits and their developmental trajectories (Boen et al., 2021; Mogg et al., 2015; Petersen & Posner, 2012; Wang & Fan, 2007). However, it is debated whether the three attentional networks interact (Callejas et al., 2004; 2005; Fan et al., 2001, 2002, 2003; 2009; Weinbach & Henik, 2012a). Answering this question can reshape our understanding of attention and advance multiple research domains. We begin with reviewing selected findings pertaining to these attentional networks and the contrasting evidence regarding their interactions.

Alertness refers to the changing levels of our arousal or vigilance. Tonic alertness is our ability to regulate wakefulness in a top-down manner and in the absence of external aids (for a review see Petersen and Posner, 2012). Phasic alertness refers to momentary fluctuations in arousal levels often induced by an external stimulus (Sturm & Willmes, 2001). Alertness level depends on norepinephrine (NE) secretion from a brain-stem nucleus—locus coeruleus (Aston-Jones & Cohen, 2005; Aston-Jones & Waterhouse, 2016). The locus coeruleus increases NE secretion upon appearance of external cues (Witte & Marrocco, 1997). Functional imaging studies suggest that phasic alertness relies on right frontal and right parietal cortices.

Orienting refers to the ability to allocate attention in space to objects (Posner, 1980). Exogenous orienting is the reflexive shift of attention, resulting from an external trigger, activating bottom-up processes (Rafal & Henik, 1994; Rohenkohl et al., 2011). Exogenous orienting is mediated by mid-brain regions and occurs even when the external trigger is task-irrelevant (Dorris, Klein, Everling, & Munoz, 2002). Endogenous orienting is the voluntary spatial shift of attention guided by top-down processes (Chica et al., 2013). Endogenous orienting in humans is mediated by a fronto-parietal network (Chica et al., 2013). The orienting system is mediated by acetylcholine (Everitt & Robbins, 1997), suggesting a neurochemical dissociation between orienting and alerting.

The executive control network refers to a set of mechanisms supporting goal-directed behaviors (Petersen & Posner, 2012). Executive control is mediated by a unique fronto-parietal network including the anterior cingulate cortex, dorsolateral prefrontal cortex, right inferior frontal gyrus, and superior parietal cortex (Braver et al., 2009; Li et al., 2017; Rossi et al., 2007; Shenhav et al., 2013). Dopamine is a central neurotransmitter impacting executive control, but the neurochemical basis of the executive control network is beyond the scope of this paper (for an extensive review see Robbins & Arnsten, 2009).

Posner and Petersen (1990) posited that alerting, orienting and executive control may rely on partially distinct brain systems. The Attentional Networks Test (ANT) is a hallmark

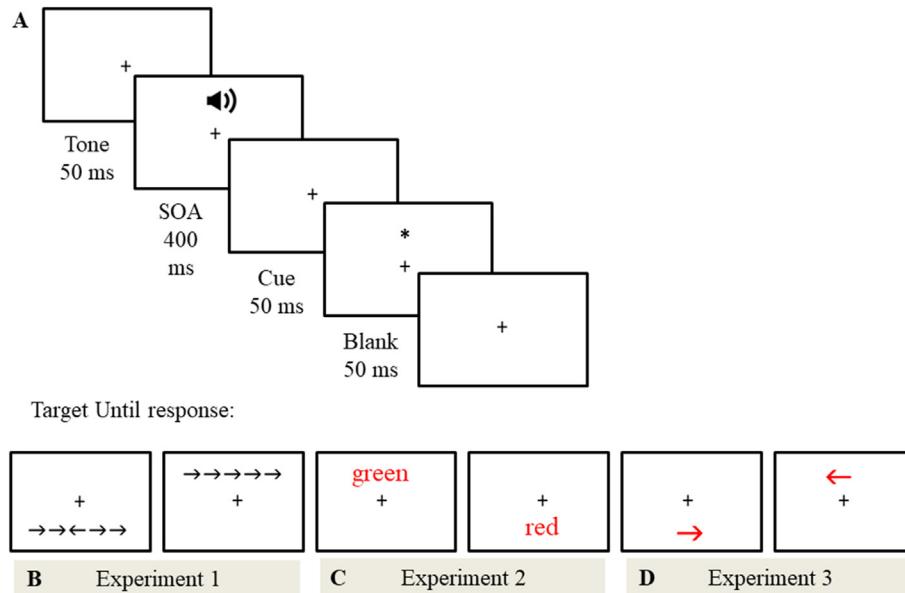
measure of these three attentional networks and their interactions (Fan et al., 2002). Fan and colleagues' theory is highly influential. For example, 240 studies with approximately 30,000 participants, used the ANT or its variants until 2019 (Arora et al., 2020). The ANT utilizes a spatial executive control task – the flanker task, while modulating the orienting and alerting systems with preceding cues. Specifically, participants identify the direction of a central arrow surrounded by several distracting arrows. The spatially distracting arrows can be either congruent or incongruent (see Fig. 1B) with the central arrow's direction. Phasic alerting and orienting levels are manipulated by different types of visual cues appearing prior to the arrows (Fan et al., 2002). Fan et al. (2002) found three main effects (i.e., alerting, orienting, and executive control networks) and a significant interaction between flanker congruency and cue type, indicative of partial independence of the three systems. However, the ANT may be limited in its ability to test the independence of the three attentional networks. The ANT uses a single visual cue for both the alerting and the orienting networks, thus confounding the two networks.

The attentional networks test-interactions (ANT-I; Callejas et al., 2004) is a variant of the ANT. The ANT-I estimates efficiency of the executive control network with the same spatial task as the ANT – the flanker task. However, the ANT-I manipulates orienting and alerting networks separately. The alerting network is manipulated by presenting a brief auditory tone prior to the onset of a flanker-trial in half of the trials. The orienting network is manipulated by presenting a visual spatial cue (i.e. an asterisk) prior to the onset of a flanker trial in a valid or an invalid location (Fig. 1A and B). The ANT-I gives rise to three main effects and three two-way interactions (Callejas et al., 2004, 2005). In contrast to Posner and Petersen's initial assertion, ANT-I results indicate that the three attentional networks are functionally dependent.

Certain evidence supports Posner and Petersen's original independence hypothesis. Weinbach and Henik suggested that the alerting and executive control networks are independent (Weinbach & Henik, 2012b, 2013). Specifically, the two networks interacted only when the conflict (i.e., activation of the executive attention system) entailed processing of spatial distractors. Weinbach and Henik (Weinbach & Henik, 2012b) suggested that alerting widens the focus of spatial attention and therefore may enhance processing of irrelevant distractors. Alerting cues may seem to affect executive control, while in fact they affect spatial processing.

We suggest that the ANT and the ANT-I may confound the orienting system with the executive control system, as they measure executive control with a spatial task – the flanker task. The orienting system is inherently spatial, whereas the executive control system's central role is to resolve conflicts, which may or may not be spatial. The alerting system affects the resolution of spatial conflicts but the underlying mechanism is debated (Fischer, Plessow, & Kiesel, 2012; Han & Proctor, 2023; Schneider, 2018, 2019; Weinbach & Henik, 2014). As such, the interactions between the three attentional networks might be a byproduct of the experimental design. Whether our attentional systems can function independently remains unknown.

The goal of the current study was to revisit the debate regarding the functional dependence of the three attentional



**Fig. 1 – Illustration of Experimental Tasks in Three Studies**

(A) Example of a single trial. (B) Example of an invalid (the cue appeared above fixation whereas the target stimulus appeared below fixation), incongruent trial and a valid congruent trial in Experiment 1. (C) Example of a valid (the cue appeared above fixation and the target stimulus appeared above fixation also), incongruent trial and an invalid congruent trial in Experiment 2. (D) Example of an invalid, incongruent trial, and a valid congruent trial in Experiment 3 (when red concurs to the left key).

networks. We test whether the attentional networks interact with three tasks assessing the efficiency of the executive control network. In Experiment 1, we test Callejas and colleagues' ANT-I (Callejas et al., 2004, 2005). In Experiment 2, we manipulate the executive control network using a non-spatial, semantic task. In Experiment 3, we manipulate the executive control network with a non-spatial, non-semantic task. We hypothesize that non-spatial tasks would eliminate the interactions between the attentional networks, demonstrating their functional independence.

## 2. Experiment 1

Experiment 1 aims to replicate the classical ANT-I results. Callejas et al. (2004, 2005) used an auditory cue to activate the alerting network, a visual spatial cue to manipulate the orienting network, and the flanker task to measure the executive control network system. They report three main effects of the attention networks: alerting, orienting and executive control, and three two-way interactions of the systems.

## 3. Method

### 3.1. Participants

Forty-seven participants (39 females, mean age [M] = 23.3, Standard Deviation [SD] = 2.14) completed the experiment for

course credit. All participants reported normal or corrected-to-normal vision. All participants gave informed consent prior to their inclusion in the study.

### 3.2. Apparatus

Data collection and stimuli presentation were controlled by a DELL OptiPlex 760 v Pro computer with an Intel core 2 duo processor E8400 3 GHz. Stimuli were presented on a DELL E198PF 19-in LCD monitor. E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA) was used for programming, presentation of stimuli, and timing operations. Responses were collected via a keyboard and the auditory alerting tone was delivered by over-the-ear headphones.

### 3.3. Stimuli

All visual stimuli were presented on a light gray background. The target consisted of a line of five horizontal arrows, which appeared either above or below the fixation point. In the congruent condition, all five arrows pointed in the same direction (left or right). In the incongruent condition, the flanking arrows pointed to the opposite direction of the middle arrow. In the neutral condition the middle arrow was flanked by double headed arrows (i.e., pointing to both sides). Alerting was induced by presenting a 50 ms, 2,000 Hz 'beep' sound via headphones in half of the trials. Orienting was manipulated by presenting an asterisk for 50 ms, above or below the fixation point. Stimuli are available at [osf.io/gkq3w/](https://osf.io/gkq3w/).

### 3.4. Procedure

Participants sat in front of a computer monitor and were requested to press 'left' or 'right' according to the direction of the middle arrow ('c' and 'm' on the keyboard, respectively). Each trial started with presenting a fixation cross for a duration between 400 ms and 1600 ms, followed by a 50 ms alerting signal (2000 Hz) in half of the trials. After a 400 ms stimulus onset asynchrony (SOA), an asterisk that served as an orienting cue was presented for 50 ms in two thirds of the trials, below or above the fixation point. The asterisk was not predictive of the target location, i.e. a cue appeared in two thirds of trials—in half of these trials the cue was valid and in the other half it was invalid. In the other third of trials there was no orienting cue. After a blank interval of 50 ms, the target and flanking arrows were presented below or above the fixation point for 3,000 ms or until the participant responded. Upon response, the fixation cross remained on screen for a varied interval depending on the total trial duration up to this point, so that every trial lasted 4,450 ms (Fig. 1A–B). Each session started with a practice block, in which participants were given feedback. After the practice block there were 2 blocks of 216 trials each (2[alert/no alert] X 3[valid/no cue/invalid] X 3 [congruent/neutral/incongruent] X 12 repetitions), amounting to 432 trials. Study procedures were in line with Callejas et al., 2004, 2005. Sample sizes, data exclusions, and inclusion/exclusion criteria were pre-determined based on the field's standards and were not pre-registered.

## 4. Results

### 4.1. Pre-processing

Mean accuracy was 97%. Due to the high accuracy rate, incorrect trials were removed and were not further analyzed. See Table S1 for a full breakdown of error rates. Reaction time (RT) z-scores were calculated for each subject in each condition. Trials with RTs larger than  $\pm 3$  standard deviations from the mean were removed, constituting 1.6% of correct trials (See Table S2 for a full breakdown of RTs).

### 4.2. Analysis

A three-way analysis of variance (ANOVA) was conducted with alerting (tone/no tone), orienting (valid cue/invalid cue), and executive control (congruent/incongruent) as independent, within-subject variables and RT as the dependent variable. As in previous studies (Callejas et al., 2004; Fan et al., 2002) we did not analyze the no cue and neutral condition for the interactions. The reason for this is that no-cue trials and neutral trials preclude assessment of the orienting and executive control, respectively. As expected, we found a main effect for alerting so that alerted trials were faster than non-alerted trials  $F(1,46) = 27.77, p < .001, \eta_p^2 = .38$ , 95% confidence interval [CI] = [.16, .55]. We also found a main effect for orienting  $F(1,46) = 183.15, p < .001, \eta_p^2 = .79$ , 95% CI = [.69, .86] so that valid

trials were faster than invalid trials. Finally, we found a main effect for executive control  $F(1,46) = 251.51, p < .001, \eta_p^2 = .84$ , 95% CI = [.76, .89] so that congruent trials were faster than incongruent trials. Panels A and B in Fig. 2 present the main effects and interactions in Experiment 1, respectively.

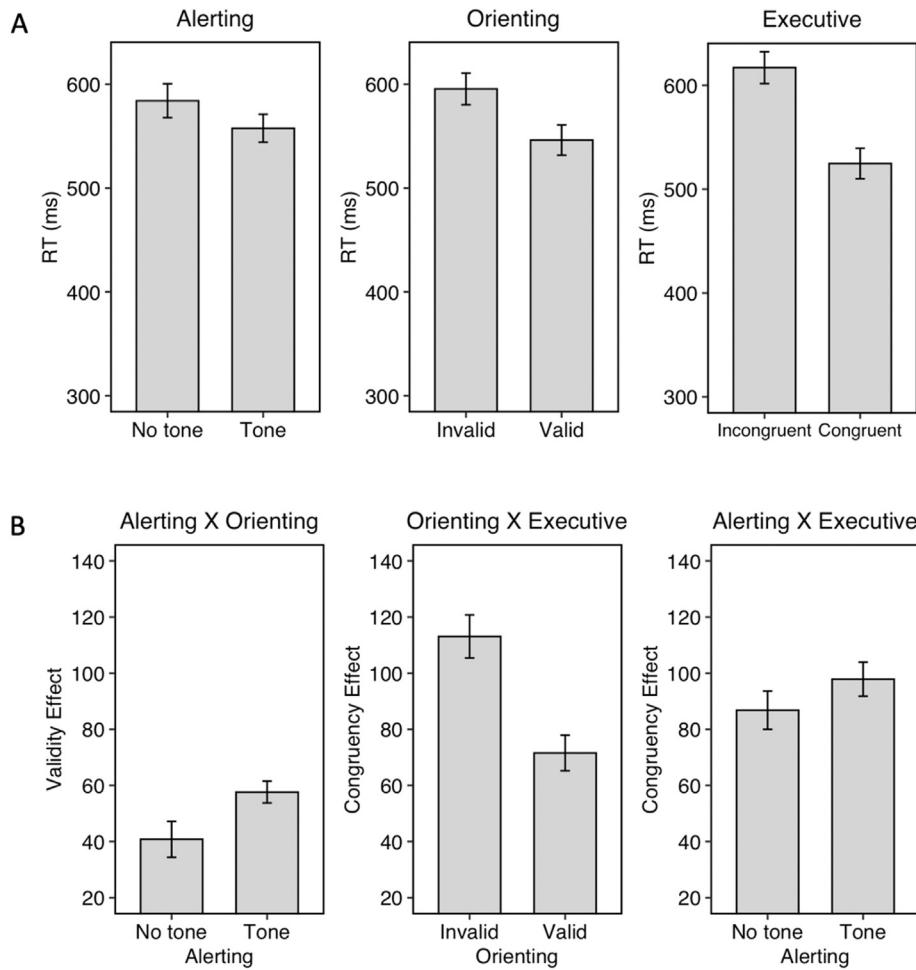
We also replicated previous studies regarding the interactions between the attentional networks (Callejas et al., 2004). There was a significant 2-way interaction between orienting and executive control,  $F(1,46) = 27.80, p < .001, \eta_p^2 = .37$ , 95% CI = [.17, 0.55], so that the congruency effect was larger on invalid trials compared with valid trials (Fig. 2B, middle plot). A significant 2-way interaction between alerting and orienting was evident,  $F(1,46) = 4.80, p = .034, \eta_p^2 = .094$ , 95% CI = [.00, .28], so that the validity effect was larger on tone trials compared with no-tone trials (Fig. 2B, left plot). Additionally, a 2-way interaction between alerting and executive control was evident,  $F(1,46) = 4.06, p = .05, \eta_p^2 = .08$ , 95% CI = [.00, .26], so that the congruency effect was larger on tone trials compared with no-tone trials (Fig. 2B, right plot).

Reliability of general RT and networks score across experiments. Reliability was examined using a modified split-half correlation (permutation approach). With a permutation approach, trials were randomly split into two halves 10,000 times. Note that in each permutation we ensured equal representation of trial types between splits. For instance, each split contained the same number of congruent, valid and alert trials (and likewise for the other trial types). Next, a correlation was computed for each split and reliability was the mean of the 10,000 correlations. Note that this modified split-half method was previously used to examine reliability of the ANT (Ishigami & Klein, 2011). We used this modified split-half correlation on general RT and the three network scores of each participant, separately. However, reported reliability scores (i.e., mean correlations) were computed across participants. In Experiment 1, reliability scores were .98, .65, .31 and .56 for general RT, executive scores, orienting scores, and alerting scores, respectively.

## 5. Discussion

This study aimed to establish a baseline for the task according to prior literature (Callejas et al., 2004). We succeeded in manipulating the three attentional networks as was evident by the main effects found for alerting, orienting, and executive control. In addition, we found the two-way interactions between alerting and orienting, orienting and executive control, and alerting and executive control. The validity effect was larger on alerted trials than non-alerted trials. The congruency effect was larger on invalid trials than valid trials and on alerted trials than non-alerted trials.

Callejas et al. interpreted these results as evidence of dependency between the attentional networks. However, the flanker task involves a spatial conflict – separating center from periphery (Callejas et al., 2004, 2005). A spatial



**Fig. 2 – Main Effects (Panel A) and Interactions (Panel B) in Experiment 1**

**Note.** Error bars represent standard errors.

component is an inherent part of the orienting system. The alerting system also affects spatial processing (Schneider, 2020), and modulates spatial preparatory processes related to orienting (Asanowicz et al., 2019; Asanowicz & Panek, 2020). It is possible that the interactions found in the ANT-I are due to the spatial component of the ANT-I and are not an inherent property of our cognitive architecture.

## 6. Experiment 2

The goal of this experiment is to test whether the interactions between the attentional networks are an inherent property of cognitive system or a result of the spatial nature of the flanker task used in the ANT-I. Accordingly, in this experiment we substituted the flanker task with another hallmark measure of the executive control system—the Stroop task. In the Stroop task participants are required to indicate the ink color of a color word. Stimuli are congruent (e.g., “RED” in red ink), incongruent (e.g., “RED” in green ink), or neutral (MacLeod, 1991). Resolving the conflict in the Stroop task requires inhibition of the irrelevant semantic information, and not

inhibiting spatial information as the relevant and irrelevant dimensions are presented in the same spatial location.

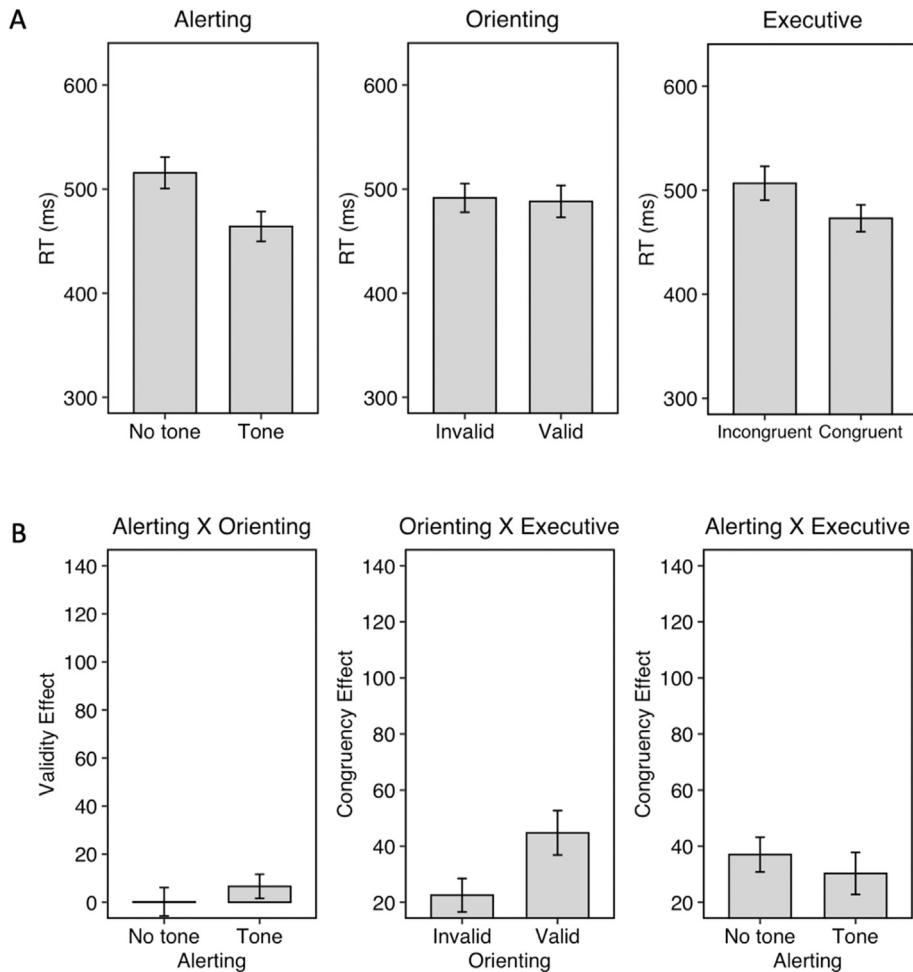
## 7. Method

### 7.1. Participants

Fifty participants (34 females, mean age = 23.3, SD = 1.43) completed the experiment for a small monetary incentive or course credit.

### 7.2. Stimuli

The target was a colored word. We used the words and colors: red, and green (the words were printed in Hebrew, and both consist of four letters). The stimuli were either congruent—a color word printed in the same color ink (i.e. the word RED printed in red); incongruent—a color word printed in a different colored ink (i.e. the word RED printed in green); or neutral—a string of the same letter (i.e., XXX) in either green or red ink (Fig. 1C). All other stimuli were identical to Experiment 1.



**Fig. 3 – Main Effects (Panel A) and Interactions (Panel B) in Experiment 2.**

**Note.** Error bars represent standard errors.

### 7.3. Procedure

The procedure was identical to Experiment 1 except that participants were instructed to press different buttons according to the ink color of the target word and ignore the meaning of the word.

## 8. Results

### 8.1. Pre-processing

Mean accuracy was 97%. Due to the high accuracy rate incorrect trials were removed and were not further analyzed. See Table S3 for a full breakdown of error rates. RT z-scores were calculated for each subject in each condition. Trials with RT larger than  $\pm 3$  standard deviations from the mean were removed, constituting 1.5% of the correct trials. See Table S4 for a full breakdown of RTs.

### 8.2. Analysis

Identical to Experiment 1.

Similar to Experiment 1, we found a main effect for alerting, so that alerted trials were faster than non-alerted trials  $F(1,49) = 71.83, p < .001, \eta_p^2 = .59, 95\% \text{ CI} = [.41, .71]$ , and a main effect for executive control, so that congruent trials were faster than incongruent trials,  $F(1,49) = 36.06, p < .001, \eta_p^2 = .42, 95\% \text{ CI} = [.22, .58]$  (Fig. 3A). We did not find a main effect for orienting ( $F < 1, \eta_p^2 = .01, 95\% \text{ CI} = [.00, .14]$ ).

The 2-way interaction between orienting and executive control was significant,  $F(1,49) = 6.96, p = 0.011, \eta_p^2 = 0.12, 95\% \text{ CI} = [0.01, 0.31]$ . However, the pattern of the interaction was different from the corresponding interaction in Experiment 1. Here, the congruency effect was larger on valid trials compared to invalid trials (Fig. 5). Given the null main effect of orienting, we tested the validity effect in each congruency condition. Responses to targets in valid trials were faster than

responses to targets in invalid trials in the congruent condition,  $t(48) = 3.6, p < 0.001$ . In the incongruent condition, this pattern was reversed – valid trials were slower than invalid trials but this difference was not statistically significant,  $t(48) = 1.56, p = 0.13$ . The opposite directions of the simple effects can explain the lack of a main effect of orienting. There was no orienting effect in the neutral Stroop condition ( $t(49) = -1.05, p = 0.29$ ). Neither of the other two-way interactions were significant ( $F < 1, \eta_p^2 = 0.02, 95\% \text{ CI} = [0.00, 0.14]$ ) (Fig. 3B). Reliability scores were .98, .61, .41 and .66 for general RT, executive scores, orienting scores and alerting scores, respectively.

## 9. Discussion

We set out to examine whether a non-spatial measure of the executive control system affects the interactions between the attentional networks. Conducting the ANT-I task while using the Stroop task instead of the flanker task revealed a different pattern of results compared to Experiment 1 and to previous literature (Callejas et al., 2004; 2005; Fan et al., 2002). Results of Experiment 2 dissociate the alerting network from executive control and orienting networks. Independence of the alerting and executive control networks replicates previous work with the Stroop task (Weinbach & Henik, 2012b). Increased alertness widens the attentional scope or enhances global processing (Schneider, 2018; Van Vleet et al., 2011; Weinbach & Henik, 2012b, but see Seibold, 2018), and thus affects processing of peripheral (flanker) distractors. The Stroop stimulus is an integrated stimulus (i.e., a word), and therefore changing the spatial allocation of attention across the word does not affect its processing (Schneider, 2019). Accordingly, there was no effect of alertness on congruency, in contrast to the results reported in Experiment 1. In addition, the interaction between alerting and orienting was not significant. Previous studies reported or reasoned about this null interaction or about the null interaction between alerting and selective attention by testing these two attentional networks at a time using different manipulations and frequentist statistics (Asanowicz et al., 2019; Asanowicz & Marzecová, 2017; Asanowicz & Panek, 2020; Dietze & Poth, 2024; Fernandez-Duque & Posner, 1997). The finding that alertness may not modulate orienting could indicate that activating these attentional networks affects the ability to identify colors independently and that the previous alerting–orienting interactions stemmed from their operationalizations.

Lastly, the interaction between orienting and executive control was significant but demonstrated a reverse pattern compared with its analogous interaction in the ANT-I with the flanker task (Experiment 1). In Experiment 2, valid trials were faster than invalid trials in the congruent condition but not in the incongruent condition. In the incongruent congruent condition, the validity effect was not statistically significant, and the descriptive results suggested a possible reverse effect – invalid trials were faster than valid trials. We suggest that in the congruent condition, valid spatial cues facilitated semantic processing of the color word, resulting in faster RTs.

Whereas, in the incongruent condition, attending to the periphery and away from the stimulus facilitated RTs. One possible explanation for these results is that the spatial orienting cue may interact with the automaticity level of semantic processing, but not with participants' ability to identify color. Humans' color perception is possible within and outside the fovea, allowing efficient color perception in the near periphery of our visual field (Hansen et al., 2009; Rosenholtz, 2016). Accordingly, incongruent-invalid trials are faster than incongruent-valid trials since both conditions allow color perception, but the semantic conflict is smaller in the invalid trials. Indirect support for this explanation can also be seen by the null effect of the spatial orienting cue in neutral Stroop trials, when there is no semantic conflict. This pattern of interaction also aligns with findings demonstrating flexible interactions between orienting and executive control interactions. For example, exogenous orienting reduces congruency in a spatial Stroop task (Funes et al., 2007) but not in a Simon task (Luo et al., 2011; Lupiáñez & Funes, 2005). In the ANT-I with the flanker task, the congruency effect is larger in invalid trials compared to valid trials. This is due to a poor separation of the spatial distractors from the target stimulus in visual periphery, especially when attention is oriented away from the stimulus (i.e., in the invalid condition). Moreover, the current pattern of the interaction between orienting and executive control networks (Fig. 3B, middle plot) eliminated the main effect for orienting. We tested our assertions regarding between-Experiment differences with direct statistical analysis in a separate section.

Experiment 2 demonstrates that some of the interactions between the three attentional networks stem from stimulus features and not from inherent cognitive architecture. We hypothesized that using a single stimulus which does not induce a semantic conflict would eliminate the interaction between orienting and executive control networks.

## 10. Experiment 3

In our third experiment we set out to test whether a conflict, which does not involve spatial distractors or semantic processing, affects the interaction between orienting and executive control networks. We tested this question by employing the experimental design of Experiments 1 and 2, while assessing the executive control network by a colored arrow. The task is identical to the Stroop task (Experiment 2) as participants identify the ink color of a single stimulus with no spatial distractors. Based on Experiment 1 and past ANT-I literature, it is possible that the spatial distractors in the flanker task drive the interactions between the attentional networks. Previous findings suggest that alertness and executive functioning do not interact when using a task with a single-colored arrow, suggesting their interaction depends on spatial attention. Using an integrated cue – a single arrow – prevented possible confounding effects alerting cues exert on executive functioning (Weinbach & Henik, 2012b, Experiment 3). It is unknown how a single-colored arrow affects interactions with the orienting network. The current task

warrants executive functioning to resolve a stimulus-response conflict between the color of the arrow and the location of its matching response key, which can be congruent or incongruent with the arrow's direction. This task differs from the Stroop task in that watching a single-colored arrow on its own does not induce conflict, whereas watching a color word printed in an incongruent color (e.g., "White") does induce conflict.

## 11. Method

### 11.1. Participants

Fifty participants (39 females, mean age = 23.1, SD = 1.34) completed the experiment for course credit.

### 11.2. Stimuli

The target was a single arrow pointing left or right. The arrow was colored green or red. The rest of the stimuli were identical to Experiment 1. The stimulus in the neutral condition was an arrow pointing in two directions, in line with previous experiments (Weinbach & Henik, 2012b).

### 11.3. Procedure

The procedure was identical to that of Experiments 1 and 2 except that participants were instructed to respond to the color of the target arrow and ignore its direction. Participants were asked to press the left key (the letter 'c' on the keyboard) if the arrow was red, and the right key (the letter 'm' on the keyboard) if the arrow was green (Fig. 1D). The color-response key coupling was counterbalanced between participants. This task requires cognitive control to resolve conflict on trials for which the arrow's color is incongruent with the color's response key. For example, a right pointing arrow colored in red, when red's matching response key is 'c'.

## 12. Results

### 12.1. Pre-processing

Mean accuracy was 97%. Due to the high accuracy rate incorrect trials were removed and were not further analyzed. See Table S5 for a full breakdown of error rates. RT z-scores were calculated for each subject in each condition. Trials with RT more extreme than  $\pm 3$  standard deviations were removed, constituting 1.6% of correct trials. See Table S6 for a full breakdown of RTs.

### 12.2. Analysis

We utilized the same analyses as in Experiments 1 and 2. All three main effects were significant; alerted trials were faster than non-alerted trials ( $F(1,49) = 59.42, p < 0.001, \eta_p^2 = 0.54, 95\% \text{ CI} = [0.36, 0.68]$ ), valid trials were faster than invalid trials ( $F(1,49) = 16.45, p < 0.001, \eta_p^2 = 0.25, 95\% \text{ CI} = [0.07, 0.44]$ ), and

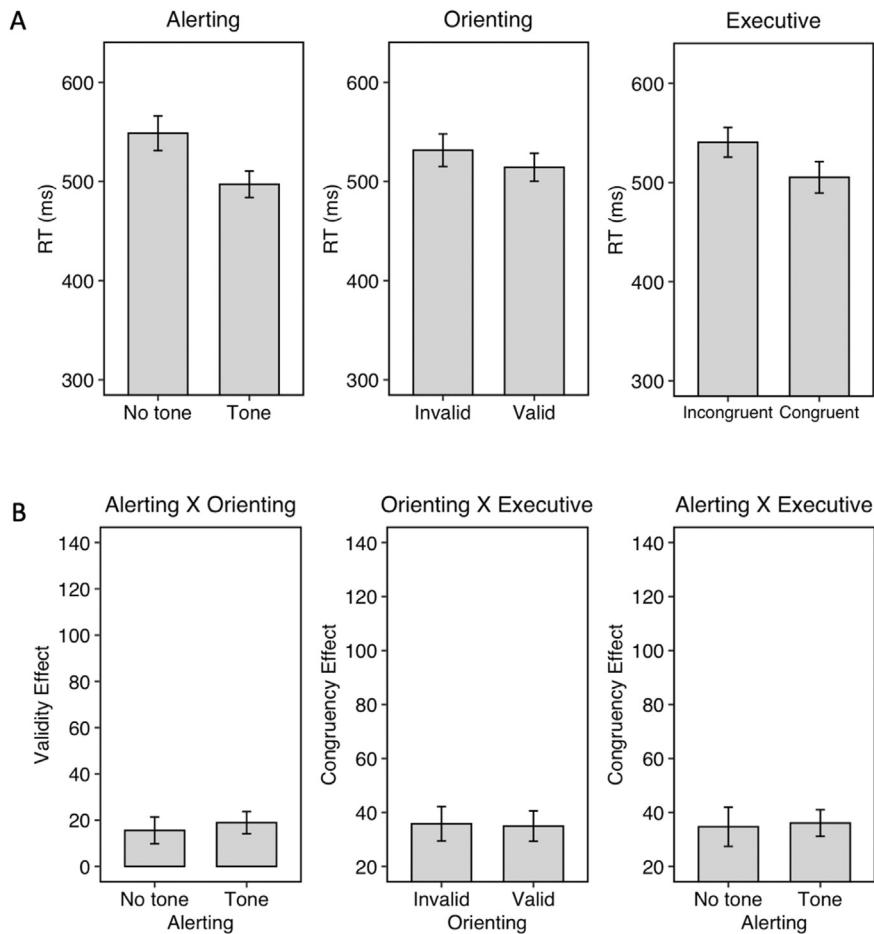
congruent trials were faster than incongruent trials (i.e., executive control effect) ( $F(1,49) = 47.35, p < 0.001, \eta_p^2 = 0.49, 95\% \text{ CI} = [0.29, 0.64]$ ) (Fig. 4A). None of the interactions were significant ( $F < 1, p > 0.5$  and  $\eta_p^2 < 0.01$  for all interaction terms). However, these analyses do not allow to infer that the attentional networks do not interact (Fig. 4B).

We tested our hypothesis regarding the lack of interactions between the attentional networks with a Bayesian repeated-measures ANOVA (JASP Team, 2023). This Bayesian procedure quantifies how likely are our results under the hypothesis of no interactions between attentional networks, compared to the hypothesis in which these interactions exist. We examined whether an ANOVA model with any of the interaction terms is more likely than a model including only our main effects (i.e., congruency, validity, and alertness). The latter served as our null model. We used the Bayes Factor ( $BF_{01}$ ) to quantify evidence in favor of our null model. Our Bayesian ANOVA revealed moderate to extreme evidence (all  $BF_{01} > 4$ ; Jeffreys, 1961) in favor of our null model over any model that includes interaction terms in addition to the main effects included in our null model (Table S7). To substantiate this conclusion, we performed analysis of effects. This analysis computes a more robust Bayes Factor for the inclusion/exclusion of terms in the model, across all possible models. This analysis revealed moderate evidence in favor of excluding all the possible two-way interaction terms (all  $BF_{\text{excl}} > 5.3$ ) and extreme evidence in favor of excluding the three-way interaction term ( $BF_{\text{excl}} = 110.2$ ) from our null model (Table S8).

In Experiment 3, none of the interactive factors were significant when mean RT was our dependent variable. This observation was further buttressed by the Bayesian ANOVA we conducted in addition to the null-hypothesis statistical testing ANOVA. Thus, in terms of Sternberg's additive factor logic (Sternberg, 1969), this additivity in RT in Experiment 3 may indicate independence of the three networks. Interestingly, if independence of the three networks is indeed the case here, we should see an additive pattern also for RT variance. Thus, to further bolster this interpretation we analyzed RT variance in Experiment 3. We conducted a three-way ANOVA, with alerting (tone/no tone), orienting (valid cue/invalid cue) and executive control (congruent/incongruent) as independent, within-subject variables and RT variance as the dependent variable. None of the model's terms reached statistical significance (all  $Fs < 1.22$ , all  $p$ -values  $>0.27$ ), except for the main effect of alerting ( $F(1,49) = 11.64, p < 0.001, \eta^2_{2p} = 0.19, 95\% \text{ CI} = [0.03, 0.38]$ ). Thus, these results are in line with Sternberg's additive factor logic and support the independence of the attentional networks we observed in Experiment 3. Reliability scores were .98, .54, .40 and .71 for general RT, executive scores, orienting scores and alerting scores, respectively.

## 13. Discussion

Results of the current experiment indicate the independence of the three attentional networks. While all three main effects were significant, none of the interactions were. This finding



**Fig. 4 – Main Effects (Panel A) and Interactions (Panel B) in Experiment 3**  
RT: reaction time. Note. Error bars represent standard errors.

corroborates the suggestions that the three attentional networks could be independent in certain tasks. In light of our results, we suggest that this task is termed ANT-dissociation (ANT-D). Our results suggest differences between attentional networks across Experiments 1–3. To test these differences directly, we ran the following analysis.

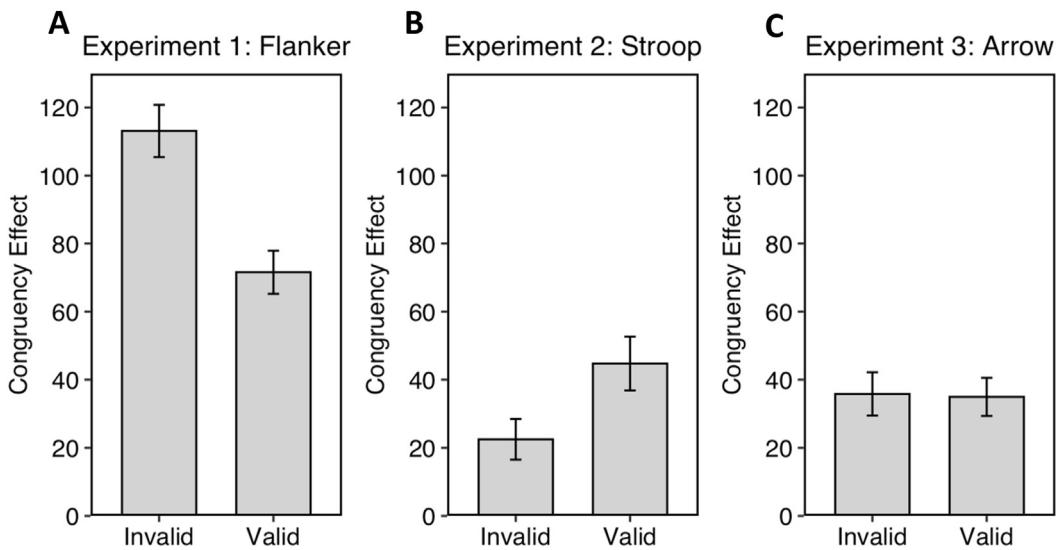
#### 14. Contrasting performance between experiments 1–3

We conducted a four-way analysis of variance (ANOVA), with Experiment (1/2/3) as an independent, between-subject variable, and alerting (tone/no tone), orienting (valid cue/invalid cue), and executive control (congruent/incongruent) as independent, within-subject variables. RT was the dependent variable.

All three within-subject main effects were significant; alerted trials were faster than non-alerted trials ( $F(1,144) = 154.90$ ,  $p < .001$ ,  $\eta_p^2 = .51$ , 95% CI = [.41, .61]), valid trials were faster than invalid trials ( $F(1,144) = 99.22$ ,  $p < .001$ ,  $\eta_p^2 = .40$ , 95% CI [.29, .51]), and congruent trials were faster than incongruent trials

( $F(1,144) = 284.72$ ,  $p < .001$ ,  $\eta_p^2 = .66$ , 95% CI = [.58, .73]). The main effect of Experiment was significant,  $F(2,144) = 7.47$ ,  $p < .001$ ,  $\eta_p^2 = .09$ , 95% CI = [.02, .19], suggesting that general RTs in Experiment 1 were longer than in Experiments 2 and 3.

All three within-subject variables interacted with Experiment. The two-way interaction between alerting and Experiment was significant,  $F(2,144) = 5.67$ ,  $p = .004$ ,  $\eta_p^2 = .07$ , 95% CI = [.01, .16], suggesting that the alerting effect differed between Experiments. The two-way interaction between orienting and Experiment was significant,  $F(2,144) = 33.16$ ,  $p < .001$ ,  $\eta_p^2 = .31$ , 95% CI = [.19, .42], suggesting that the validity effect differed between Experiments. The two-way interaction between executive control and Experiment was significant,  $F(2,144) = 35.87$ ,  $p < .001$ ,  $\eta_p^2 = .33$ , 95% CI = [.21, .44], suggesting that the congruency effect differed between Experiments. Additionally, the two-way interaction between orienting and alertness was significant,  $F(1,144) = 4.77$ ,  $p = .031$ ,  $\eta_p^2 = .03$ , 95% CI = [.00, .11], as the validity effect was larger in alerted trials compared with non-alerted trials. Finally, the three-way interaction Experiment, congruency, and validity was significant,  $F(2,144) = 18.02$ ,  $p < .001$ ,  $\eta_p^2 = .20$ , 95% CI = [.09, .31] (Fig. 5). Planned comparisons suggested that the congruency



**Fig. 5 – The Interaction Between Orienting and Executive Control in Experiments 1–3**

Note. Error bars represent standard errors.

effect was modulated by orienting differently in each experiment; in Experiment 1, the congruency effect was larger in invalid trials compared with valid trials,  $t(144) = 5.39, p < .001$ ,  $\eta_p^2 = .17$ , 95% CI = [.07, .28] (Fig. 5A); in Experiment 2, the pattern was reversed—congruency effect was larger in valid trials compared with invalid trials  $t(144) = -2.97, p = .003$ ,  $\eta_p^2 = .06$ , 95% CI = [.01, .15] (Fig. 5B); in Experiment 3, the congruency effect was not modulated by validity ( $p = .9$ ,  $\eta_p^2 = 0$ ; Fig. 5C). The remaining interaction terms did not reach statistical significance. Figs. S1–S2 depict the non-significant interactions between Experiment \* Orienting \* Alerting and Experiment \* Alerting \* Executive Control, respectively.

## 15. Discussion

Direct comparisons between the Experiments allowed a stronger inference regarding our hypotheses. The main effects of alertness, validity, and congruency suggest that we activated all three attentional networks in our three experiments. These main effects also differed as a function of Experiment. The Experiment also affected the interaction between orienting and executive control. These results support our hypothesis that attentional networks interact differently in different states. We elaborate on these differences in the general discussion below.

## 16. General discussion

The current research set out to test the independence of the attention networks – alerting, orienting, and executive control. To achieve this goal, we conducted three experiments testing the interactions between attentional networks with different executive control conflicts. In Experiment 1, we

conducted the classical ANT-I with the flanker task and replicated previous findings suggesting that our attentional networks interact with one another (Callejas et al., 2004, 2005). In Experiment 2, we manipulated executive control with a non-spatial, semantic conflict (i.e., the Stroop task), and demonstrated partial dependence of the networks. The only significant interaction was between the orienting and executive control, but its pattern was opposite to Experiment 1. In Experiment 3, we manipulated executive control with a colored arrow that is an integrated stimulus, like the Stroop word, but does not feature semantic information (ANT-D). Experiment 3's results suggest independent functioning of the three attentional networks. Our between-Experiment analyses support the notion of flexible functioning of these attentional networks.

Seminal studies discussing the dependence of attentional networks probed executive control with a variation of Erickson's flanker task (Eriksen & Eriksen, 1974). The flanker task requires responding to a central target while inhibiting information coming from peripheral distractors. Probing the executive control network with a non-spatial task may be instructive since the orienting system explicitly modifies spatial attention and alerting cues widen the attentional scope (Weinbach & Henik, 2013). We hypothesized that testing the interactions between the attentional networks with a non-spatial executive control task will clarify whether the interactions between the attentional networks are inherent to their function. We tested this hypothesis by measuring the efficiency of attentional networks with the Stroop task, where relevant and irrelevant dimensions are physically integrated. Using a non-spatial manipulation (i.e., the Stroop stimulus) changed the interactions between the networks, suggesting that the attentional networks operate independently in some cases. However, the orienting network may have impaired participants' ability to process the semantic meaning of Stroop

stimuli when presented in invalid locations, indirectly affecting the executive control network. Specifically, when participants' attention was directed to a different location than the target (i.e., invalid trials), it might have been more difficult to process the semantic meaning of the word, but color processing remained intact. Accordingly, we tested a non-spatial and non-semantic executive control task. In this setting we only found main effects of the networks. We then compared performance between Experiments and demonstrated that the Experiment factor, which differed only in the executive control task we used, interacted with all the attentional networks and with the two-way interactions involving the orienting system. Taken together, these findings suggest that the interactions of the attentional networks are flexible.

Our work highlights a new conceptual framework for human attention which we refer to as 'adaptive modes of attention'. Attention is a key ability in human functioning (Raz & Buhle, 2006). Attentional resources are limited but their effective deployment in different situations is imperative. Our findings imply that Posner and Petersen's attentional networks interact in a flexible and adaptive manner. The attentional networks are not inherently dependent. We demonstrate this point by highlighting space as one modifier of these interactions, but other properties such as stimulus valence or exogenous\endogenous cuing may also prove pertinent (Cohen et al., 2011; Dietze & Poth, 2024; Fernandez-Duque & Posner, 1997; Funes et al., 2007; Luo et al., 2011; Lupiáñez & Funes, 2005). Another factor which may impact the attentional networks' interactions is the contingency between the orienting cue and the target (Folk et al., 1992; Folk & Remington, 2008). Our orienting cue consisted of a rapid onset asterisk and it had greater impact on detecting arrow's direction (Experiment 1) compared with color discrimination tasks (Experiments 2 & 3). Using a color cue in color discrimination tasks may increase the orienting cue's effect on color discrimination tasks.

The study of attentional networks is central in different fields of psychology, cognitive neuroscience, and psychiatry. We believe our findings can advance understanding of these fields since most existing research of Posner and Petersen's attentional networks utilized variations of the flanker task or spatial conflicts (Arora et al., 2020; Ishigami et al., 2016; Klein et al., 2017; Luna et al., 2018; Roca et al., 2011). For a recent review see (de Souza Almeida et al., 2021).

Numerous studies used the ANT and its more recently developed variations to theorize about the neural correlates of attention and attentional networks (Fan et al., 2005; Hu et al., 2013; Liu et al., 2013; Santhana Gopalan et al., 2019; Westlye et al., 2011; Xiao et al., 2016; Xuan et al., 2016). Different brain regions have been associated with interactions between the attentional networks. The pulvinar nucleus (Xuan et al., 2016) and the middle frontal gyrus (Kellermann et al., 2011) have been associated with the interaction between orienting and executive control networks. Distinct regions of the frontoparietal network (e.g., dorsolateral prefrontal cortex, frontal eye fields, and the intraparietal sulcus) have been associated with the interaction between alerting and the executive

control networks (Xuan et al., 2016). Other studies reported overlapping neural activations in the thalamus and in the left fusiform gyrus for alerting and executive control networks (Fan et al., 2005). Our results are in line with previous findings which reported flexible interactions between two attentional networks (Cappucci et al., 2021; Dietze & Poth, 2024; Fernandez-Duque & Posner, 1997; Funes et al., 2007; Martínez-Pérez et al., 2020) and warrant considering whether these aforementioned brain regions are implicated in interactions between the attentional networks or in processing certain features that impact the attentional networks. We suggest that the known neural correlates of interactions between attentional networks may partially stem from different properties of the tasks employed in the imaging studies.

The possible dissociation of executive control from different attentional networks reveals the underpinnings of executive or cognitive control. Various executive control and selective attention studies discuss inhibition as one of the central pillars of such control. Indeed, discussing executive control may give the impression that inhibition is unitary and that different tasks examining inhibition should correlate. However, factor analytic studies suggest that the correlations among various tasks that examine inhibition are only moderate (Eisenberg et al., 2019; Miyake et al., 2000). The current work clarifies why this may happen. Between-task correlations may stem from confounding processes, such as spatial features of the task, which modify inhibition and how it modulates control.

Whether our attentional networks operate independently is highly relevant to our understanding of multiple psychopathologies and neurological disorders. Multiple studies with clinical populations utilized the ANT task for assessment and as a treatment marker; e.g., Schizophrenia (Gooding et al., 2006; Nestor et al., 2007; Wang et al., 2005), Autism (Keehn et al., 2013); affective disorders (Gruber et al., 2007; Murphy & Alexopoulos, 2006; for a recent meta-analysis see (Sinha, Arora, Srivastava, & Klein, 2022), anxiety disorders (Heeren et al., 2015), Alzheimer's disease (Firbank et al., 2016) and Parkinson's disease (Madhyastha et al., 2015). Results of these studies relate to the function of our attentional networks and reasoning about the nature of attention in these special populations. Our results indicate that the ANT and its variations may capture only parts of the complexity of human attention. When using our non-spatial and non-semantic conflict, we see that our attentional networks do not interact. It is possible that our attentional networks interact in certain clinical populations irrespective of spatial processes. We suggest that testing attentional networks with the task we use in Experiment 3 (ANT-D) would achieve a nuanced account of the attention system in clinical populations.

Future research should compare functional connectivity between the attentional networks using the experimental design that was presented in the current Experiment 3 (ANT-D). A natural next step is replicating our work and incorporating the ANT-I's design with additional spatial tasks, such as the spatial Stroop and Simon tasks (Funes et al., 2007; Luo et al., 2011; Lupiáñez & Funes, 2005; Schneider, 2020). These

studies will contribute to a fine-grained understanding of how spatial properties affect our attentional networks. Studies may also test whether the overlap between the orienting cue and the target modulate the interaction between orienting and executive control network (Folk et al., 1992; Folk & Remington, 2008) and possibly utilize different neural conditions to assess the orienting cues' impact on the reading task versus semantic processing. To conclude, the current work entailed three experiments that broaden our current theoretical framework of attention. Mainly, we suggest that human attentional networks can work in concert and independently under different conditions.

## Open practices section

The study in this article has earned Open Data, and Open Materials badges for transparent practices. The data, and materials are available at: [osf.io/gkq3w/](https://osf.io/gkq3w/).

## CRediT authorship contribution statement

**Omer Linkovski:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Naama Katzin:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Aviv Avitan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Noam Weinbach:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Avishai Henik:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

## Conflict of interest

None.

## Scientific transparency statement

**DATA:** All raw and processed data supporting this research are publicly available: <https://osf.io/gkq3w/>

**CODE:** All analysis code supporting this research is publicly available: <https://osf.io/gkq3w/>

**MATERIALS:** All study materials supporting this research are publicly available: <https://osf.io/gkq3w/>

**DESIGN:** This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

**PRE-REGISTRATION:** No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans

was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the online version of this article.

## Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cortex.2024.11.018>.

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