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Attentional Demands of Executive Function Tasks in Indoor and Outdoor Settings: Behavioral and Neuroelectrical Evidence

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Abstract

This study explored the influence of green environments on children's cognitive functions by using an experimental, within-subjects design to compare children's neural responses as they engaged in assessments of attention, inhibitory control, and spatial working memory in two different environments: a natural outdoor area and an indoor laboratory room. Ten children ages 6 to 11 years (M= 9.3; SD= 1.5) participated. Children performed significantly better on the spatial working memory task outdoors compared to indoors. There were no significant differences in attention or inhibitory control, but two markers of neurological activity were significantly larger indoors than outdoors, suggesting that more cognitive resources were needed to achieve the same level of performance indoors compared to outdoors.

Keywords: attention, spatial working memory, EEG, inhibitory control, cognitive resources, executive functions

There is growing evidence that exposure to natural environments can help restore directed attention in children (Kuo & Faber Taylor, 2004; Faber Taylor & Kuo, 2009; Wells, 2000). This research is primarily based on Attention Restoration Theory (ART; Kaplan, 1995) which posits that "directed attention," which is effortful and susceptible to fatigue, can recover when the less-effortful "fascination" attention system is deployed in the context of intrinsically interesting environmental stimuli. According to ART, natural environments elicit involuntary "fascination" attention because they are dynamic, moderately stimulating, and complex (Kaplan, 1995). Consistent with ART, Kuo and Faber Taylor (2004) reported that weekend leisure activities in "green" (i.e., more natural) outdoor settings reduced symptoms of attention deficit hyperactivity disorder (ADD/ADHD) for children 5 to 18 years of age, while activities in built or indoor settings did not. In addition, children ages 7 to 12 diagnosed with ADD or ADHD demonstrated improved attention after a 20-minute walk in a park compared to a 20-minute walk in an urban area (Faber Taylor & Kuo, 2009), and the effect size was comparable to the reported effect size of methylphenedate, a medication commonly prescribed for ADD/ADHD.

Children who are not diagnosed with attention deficits also benefit from exposure to natural environments. Low-income girls 7 to 12 years of age demonstrated better concentration, inhibitory control, and delay of gratification when their apartment windows had more natural views (Faber Taylor, Kuo, & Sullivan, 2002). Similarly, parents reported fewer symptoms of ADHD in their children after moving from homes with "less natural" surroundings to "more natural" surroundings (Wells, 2000). Additionally, Schutte, Torquati, and Beattie (2015) reported that 7- and 8-year-old children not diagnosed with ADHD performed better on an attention task after a nature walk than after an urban walk, and preschool children's performance on a spatial working memory task was more stable following a nature walk compared to an urban walk.

Researchers have also measured symptoms of hyperactivity and inattention among typically developing children (i.e., those not diagnosed with attention disorder) and have reported benefits of time spent in natural environments. For example, preschool children in Sweden with daily access to natural outdoor spaces demonstrated more focused attention than children who did not have access to natural areas, according to their teachers (Grahn, Martensson, Lindblad, Nilsson, & Ekman, 1997; Martensson et al., 2009). Frequency of park and playground use by children in the U.K. was associated with decreased hyperactivity (Flouri, Midouhas, & Joshi, 2014), and a study in Munich found that distance from a child's home to the nearest urban green space was inversely associated with symptoms of hyperactivity/inattention (Markevych et al., 2014). Amoly and colleagues (2014) reported that time spent in natural areas was inversely associated with ADHD symptoms.

Despite the growing body of evidence that children perform better on measures of attention in natural outdoor environments compared to built or indoor environments, little is known about the psychophysiological underpinnings of these improvements in attention. A longitudinal epidemiological study of primary school children in Spain found that associations between exposure to greenness at school and improvements in working memory and attentiveness were partially mediated by reductions in traffic-related air pollution measured in the school building (Dadvand et al., 2015), which has been associated with cognitive development (Sunyer et al. 2015). Including air pollution in the model accounted for 20-65 percent of the improvements in cognitive functions associated with greenness. The authors noted that 35-80 percent of the improvement in cognitive functioning may be explained by other factors.

The current study took a different approach; rather than examining environmental factors that mediate the effects of greenness on cognitive functioning, we explored the influence of green environments by comparing neural responses in children as they engaged in assessments of attention, inhibitory control, and spatial working memory in two different environments: a natural outdoor area with many mature trees and lush vegetation, and an indoor laboratory room containing only the equipment for data collection.

It is important to understand environmental influences on attention, because attention is a critical resource necessary for academic achievement (e.g., Molfese et al., 2010; Roderer, Krebs, Schmid, & Roebers, 2012), emotion regulation (e.g., Rueda, Posner, & Rothbart, 2004), and social competence (Acar, Rudasill, Molfese, & Torquati, 2015). Moreover, attention is a basic cognitive process that underlies other higher order executive functions such as working memory, inhibitory control, and cognitive flexibility (e.g., Rueda et al., 2004). Executive functions are highly stable over time and are associated with concurrent and future social, cognitive, and academic competence as well as mental health (Blair & Razza, 2007; Bull et al., 2011; Mazocco & Kover, 2007). Thus, it is important to understand the influence of environments on attention and other executive functions, which are central to adaptive behavior in everyday life as well as mental and physical health across the lifespan.

Attention involves “bottom-up” exogenous processes as well as “top-down” endogenous processes coordinated among three attentional networks that are temporally, functionally and structurally linked (Fan, McCandliss, Fosella, Flombaum, & Posner, 2005; Posner & Rothbart, 2007). The alerting network activates sensitivity to predominantly exogenous environmental stimuli, followed by activation of the orienting network involved in allocating attention to selected stimuli (selective attention). The executive attention network is involved in conflict resolution, decision-making, and coordination of behavioral responses. Because the executive attention network involves comparing internally represented ideas stored in working memory with ongoing perceived events, executive attention coordinates exogenous and endogenous processes.

In this study we investigated variation in attention, spatial working memory, and inhibitory control as a function of environment (outdoor natural environment vs. indoor environment). In conjunction with the executive function tasks, we also investigated variation in event-related brain potentials to examine neuropsychological underpinnings of observed variations in attention as a function of environment. *Event-related potentials* (ERPs) are electrical responses in the brain that occur in response to a stimulus, which can be recorded using electrodes placed on the surface of the scalp. This research builds on a study that examined variation in electroencephalogram (EEG)[1] activation while participants walked from an urban street with shops to a green space and then a busy commercial district (Aspinall, Marvros, Coyne, & Roe, 2013). The mobile EEG device used in the study, the Emotiv EPOC, uses a proprietary algorithm to identify different emotional states: excitement, frustration, engagement (attention), and meditation. Results indicated that when participants moved into the green space they experienced higher meditation and lower frustration and engagement, providing evidence that there are meaningful differences in neural responses when comparing built and natural contexts.

Because few previous studies have examined variability in neuropsychological functioning in the context of outdoor environments, we draw upon a model of neural development proposed by Molfese and colleagues (Molfese et al., 2008) to identify candidate neuroelectrical indicators of more efficient performance on attention and inhibitory control tasks as a function of environment. Considering the conceptualization of directed attention "costing less" in the context of a natural view or after exposure to a natural environment, we examine potential neuroelectrical processes underlying these differences. We first consider a developmental model of emerging neural networks to consider generally how "better" or "more efficient" processing might be observed on a neuroelectrical level, and then we review research on specific neural networks implicated in attention and inhibitory control. Together these two bodies of research informed our hypotheses for this study.

Although we do not propose that moving children outdoors necessarily elicits the equivalent of "more mature" neural functioning, identifying possible efficiency gains from natural environments in the context of early development has the potential to expand our understanding of the factors underlying the restorative benefits of natural environments. Molfese and colleagues (2008) proposed a developmental model in which neural networks become temporally (i.e., latency and/or order of neural activation processes), spatially (i.e., regions of the brain), and functionally (organized sequence of neural activation) more stable and efficient as learning and mastery occur. Molfese and colleagues (2008) presented ERP and functional magnetic resonance imaging (fMRI)[2] evidence indicating that neural activation is widely distributed in early stages of learning and becomes more localized as skills are mastered. The brain initially recruits multiple regions to perform a specific cognitive function, and with repeated experience the most useful areas are prioritized and others are eliminated from the network. Prioritization occurs implicitly through observation of statistical regularities in experience (Meltzoff, Kuhl, Movellan, & Sejnowski, 2009). Neural activation becomes more efficient as fewer areas of the brain are activated to accomplish the same task. This is consistent with processes of synaptogenesis, blooming, pruning, and myelination

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[1] Continuous recording of electrical activity of the brain using electrodes placed on the scalp

[2] Functional magnetic resonance imaging is a method for mapping brain activity that uses a magnetic field to detect blood flow and oxygenation.

involved in learning (Bauer, 2009). Overall, localized and temporally stable neural networks characterize more efficient processing.

Neurological Markers of Attention

The amplitude (i.e., peak height of an electrical impulse) and latency (i.e., delay) of ERPs can also indicate greater efficiency in processing. Molfese and colleagues (2006) observed greater-amplitude ERPs in poor readers compared to average readers during a reading task, which seems to indicate that poor readers had to exert greater effort in terms of attention and executive function to accomplish the same task. Lewis, Lamm, Segalowitz, Stieben, and Zelazo (2006) reported that frontal P300,[3] an electrical impulse that is considered an indicator of attention, decreased in amplitude and latency with age, consistent with the conceptualization of increasing cortical efficiency across development. However, according to Key, Dove, and Maguire (2005), larger amplitude and shorter latency are generally associated with better performance on attention measures; in this case, greater amplitude may indicate greater use of resources to achieve better performance.

Neuropsychological evidence supports the conceptualization of attention as a resource. In particular, the P300 is sensitive to the amount of attentional resources associated with task demands (Polich, 2007). The P300 is elicited by infrequent or novel stimuli and is associated with stimulus-driven alerting mechanisms and working memory-related processes. Larger frontal P300 amplitudes tend to be associated with lower-probability events (i.e., infrequent stimulus in an oddball task). One study provides evidence of greater P300 amplitude indoors compared to outdoors. Debener, Minow, Emkes, Gandras, and De Vos (2012) used a wireless Emotive EEG unit to compare P300 responses to an auditory oddball task (participants responded to an infrequent tone) in adult participants while walking outdoors and while seated indoors, and found significantly greater amplitude P300 indoors compared to outdoors, particularly for the infrequent tones, suggesting that the task required fewer cognitive resources outdoors compared to indoors.

A key early ERP component associated with levels of selective attention is the N100 electrical impulse[4] (Haider, Spong, & Lindsley, 1964), which has been shown to have a larger (i.e. more negative) amplitude at higher levels of attentional resource allocation (Van Voorhis & Hillyard, 1977; Luck et al., 1994). In visual paradigms (i.e. designs in which participants attend to visual stimuli), the N100 appears to indicate the allocation of attention to a spatial location. When a visual stimulus is presented at an attended location, the N100 amplitude is larger than when the stimulus is presented to an unattended location.

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[3] P300 is a positive-valenced electrical impulse that occurs approximately 300 milliseconds after presentation of a stimulus.

[4] N100 is a negative-valenced electrical impulse that occurs approximately 100 milliseconds after presentation of a stimulus.

The Current Study

Extant research has examined children’s performance on attention and executive function tasks after exposure to natural environments, or has correlated performance with the density of or distance to nearby nature, but no studies to date have investigated children’s performance on such tasks while in natural outdoor environments. Furthermore, it has not been investigated whether children's neuroelectrical activity in outdoor settings is different from that in indoor settings. We used an experimental, within-subjects design to compare task performance and neural responses of children as they completed attention and inhibitory control tasks in natural outdoor and indoor environments.

Consistent with the conceptualization of natural environments as restorative and attention as a limited resource that supports other executive functions (Baumeister et al. 2007; Kaplan & Berman, 2010), we hypothesized that children would perform better on assessments of attention, inhibitory control, and spatial working memory in an outdoor natural environment compared to an indoor environment (Hypothesis 1). Building on previous research documenting enhanced attention after nature exposure, evidence of greater ERP amplitude indoors compared to outdoors (Debener et al., 2012), and evidence of greater ERP amplitude in response to more demanding tasks (e.g., Luck et al., 1994; Van Voorhis & Hillyard, 1977), we hypothesized that neuroelectrical activity over regions of the brain associated with attention and working memory would reflect more optimal functioning while outdoors. Specifically, if a cognitive task requires fewer attentional resources outdoors (is less demanding), we would expect the amplitude of ERPs indexing attention to be smaller (Hypothesis 2). We therefore examined N100 and P300 as markers of attention.

Methods

Participants

Ten children (mean age = 9.3 years, *SD* = 1.5) participated in the study. Participants were recruited through local grade schools and flyers posted in the community. Participating children were predominantly Anglo-American (90 percent). Their mean family income was slightly less than $80,000 per year (*SD*=$51,000). A majority of the families lived in an urban or suburban home with a yard (60 percent), while 30 percent lived on acreage and 10 percent lived in an apartment. None of the children had been diagnosed with attention deficits (according to parent report). Parents provided written consent and children provided assent. Children participated in two sessions, one indoors and one outdoors.

Apparatus and Measurements

EEG Apparatus

Neuroelectric activity (EEG) was recorded while participants completed behavioral tasks. Participants wore a soft net with embedded electrodes that recorded electrical activity on the scalp.[i] Each participant sat in front of a computer monitor placed at eye-level 1 m from the child. A computer speaker was centered behind the child approximately 1 m from the top of the participant's head.

Behavioral Tasks

The participants completed four behavioral tasks that measured working memory, spatial working memory, attention, and inhibitory control. Three of the tasks were computerized. These took place on a 13.4 in x 10.75 in 34 cm x 27.3 cm) liquid crystal display (LCD) computer monitor with a resolution of 1024 x 768 pixels. Each of the tasks are described below.

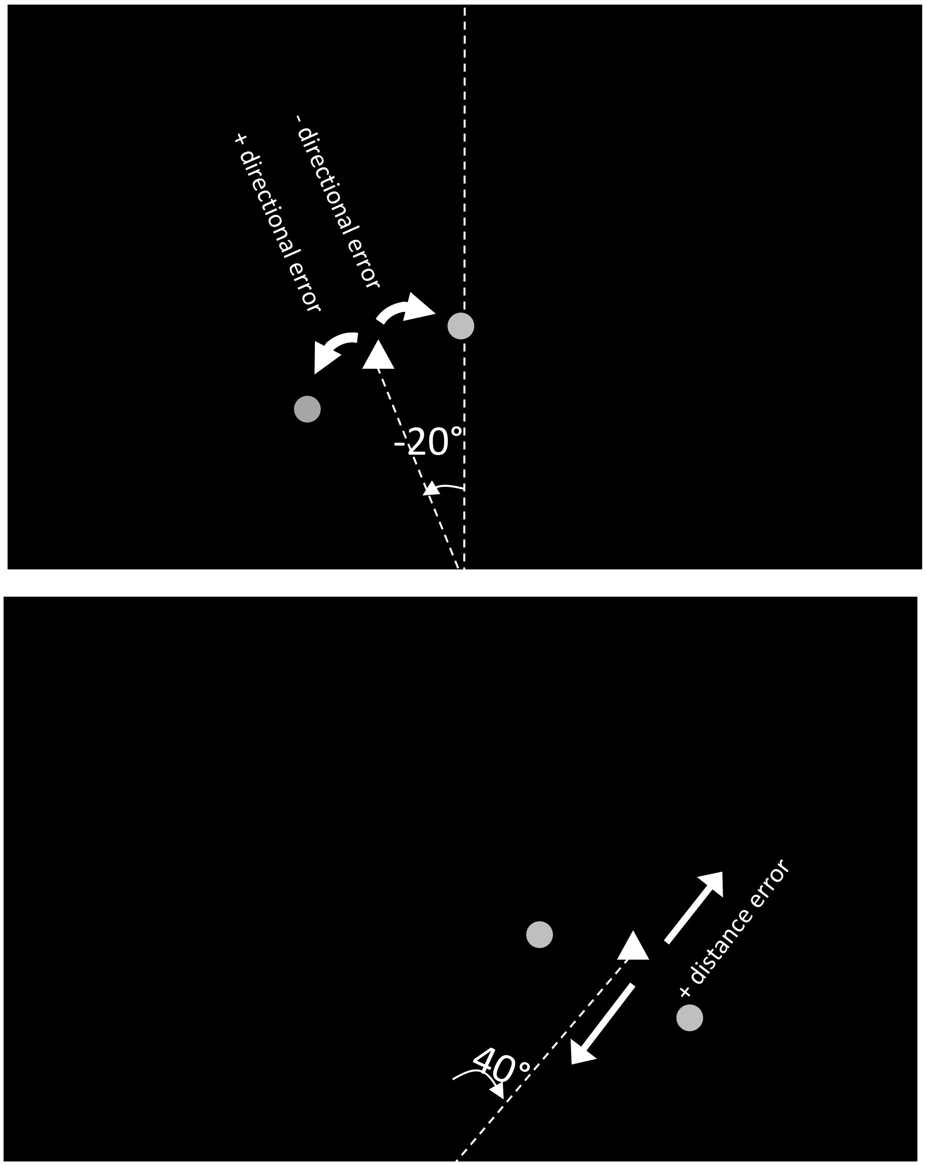
***Digit Span Backwards*.** Participants listened to the experimenter say a randomly generated sequence of numbers ranging from two to eight digits long (e.g., 1-2-3). Participants repeated the digits back to the experimenter in the reverse order (e.g., 3-2-1). A participant had to repeat two out of three sequences correctly at a given span to move on to the next span that was one digit longer. If the child was unable to complete two out of three sequences correctly at a given span, the task ended. The participants' score was the longest span at which they were able to complete two sequences.

Spatial Working Memory Task. The spatial working memory task (Schutte, Keiser, & Beattie, in press; Schutte & Spencer, 2002) measured children's ability to remember the location of a target (a 1 cm x 1 cm spaceship), while ignoring a distractor (i.e., a yellow dot, 1 cm in diameter) that appeared on the screen during the delay. The participants were told that they would be playing a game that would involve "finding a lost spaceship." The task started with a demonstration trial (exactly the same as the test trials) performed by the experimenter. The child completed two practice trials prior to the test trials. At the start of each trial the computer said, "Let's look for a spaceship." After this prompt, the target appeared for 2000 milliseconds (ms). Following a delay, the computer said "go, go, go" and the mouse cursor (arrow) appeared at the bottom center of the screen. The participant used the mouse to move the cursor to the remembered target location. After each trial, the target was re-illuminated for 4000 ms followed by verbal and visual feedback from the computer based on whether the participant found the target (i.e., was within 1.5 cm of the center of the target), was close to the target location (i.e., was within 4 cm of the center of the target), or did not find the target (see Schutte & Spencer, 2009).

Participants completed 28 test trials. On each trial they saw one of two possible target locations (i.e., there were 14 trials to each target). One target appeared 40° to the right of the midline of the monitor (40° target) and the other target appeared 20° to the left of midline (-20° target; see Figure 1). The length of delay between seeing the target and recalling its location varied: in two of the trials, the participants responded after no delay (i.e., the target remained illuminated until the child responded); in two trials, there was a delay of 100 ms; in 12 trials the delay was 5000 ms (five seconds); and in 12 trials the delay was 10,000 ms (10 seconds). During two-thirds of the five- and 10-second delays (eight trials per delay), a distractor dot appeared at a location 20° from the target location. For the -20° target, the distractor appeared at either -40° (four trials) or 0° (four trials)

(Figure 1a). For the 40° target the distractor appeared either at 60° (four trials) or 20° (four trials) (Figure 1b). The distractor appeared 2500 ms prior to the "go" signal and remained illuminated for 1000 ms.

Figure 1. Diagrams of the computer screen for the spatial working memory task showing the possible target locations (white triangles) for the (a) -20° target and the (b) 40° target. Gray dots mark the possible distractor locations for each target location.



Go/No-Go Task. Participants completed a go/no-go (GNG) task designed by Wiebe et al. (2011; Wiebe, Sheffield, & Espy, 2012). At the start of each trial either a fish or a shark appeared on the monitor. Participants pressed a button each time they saw a fish, but did not press the button for a shark. An experimenter instructed the participants that the fish would “get away” if they were too slow to press the button. The task began with a training procedure. First, children saw a screen containing pictures of the fish followed by four practice “go” trials. Next, they saw a screen with pictures of the sharks that was followed by four practice “no-go” trials. Following the training procedure, children completed 40 trials with 30 (75 percent) requiring “go” responses (i.e., fish) and 10 (25 percent) requiring “no-go” responses (i.e., sharks).

Continuous Performance Task. The procedure for the continuous performance task (CPT; Wiebe et al., 2011; Wiebe et al., 2012) was identical to the GNG task except that the number of “go” trials was 15 (24.6 percent) and the number of “no-go” trials was 46 (75.4 percent).

Procedure

Participants completed two sessions approximately one week apart. Consent forms were completed at the beginning of the first session. Two experimenters were present for each session. One experimenter monitored the participants and the other monitored the real-time EEG waveforms. The procedure for each session was the same except one occurred outdoors and one occurred indoors, and the order of sessions was counterbalanced (i.e., the same number of participants completed the outdoor session or indoor session first). The outdoor sessions were conducted in a naturalized play area of a university lab school, which features many mature trees, grass, gardens, and diverse vegetation. The area is bounded by a building on one side (to the participant’s back), a wall approximately 15 meters to the left of the participant, a fence approximately 15 meters in front of the participant, and fence approximately 30 meters to the right of the participant. The boundaries within the participants’ visual field were partially obstructed by vegetation (see Figure 2). The participant was seated beneath a canopy of pine trees and upon a wood mulch surface. The indoor session took place in a laboratory room that contained only the experimental equipment. There was a window in the room but the blinds were closed.

Figure 2. Outdoor experimental site

At the start of the session, participants completed the digit span backwards task. Next, the experimenters applied the EEG net. Before applying the net, an experimenter measured the participant's head and marked reference points to aid in the application. After the net had been applied, electrode impedances were then adjusted to be below 60 kOhms before the first task. After each task, impedances were checked and readjusted until they were below 60 kOhms.[5] After the net had been applied and impedances had been adjusted children completed the spatial working memory task, followed by the GNG task, CPT, and passive viewing of photos (not reported here).

Data Analysis

EEG Preprocessing

The electrical signal was segmented into epochs beginning 150 ms prior to the onset of stimulus (appearing on the screen for the go/no-go or CPT) and continuing for 1000 ms post-stimulus onset. In the CPT task, one participant did not meet the criterion of having at least eight artifact-free trials in all categories while all participants met this criterion in the GNG task. The average number of clean trials used to compute each of the averages was 14.43 (SD=1.50) for CPT go, 43.44 (SD=5.23) for CPT no-go, 29.63 (SD = 0.88) for GNG go and 9.63 (SD = 0.72) for the GNG no-go trial types, respectively.

All event-related potentials (ERP) data were examined to determine the quality of each segment (i.e., signal-to-noise ratios, bad channels, eyeblink or muscular

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[5] Electrode impedances are an indicator of how well the electrical signal is conducted from the scalp through the electrode.

artifacts) and only segments meeting good quality criteria were retained for analysis.[ii]

Analyses of Behavioral Data

Spatial Working Memory Task. For the spatial working memory task, we analyzed constant directional and distance errors. Directional errors away from the midline symmetry axis of the monitor were coded as positive errors and directional errors toward midline were coded as negative (see Figure 1). Distance errors that were between the bottom center of the monitor and the target location were coded as negative (responses "undershot" the target), and distance errors that were between the target location and the top of the monitor were coded as positive (responses "overshot" the target; see Figure 1).

On a few trials participants accidently clicked the mouse early. To control for this, E-prime recorded up to two mouse clicks and the response closest to the target location was included in the analyses. Also, on a few trials participants did not see the target. To control for this, trials with directional errors greater than 35° were not included in the analyses. Three trials had errors greater than 35° (0.6 percent of trials). Spatial working memory data from the second session for one participant did not get recorded so that participant's data were not included in the analyses.

To test the hypothesis that spatial working memory performance would be better outdoors than indoors, constant directional and distance errors on individual trials were analyzed in a mixed linear model using Proc Mixed in SAS. All analyses used a compound symmetry covariance structure in which all variances and covariances were assumed to be equal. Initial analyses revealed no significant effects of gender, so gender was not included in the final models. Only trials that required memory, that is the five-second and 10-second delay trials, were used in the analyses. The main effects of, as well as the interactions between, the variables environment (indoors, outdoors), delay (five second, 10 second), target location (-20°, 40°), and distractor (no distractor, inner distractor [20° toward center of screen], outer distractor [20° toward outer edge screen]) were examined. Here, we only report the main effects of or interactions with environment, because that is the variable of interest. Effect sizes for these analyses were computed using pseudo-R^2 statistics (Singer & Willett, 2003) that reflect the change in the relevant variance components after including environment as a variable in the model.

Go/No-Go and CPT. Accuracy on the GNG task and the CPT was high, suggesting a ceiling effect in terms of accuracy. On the GNG task participants missed an average of 1.5 out of 30 go trials and 1.0 out of 10 no-go trials. Accuracy on the CPT was also high. On average participants missed 0.44 out of 15 go trials and .32 out of 46 no-go trials. There were no significant differences in accuracy between trial types (all *p*'s > .30). Therefore, we only analyzed reaction times for the GNG and CPT tasks. One participant did not complete the CPT due to equipment problems.

To examine the hypotheses that environment influenced children's performance on the GNG task, CPT, and digit span backwards, we conducted an ANOVA for each measure with gender (male, female) as a between-participants variable and environment (indoors, outdoors) as a within-participants variable. The dependent variable for the GNG task and CPT was mean reaction time on correct go trials. The dependent variable for Digit Span Backward was longest correct span.

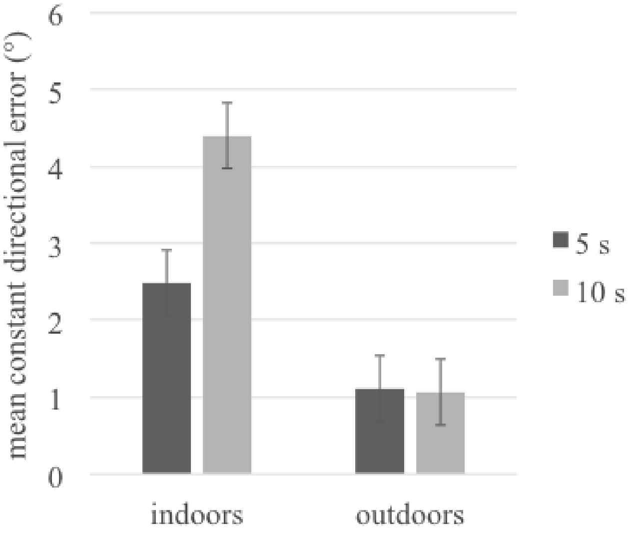
Results

Results of Behavioral Data Analyses

Spatial Working Memory

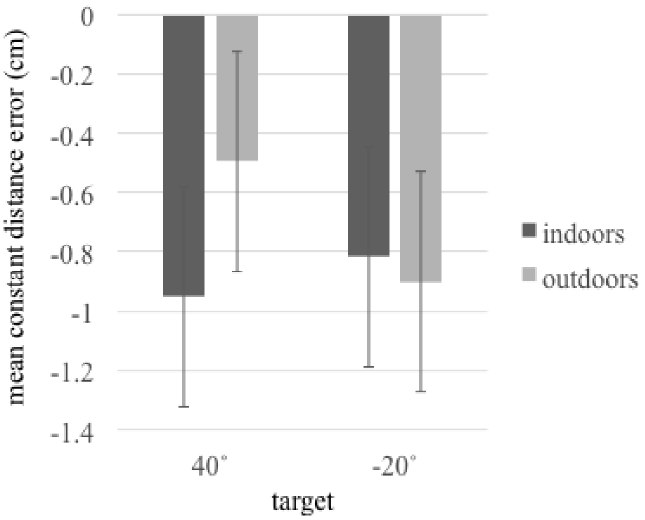
For these analyses, we used a Restricted Maximum Likelihood (REML) approach to estimation in reporting model parameters and to assess the significance of random effects and we calculated degrees of freedom using the between-within method. In the first analysis, constant directional error was the dependent variable. There was a significant main effect of environment, $F(1, 8) = 32.55$, $p < .001$and a significant Delay x Environment interaction, $F(1,8) = 5.66$, $p = .045$. Adding environment to the model for directional error accounted for an additional 2.1 percent of the residual variance. As can be seen in Figure 3, all memory responses were biased away from the midline of the monitor, but, at both five- and 10-second delays, children's responses were less biased outdoors than indoors. In fact, outdoors constant directional error did not increase from five to 10 seconds and was near zero.

Figure 3. Mean constant directional error in degrees indoors and outdoors for five-second delay (dark gray bars) and 10-second delay (light gray bars) delays. Error bars are standard error.



The independent variables in the second analysis were the same as the first, but the dependent variable was constant distance error. As with the directional errors, we only report significant effects of environment. There was a significant Target x Environment interaction, *F*(1, 8) = 6.00, *p* = .040. Adding environment to the model for distance error accounted for an additional 7.8 percent of the residual variance. Responses to the 40° target, but not the -20° target, were less biased outdoors than indoors (Figure 4).

Figure 4. Mean constant distance error in cm for the 20° and 40° target indoors (dark gray bars) and outdoors (light gray bars) delays. Error bars are standard error.



Go/No-Go and Continuous Performance Task

Mean reaction time on the correct go trials did not differ significantly by environment for the GNG task, *t*(9) = -.658, *p* = .58, Cohen's *d* = .22 (indoors: *M* = 523 ms, *SE* = 19 ms; outdoors: *M* = 512 ms, *SE* = 21 ms), or the CPT, *t*(8) = 1.14, *p* = .29, Cohen's *d* = .52 (indoors: *M* = 518 ms, *SE* = 11 ms; outdoors: *M* = 532 ms, *SE* = 20 ms). Thus, there was no difference in performance across environments on either the go/no-go or continuous performance tasks.

Digit Span Backwards

Participants correctly remembered three to four digits on average. Length of span did not vary by environment (*t*(9) = 1.81, *p* = .104, Cohen's *d* = 0.58 (indoors: M = 3.6, SE = .27; outdoors: M = 3.2, SE = .25).

ERP Analysis

To assess the possibility of a noise confound (i.e., electrical signals not related to neurological activity) wherein the outdoor response signals could potentially have more noise (i.e., be less reliable) than indoor ones, the noise in each ERP average was estimated by inverting the polarity of every other trial that contributed to that average. Inverted and un-inverted trials were then re-averaged so that consistent ERP signals cancelled out, leaving just a noise estimate (Schimmel, 1967). Paired t-test comparisons between indoor and outdoor environments showed no significant difference in noise levels between the two in both the GNG, *t* (7) = .74, *p* = 0.49, and CPT sessions, *t* (9) = -1.194, *p* = 0.26.

The ERP components were quantified using temporal-spatial Principal Components Analysis (PCA) using the ERP PCA Toolkit version 2.43 (Dien, 2010a). First, temporal PCA with a Promax rotation (Dien, 2010b) was performed followed by a spatial Independent Components Analysis[6] with an Infomax rotation. This procedure decomposed both the temporal and spatial variance in the ERP signals, allowing for the specific components of interest to be isolated. In the CPT session, 12 temporal and five spatial factors were selected based on parallel analyses. In the GNG session, which had higher noise levels than the CPT session (again estimated using the Schimmel (1967) procedure, *t[*34] = 2.63, *p* = 0.01), a 99 percent variance-accounted-for criterion was used to extract 35 temporal factors (the majority representing noise components) and five spatial factors based on parallel analyses.

Based on past ERP work in this area (Debener et al., 2012; Lewis et al., 2006; Polich, 2007) two ERP components were selected for quantitative analysis based on their topography and temporal time course. The first was the N100, a posterior component spanning 136-220 ms and 120-160 ms in the GNG and CPT sessions, respectively. The second was the P300, a posterior component spanning 564-800 ms and 472-752 ms in the GNG and CPT sessions, respectively. No other components with non-artifactual topographies and sources within the typically observed time windows of the N100 and P300 were observed. The average waveform at Cz (center top of scalp) for the indoor and outdoor environments, along with the factor topographies at their peak time point for the GNG and CPT sessions are shown in Figures 5 and 6, respectively.

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[6] The ICA is a variant of PCA more suited for the separation of spatial sources (Dien, 2010b).

Figure 5. ERP components extracted for go/no-go task. Solid line represents no-go trials and dotted line represents go trails.

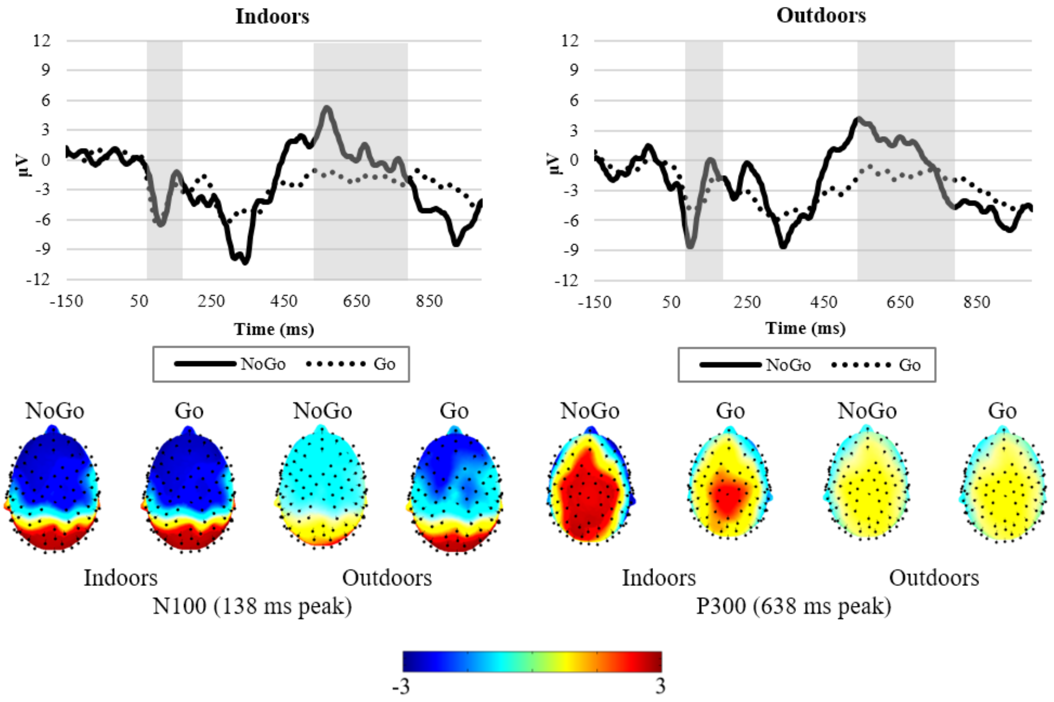
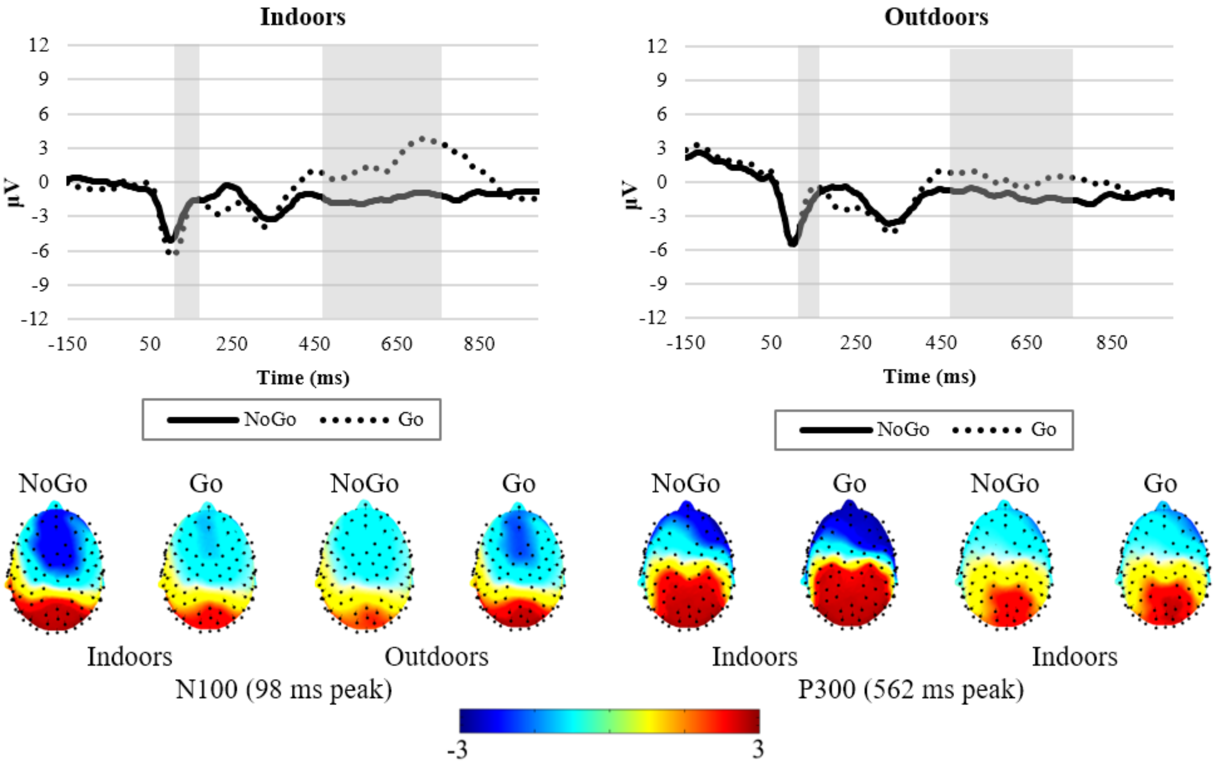


Figure 6. ERP components extracted for continuous performance task. Solid line represents no-go trials and dotted line represents go trials.



Comparison of N100 Temporal-Spatial Factors by Environment and Trial Type

The N100 factor scores from the GNG and CPT sessions were analyzed separately using a 2 (Environment: Indoor vs Outdoor) * 2 (Trial type: go vs. no-go) repeated measures ANOVA with the effect degrees of freedom being approximated using the Welch-Satterthwaite approximation method (a more robust approach to error estimation that does not assume equal variances across trial types).

On the GNG task, there was a significant main effect of environment, *F* (1,12.6) = 6.82, *p* = 0.02, with the overall N100 factor voltage being more negative (larger) indoors versus outdoors. This effect was significant between no-go responses, *t* (13.3) = 2.58, *p* = 0.02, and marginally significant between go responses, *t* (11.2) = 2.07, *p* = 0.06. The main effect of trial type (go, no-go) and the interaction between trial type and environment were not significant.

On the CPT, while the main effect of environment and trial type were not significant, *p* = 0.78 and *p* = 0.59 respectively, there was a significant interaction between the two, *F* (1,8.37) = 8.46, *p* = 0.03. Follow-up t-tests showed that while there was not a significant N100 difference between go responses across indoor and outdoor environments (*p* = 0.72), there was a significant N100 difference between indoor no-go and outdoor no-go responses, *t* (10.4) = 2.16, *p* = 0.05, with indoor N100 no-go responses being more negative.

Comparison of P300 Temporal-Spatial Factors by Environment and Trial Type

The P300 factor scores from the GNG and CPT sessions were analyzed separately using a 2 (Environment: Indoor vs Outdoor) * 2 (Trial Type: go vs. no-go) repeated measures ANOVA with the effect degrees of freedom being approximated using the Welch-Satterthwaite approximation method.

In the GNG session, there was a significant main effect of environment, *F* (1,11.4) = 4.39, *p* = 0.05, with the overall P300 factor voltage being more positive indoors versus outdoors. This effect was conditionalized by a significant interaction between environment and trial type, *F* (1,12.1) = 5.30, *p* = 0.04, in which the difference between environments was only present for no-go responses, *t* (13.9) = 2.68, *p* = 0.02, and absent for go responses (*p* = 0.30). Furthermore, the effect of trial type was only significant indoors, *t* (14.7) = 2.32, *p* = 0.04, with no-go responses being more positive than go responses. The effect of trial type outdoors was not significant (*p* = 0.98).

In the CPT session, there was a significant main effect of environment, *F* (1,9.7) = 5.54, *p* = 0.04, with the overall P300 factor voltage being more positive indoors versus outdoors. This effect was significant across no-go responses, *t* (10.6) = 2.49, *p* = 0.03, and marginally significant across go responses, *t* (8.71) = 1.88, *p* = 0.09.

Discussion

This study compared children's performance on executive function tasks while indoors and outdoors. There were no significant differences in children's performance on go/no-go or continuous performance tasks as a function of environment (indoor vs. outdoor). Because this is the first study to compare children's performance on cognitive tasks while in natural versus indoor environments, we cannot make direct comparisons to previous research. However, Schutte and colleagues (2015) reported that children performed better on a CPT after a nature walk compared to an urban walk, although there was no significant difference in performance on a go/no-go task as a function of walk type. In the present study children did, however, perform better on a spatial working memory task while outdoors compared to indoors. Children's responses were less biased outdoors in terms of both constant directional error and constant distance error. These findings are consistent with Schutte and colleagues (2015), who reported that preschool children's responses on a spatial working memory task were more stable (i.e., less biased) after a nature walk compared to an urban walk.

This study also compared neuroelectrical activity (i.e., ERP) while children engaged in the executive function tasks in order to better understand potential mechanisms whereby natural environments may be restorative. Results indicated that for the go/no-go task, the amplitude of the N100 was significantly greater indoors compared to outdoors, particularly for no-go responses. In addition, the N100 was greater for the no-go trials compared to the go trials indoors. For the CPT, the N100 was significantly greater for no-go responses indoors compared to no-go responses outdoors. The no-go stimulus is infrequent for the go/no-go task (25 percent) and frequent for the CPT (75 percent), therefore the amplitude of the N100 was greater indoors compared to outdoors regardless of the stimulus frequency.

Similar results were obtained for the P300. On the go/no-go task, a significant main effect of environment indicated greater amplitude indoors compared to outdoors for the no-go trials. However, the difference in trial type (go vs. no-go) was only significant indoors. This is interesting because the no-go response requires greater neural resources to inhibit the response, and, as a result, the P300 amplitude is typically larger than the go response. However, in this study it appears that this difference only occurred indoors and there was no difference in resources necessary to successfully complete either response outdoors. This suggests that processes involved in the P300 when an inhibitory response is required are more efficient outdoors compared to indoors. Our results are consistent with those of Debener and colleagues (2012), who reported a larger P300 in an auditory oddball task, particularly for the infrequent tones, when participants were seated indoors compared to walking outdoors.

Considering the results of behavioral performance (i.e., task performance) and electrophysiological data together, children performed equally well on the go/no-go and CPT tasks indoors and outdoors, but smaller amplitude ERPs were observed outdoors compared to indoors, especially for the no-go trials. Building on previous research inferring that larger amplitude indicates greater resource allocation (e.g., Haider et al., 1964; Key et al., 2005; Luck et. al, 1994: Van Voorhis & Hillyard, 1977), our findings indicate that children engage fewer neuroelectrical resources outdoors compared to indoors to achieve the same level of performance.

Implications for Education and Intervention

This study provides evidence that some cognitive processes may take less effort outdoors compared to indoors, thus adding to the evidence that children and adults perform better on cognitive tasks after experiencing a natural versus urban or indoor setting (e.g., Amoly et al., 2014; Aspinall et al., 2013; Debener et al., 2012; Faber Taylor & Kuo, 2009; Kuo & Faber Taylor, 2004), indicating that natural environments can be restorative with respect to executive functions. These findings suggest that spending time in natural spaces can be beneficial for executive functions, and that applications of this knowledge such as ensuring adequate recess time, and with sufficient natural surroundings (e.g., vegetation) is important for children to restore cognitive processing resources during the school day. Such opportunities for restoration may be especially important for children who experience challenges with attention.

Limitations, Future Directions, and Contributions

This study is the first to compare neural responses indoors and outdoors in a group of children. The results of this study suggest that children must use greater attentional resources while indoors than outdoors in nature in order to perform at the same level behaviorally on tasks requiring attention and inhibitory control. While these results are encouraging, there are some limitations that need to be considered. Due to the challenges inherent in collecting high-density EEG data from the target population in an outdoor environment and the exploratory nature of this study, the overall sample size is somewhat smaller than is standard. Despite these limitations, our results demonstrate the potential for further investigation.

Although replication is needed, this study is important for several reasons. First, it is the first study to examine neural responses in children while engaged in executive function tasks indoors and outdoors. Critically, the study determined that two components involved in attention, the N100 and P300, differed indoors and outdoors. Second, although other studies have collected auditory ERPs outdoors (e.g., Debener et al., 2012) this study is the first to collect visual ERP data outdoors. Despite the potential for greater noise in the ERP signal outdoors due to being a less controlled environment with more potential visual and auditory distractions, the level of noise in the signal did not differ between environments. This finding opens up the possibility for more research in this area using ERPs outdoors.

Endnotes

i. A 128-electrode high-density AgCl electrode Hydrocel Geodesic Sensor Net was connected to a NetAmps 300 amplifier (Electrical Geodesics Inc.) using Netstation version 4.4.2 running on a Mac computer. Recordings were collected using a vertex sensor (Cz), later re-referenced to an average reference. Electrode impedances were kept below 60 kΩ, appropriate for the high impedance system used. The incoming data were analogue filtered from 0.1-100 Hz and digitized at 250 Hz. Tasks were administered using E-Prime version 2, running on a Dell PC. The PC was connected to the Mac via a combination of an Ethernet (CAT-5) cable and a PCI-ribbon-cable interface.

ii. Segments were digitally filtered in EEGlab (Delorme & Makeig, 2004) using a 0.3–30 Hz zero-phase shift FIR bandpass filter. The data were then re-referenced using ERP PCA Toolkit (Dien, 2010a) to an average reference and baseline corrected. EEGlab's Automatic Artifact Removal (AAR) toolbox (Gomez-Herrero et al., 2006) was then used to remove ocular and electromyographic artifacts. Bad channels were then identified and interpolated using ERP PCA Toolkit (Dien, 2010a). Bad channels were then identified across the entire session via their poor overall correlation (<0.40) between neighboring channels, and within each segment via either unusually high differences between the average voltage of an electrode and that of their neighbors (>30µv) or as extreme voltage differences within the electrode (>100µv min to max). A channel was also marked as bad for the entire session if more than 20 percent of its segments were classified as bad. All identified bad channels were replaced using whole head spline interpolation. After the bad channels were identified and interpolated, trials with more than 10 percent interpolated channels were removed from the analysis set.

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