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# Attentional Functions and Dysfunctions in ADHD

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Attention is considered to be one of the key elements in human cognition. As its name implies, attentional functions are known to be impaired in individuals with Attention Deficit/Hyperactive Disorder (ADHD). However, various studies have investigated different types of attentional deficits among patients with ADHD. The purpose of this review is to take a comprehensive look at evidence on different types of attentional dysfunctions in ADHD. Three different domains of attention are of interest in this review: response inhibition, attentional control, and attentional orienting systems. A number of studies demonstrate that response inhibition and attentional control are major attentional deficits in ADHD. Disengagement and attentional reorienting systems also seem to be impaired. In this review, behavior, neuroimaging, and electrophysiological findings are discussed to understand fundamental attentional deficits in ADHD. Future direction for studies aiming to elucidate and treat attentional deficits in ADHD is also discussed.

*Key words : ADHD, Response Inhibition, Attentional Control, Orienting and Disengagement*

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What is the term *attention* in psychological literatures? Generally speaking, attention is a cognitive process of selectively concentrating on one aspect in the environment while ignoring others, and is considered as a key element in human cognition. Attentional deficits, broadly defined, have been reported in many psychological disorders, such as Attention Deficit/ Hyperactive Disorder (ADHD), schizophrenia, bipolar disorder, and autism spectrum disorder. Among those disorders, ADHD has been extensively studied. However, attention is not a unitary system. In fact, it involves various distinct functions, such as selection, inhibition, and orientation. Although it is important to know each of the attentional deficits in patients with ADHD independently, convergent knowledge on impaired or intact attentional functions in a certain disorder can be useful to treat each impairments more effectively.

Thus far, three major domains of attentional processes have been widely studied on ADHD: selection and inhibitory mechanisms, attentional control, and attentional orienting and reorienting systems. Selection and inhibitory mechanisms refer to the ability to choose certain targets while ignoring others (Treisman & Riley, 1969). This mechanism can be involved in both stimulus and response levels. Attentional control includes functions of attentional planning and conflict resolution. It also controls the amount of resources to be allocated to complete a task at hand. Lastly, attentional orienting and reorienting systems are related to a spatial property of attention processes. This mechanism consists of alerting, orienting, attentional disengaging and reorienting (Posner, 1980; Posner & Petersen, 1990). Despite the fact that these three mechanisms of attention have been extensively studied, to my knowledge, there is no comprehensive review on functions and dysfunctions in attentional mechanism in children with ADHD encompassing all of the three attentional components. Although the three domains are not mutually exclusive, a comprehensive review on deficits in each of the attentional domains will be able to provide us with useful knowledge to treat patients with ADHD more effectively.

The present review will thus take a comprehensive look at evidence on how each type of attentional component is affected in people with ADHD. By reviewing different attentional functions and dysfunctions in ADHD, the current review provides knowledge and insights on behavioral and neural mechanisms underlying the attentional deficits in ADHD, which in turn can lead therapeutic intervention to treat ADHD.

## Attention deficit/hyperactive disorder (ADHD)

Attention deficit/hyperactive disorder (ADHD) is a neuro-developmental condition characterized by "a persistent pattern of inattention and/or hyperactivity-impulsivity that is more frequent and severe than is typically observed in individuals at a comparable level of development" (APA, 1994). It is distinguished by excessive and situationally inappropriate motor activity (Halperin et al., 1992; Kinsbourne, 1977), limited inhibitory control of responses (Barkley, 1997; Chelune, Ferguson, Koon, & Dickey, 1986; Nigg, 2001), and impaired ability to focus, sustain, and switch attention (Cepeda, Cepeda, & Kramer, 2000; Epstein et al., 1997; Levine, Busch, & Aufseeser, 1982; Seidel & Joschko, 1990). Considered as the most common diagnosis for children seen in psychiatric clinics, ADHD is estimated to affect approximately 6.7 % of children (between the ages 4 - 17 years) in the United States (CDC, 2003). Likewise, the prevalence rate of ADHD has been estimated to be 6.5 % in school-age children in South Korea (Yang, Cheong, & Hong, 2006). As its name implies, individuals with ADHD especially suffer from attentional deficits. However, attention contains multiple components, such as selection, inhibition, orientation, and executive control. For example, children with ADHD generally reveal high impulsivity. Impulsivity is a multidimensional concept that incorporates failure of response inhibition, rapid processing of information, and inability to delay gratification (Barratt, 1994). Researchers suggested that high level of impulsivity tends to be explained by inhibitory system, especially in the response level (i.e., response inhibition; Barkley, 1997; 2006). Further, children with ADHD also tend to underachieve academically and experience social and disciplinary problems (Barkley, 2006), which seem to be attributed to their inability to prioritize attentional resources to complete goal-directed behaviors (i.e., attentional control). Thus, it is not surprising that numerous researchers have claimed separate and different dysfunction patterns of attention in ADHD. Although existing studies on attention deficits in ADHD by themselves provide useful knowledge on diagnosing and treating patients with ADHD, it will be enlightening to examine various attentional functions and dysfunctions in ADHD in an inclusive review in order to understand which types of attentional mechanisms are intact or mostly deviant in individuals with ADHD. The current review, therefore, provides evidence on functions and dysfunctions in separate attentional mechanisms in children with ADHD: namely, 1) inhibitory system and response inhibition, 2) attentional control, and 3) attentional orienting mechanism including alerting, orienting, and disengaging.

## Impairments of Response Inhibition

Impairments in inhibitory mechanisms in individual with ADHD have been widely studied in individuals with ADHD. Researchers have suggested that deficits in inhibitory control are one of the major characteristics of the disorder along with hyperactivity, impulsivity, and other inattentive symptoms in ADHD (Barkley, 1997). In fact, several researchers have argued that impaired response inhibition is one of the primary features contributing to the pathophysiology of ADHD (Barkely, 1997; Durston, 2003; Heilman et al., 1991). In particular, in the hybrid neuropsychological model of executive (self-regulatory) functions, Barkley (1997) has argued that the primary deficit in ADHD is poor behavioral inhibitory control affecting four types of executive functions leading to deficits in motor control, fluency, and/or syntax (Barkley, 1997). A number of empirical studies have supported this notion that response inhibition is a primary deficit in ADHD. For example, studies on ADHD have used variations of a go/no-go task to examine inhibitory processing. These tasks contain stimuli that elicit a response (i.e., “Go trials”) interspersed with those that necessitate an inhibition of response (i.e., “No-Go trials”) (Booth et al., 2005; Casey & Castellanos, 1997; Nigg, 1999; Trommer, Hoeppner, & Zecker, 1991). Typically, these tasks establish a dominant response set by making most trials “go trials” so that participants must withhold their responses on the relatively rare “no-go trials”. Previous research demonstrated that children with ADHD, compared to typically developed children, produced greater errors of commission on no-go trials, along with greater omission errors on go trials in go/no-go tasks (Booth et al., 2005; Trommer, Hoeppner, & Zecker, 1991; Wodka et al., 2007).

Along with the findings on behavioral performance, neural evidence has also supported the idea that response inhibition is one of the major deficits in ADHD. For example, Booth et al. (2005) provides evidence on deviant neural networks in response inhibition mechanism in individuals with ADHD. Using a go/no-go task, the authors found that the performance on response inhibition task was significantly poorer in children with ADHD than in healthy controls. Furthermore, the researchers found large group differences (i.e., ADHD vs. controls) in brain activity during the task. Specifically, compared to healthy controls, children with ADHD showed reduced activity in fronto-striatal brain regions, including bilateral precentral gyrus, right caudate head/body, right inferior frontal gyrus and bilateral thalamus. In fact, previous neuroimaging studies with healthy individuals have demonstrated that those fronto-striatal regions are involved in various types of response inhibition tasks, such as go/no-go tasks (Bunge et al., 2002; Casey & Castellanos, 1997, Durston et al., 2002), stop tasks (Rubia et al., 2000), and anti-saccade tasks (Luna et al., 2001). Thus, such findings in Booth et al. (2005) suggest that response inhibition is selectively and primarily affected in children with ADHD. Similarly, Casey and Castellanos (1997) also found that children with ADHD revealed deviant neural correlates of attentional process during response inhibition tasks. The researchers tested 52 children (26 children with ADHD; 26 matched controls) with three types of response inhibition tasks and examined their brain activation using magnetic resonance imaging (MRI). Specifically, they examined the relationships between response inhibition deficits and specific frontostriatal structures (i.e., prefrontal cortex (PFC) and basal ganglia) in ADHD, which have been known to be involved in performance in response inhibition task and also known to be impaired in ADHD (Booth et al., 2005; Castellanos et al., 1996; Rubia et al., 1999). In their behavioral results, the researchers found significant impairments in performance on go/no-go task in the ADHD group. Importantly, the relationship between anatomical measures of frontostriatal circuitry and the task performance was revealed to be deviant in children with ADHD. Specifically, whereas the normal control group showed the significantly positive correlations between task performance and anatomical measures of the right PFC and caudate nuclei, those correlations were absent in children with ADHD. Further, the ADHD group showed significantly negative correlation between right prefrontal volume and mean accuracy on the go/no-go task, suggesting that activity in the right PFC associated with response inhibition was abnormal in children with ADHD.

Studies with electrophysiological methods also provide evidence on dysfunctions in the inhibitory system in ADHD. Specifically, Pliszka et al. (2000) compared performance on the Stop signal task between children with ADHD and their neurotypical counterparts. During the Stop signal task, participants have to withhold their responses on infrequent no-go trials, while making responses to the target identity. In their study, the researchers manipulated inter-t rial interval (ITI) between the go-trial and the stop-trial. If the stop signal occurred after a long interval following the go-trial, it was expected that the participant would more often fail to inhibit his/her response (Schachar & Logan, 1990). Using such task, the researchers found that children with ADHD showed almost flat slopes as a function of ITI, whereas the control group showed significantly better inhibition performance on the shorter ITI trials than the longer ones. Further, the researchers found that N200 amplitude (i.e., negative waves after 200ms of the stimulus onset) in event-related potentials (ERPs), reflecting the efficient onset and implementations of the response inhibition processing, was significantly smaller in the ADHD group than that in controls. The difference in the N200 amplitude was exclusively revealed over the right anterior inferior scalp region, suggesting that response inhibition involving the prefrontal functions was impaired in patients with ADHD. More recently, Shen and colleagues (2011) also found atypical error ERP components during the Stop signal task in children with ADHD. In particular, the ADHD group showed normal error-related negativity (ERN), reduced error positivity (Pe), and reduced late positive wave (LPW) associated with stop signals, suggesting abnormal later error monitoring process and intact early monitoring process related to error detection in children with ADHD.

Although studies with children with ADHD offer valuable evidence on attentional impairments in those populations, the impairments in response inhibition could possibly be attenuated with developmental progression. However, the deviant neural activity in the frontal regions during the response inhibition task has also been evident in a study with adolescents and adults with childhood ADHD (Epstein et al., 2007; Gow et al., 2012; Mulligan et al., 2011; Schulz et al., 2004). For examples, using a go/no-go task, Schulz et al. (2004) demonstrated that adolescents who were diagnosed with ADHD in their childhood produced significantly more commission errors on no-go trials than typically developed adolescents. Further, Epstein and colleagues (2007) conducted an innovative fMRI study using a go/no-go task in adolescents with ADHD and their parents who were also diagnosed with ADHD. Interestingly, results in this study showed reduced activation in the righ inferior frontal gyrus and caudate regions in both parents and adolescents with ADHD compared to their age-matched counterparts, indicating that ADHD-related functional activation deficits during response inhibition may not change with age. Additionally, a study with ERP demonstrated that adolescents with ADHD showed abnormal centroparietal ERP response during response inhibition (Gow et al. , 2012). Although behavioral performance was comparable between adolescents with ADHD and their typically developing counterparts, the ERP data showed significant impairments in brain function in the ADHD for late, endogenous ERPs (N2, P3a, and P3b), suggesting impaired inhibitory process in adolescents with ADHD. Taken together, findings from studies with adolescents with ADHD suggest that age or developmental progress does not significantly modulate the response inhibition deficits in people with ADHD.

Despite repeated findings of severe impairments in response inhibition in ADHD, other researchers have questioned the idea that response inhibition was the major deficits in ADHD. Those researchers argued that response inhibition is not a primary but a secondary deficit in ADHD. For example, Scheres et al. (2004) tested different types of attentional and executive functions in children with ADHD, including response inhibition. In their first analysis, the researchers replicated the finding that the response inhibition measured with a go/no-go task was affected in ADHD children. After controlling for effects of age, IQ, and performance on non-executive control tasks, however, the significant impairments in response inhibition in ADHD were eliminated. Similarly, Alderson and colleagues (2008) found contrasting evidence to the idea that response inhibition was the most critical deficits in ADHD. Specifically, they argued that generally slower processing of visual stimuli accounted for impaired performance on response inhibition task. However, as reviewed earlier, a number of studies demonstrated that not only performance on response inhibition but also the neural mechanisms related to inhibitory functions were deviant in individuals with ADHD (Berkley, 1997; Booth et al., 2005; Castellanos et al., 1996, 2008; Pliszka et al., 2000; Rubia; 1999). Furthermore, a recent study demonstrated that the deficits in response inhibition in ADHD are still found regardless of other associated executive functioning demands, such as increased load of working memory or provision of reward/response cost (Wodka et al., 2007). Overall, the majority of studies on response inhibition suggest that the problem with response inhibition in ADHD is not a secondary but a primary attentional deficit in these patients.

In summary, although some researchers have suggested that the response inhibition is not the primary but the secondary deficit in individuals with ADHD (e.g., Alderson et al., 2008; Scheres et al., 2004), numerous behavioral, neuroimaging, and electrophysiological findings have provided evidence that impaired response inhibition process is the major attentional deficit in ADHD population (e.g., Barkely, 1997; Booth et al., 2005; Cast ellanos et al., 1996; Pliszka et al., 2000; Schulz et al., 2004; Wodka et al., 2007). As the DSM-IV and V (American Psychiatric Association, 1994) make the distinction among Predominately Hyperactive-Impulsive (ADHD/H), Predominately Inattentive (ADHD/I), and Combined Type (ADHD/C), it would be informative to separately test attentional deficits in ADHD according to its subtypes. However, most of the studies on response inhibition tend to include all three ADHD subtypes in their studies due to small sample sizes (Casey et al., 1997; Durston et al., 2003; Pliszka et al., 2011; Shen et al., 2011). One study, however, tested differences in response inhibition between ADHD/I and ADHD/C, and found no differences in response inhibition performance in a go/no-go task between different subtypes (Wodka et al., 2007). Further, in Booth et al. (2005), the ADHD participants were mainly the ADHD/H type, and the researchers found similar deficits in response inhibition in those patients to other studies with ADHD/I and ADHD/C at both behavioral and neural levels. Taken together, deficits in response inhibition seem to be a core impairment in childeren with ADHD regardless of its subtype, and such deficits may affect impulsivity in individuals with ADHD, which is assumed to be a major characteristic of ADHD (DSM-IV and V).

## Attentional Control: Managing limited resources and Conflict resolution

Attention is known to be a limited process. Previous researchers have demonstrated that the attentional process can be affected by other cognitive processes, such as working memory (Awh & Jonides, 2001; De Fockert el al., 2001; Kim, Kim, & Chun, 2005), perceptual processing (Lavie, 1995; Lavie & De Fockert, 2004), or other irrelevant information in the visual filed (Triesman, 1969; Trisman & Gelad, 1980) due to its limited capacity. Thus, the attentional control mechanism managing the limited resources should be addressed when examining attentional impairments in individuals with ADHD.

One of the widely used tasks for testing attentional control is the Stroop color naming task (Stroop, 1935). In this task, participants are asked to name the ink color of a colored word ignoring the meaning of the word. When the meaning of a colored word is congruent with the ink color of the word, people are significantly faster to name the ink color of the word compared to when naming a color of a neutral word (i.e., Stroop facilitation effect). In contrast, participants in this task are significantly slower to name the ink color of a colored word when the meaning of the colored word is incongruent with the ink color of the word (i.e., Stroop interference effect). Certainly, both inhibition of irrelevant information and selection of relevant information play a critical role in successfully performing such tasks. However, as Macleod (1991) claimed, no single attentional mechanism captures the wealth of determinants of Stroop performance. Several researchers explained the Stroop interference effects with a filtering error, automatic processing of semantic information, a failure to inhibit response tendencies, or a failure of attentional control functions to distribute and allocate attentional resources (Barkley et al., 1992; Tzelgov et al., 1992). Although each explanation focuses on different aspects of the Stroop task, it is broadly accepted that the performance on the Stroop task involves mechanism of conflict resolution to allocate attentional resources to the most relevant domains of stimulus. Thus, in this review, I will focus on the characteristic of Stroop task to examine the control of attention to resolve the conflict and to allocate attentional resources to task-relevant information.

Several studies have reported deficits in performance on the standard Stroop task in ADHD (Barkley et al., 1992; 1997; Carter et al, 1995; Seidman et al., 1997). Those researchers found that whereas children with ADHD revealed normal facilitation effects on the congruent condition, they showed increased interference effects compared to typically developing children (Carter et al., 1995; Seidman et al., 1997). Critically, the interference effect was only evident in the slowed response to the incongruent conditions, and the ADHD patients did not make significantly more errors than their neurotypical counterparts. Thus, the increased interference effects in individuals with ADHD do not seem to be due to their response inhibition problem. Instead, conflict resolution and interference control to allocate attention to task-relevant dimension (e.g., “ink-color” of the colored word) seems to be impaired in individuals with ADHD, especially when conflicting information concurrently exists.

Other researchers using variants of the Stroop task repeatedly showed a similar deficit in conflict resolution in ADHD (e.g., Albrecht et al., 2008; Barkley, 1997; Kilic et al., 2007). Two meta-analyses by Barkley and colleagues (1992; 1997) confirmed that ADHD children revealed significant impairments on the Stroop color naming task. Moreover, Kilic et al. (2007) used a Turkish version of Stroop color naming task, and found increased interference effects in ADHD children compared to the matched controls. Further, the increased interference effects in ADHD participants were reported even when the processing speed or reading and naming speed (Lufi, Cohen & Parish-Plass, 1990; MacLeod, 1991) was controlled out. In sum, previous studies have confirmed that individuals with ADHD have abnormalities in attentional control and conflict resolution, as reflected in the Stroop task, which indicates deficits in allocating attentional resources to task-relevant dimension.

Consistent with those behavioral findings, an fMRI study reported evidence on deviant neural processing associated with the behavioral impairments in individuals with ADHD during a Stroop task. Specifically, Bush and colleagues (1999) developed a counting Stroop task. In the counting Stroop task, participants were instructed to report the number of identical words that appeared on the screen, ignoring word meaning (Bush et al., 1998; 1999). The word could be a number (e.g., FOUR), or neutral (e.g., DOOR) creating congruent, incongruent, and neutral conditions. With this task, the researchers found that individuals with ADHD showed more interference effects than control participants on incongruent trials. Further, Bush et al. (1999) found that the impaired performance in the Stroop task was associated with abnormal brain function in ADHD. Whereas the control group showed significantly enhanced activation in the anterior cingulate cognitive division (ACcd) in the incongruent trials compared to the neutral trials, the ADHD group failed to show the same enhancement of the region in the same contrast. Moreover, the authors found that, only in the interference condition, the control group showed significantly more activation in the ACcd than the ADHD group, although the activation in ACcd was similar in both group on the neutral condition. In fact, the anterior cingulate

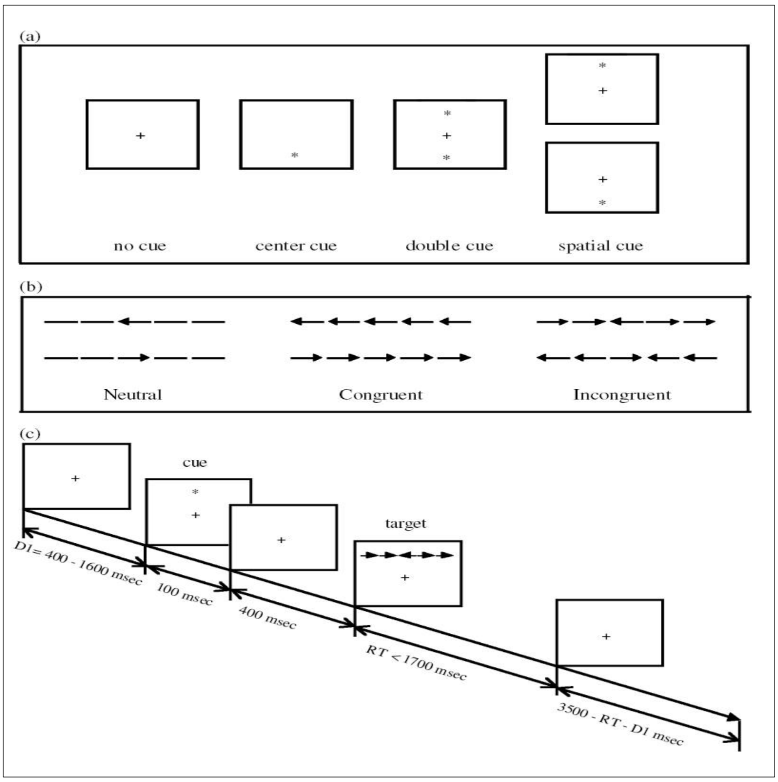

Figure 1. The Attention Network Test (Fan et al 2002). (a) The four cue conditions; (b) An example of a flanker task; and (c) An example of the procedure.

plays a critical role in attentional control processing, such as conflict resolution or attentional allocation (Peterson et al., 1999). Thus, Bush et al. (1999) concluded that individuals with ADHD revealed large interference effects on the Stroop task and these effects were related to the abnormal ACcd function for detecting conflict required for proper allocation of attentional resources.

Inefficiency in conflict resolution in people with ADHD was also found in studies using a different conflict-related task, namely a flanker task. A recent fMRI study with an attention network task (ANT) provides evidence that the control of conflict resolution is deviant in individuals with ADHD (Konrad et al., 2006). The ANT has been used to determine functions of each attentional network, namely alerting, orienting, disengaging, and executive attentional controls (Fan et al., 2002; Figure 1c). Specifically, this task involves both Posner 's cueing task and the flanker task. Since the attentional orienting systems will be discussed more thoroughly in the next section, I will focus on findings from the flanker task only in the current section.

In ANT, the flanker task was followed after one of the four types of cue conditions in each trial (Figure 1a). The targets in this task were presented either above or below the central fixation, and were either a single arrow or a single arrow flanked on each side by two additional arrows in the same direction (Figure 1b). The task was to determine the direction of the central arrow. The flanking arrows in the flanked condition pointed either to the same side as the target arrow (*congruent condition*) or in the opposite direction (*incongruent condition*). The differences between performance in the congruent and the incongruent condition reflect the efficiency of attentional control function for conflict resolution. Using this paradigm and fMRI, Konrad et al. (2006) found a significant behavioral impairment in the ADHD group only in the attentional control network reflected by the flanker task. That is, compared to neurotypical controls, individuals with ADHD showed greater increases in RTs on the incongruent flanker condition than on the congruent condition. Furthermore, control participants showed significantly greater activation than ADHD groups in the neural network associated with conflict resolution, namely the left medial frontal gyrus, ACC, and the right putamen. Thus, both behavioral and neuroimaging results in Konrad et al. (2006) indicate impairments in attentional control processing in individuals with ADHD. Such findings have also been replicated in a recent study with the ANT task showing that attentional control processing is significantly impaired in children with ADHD (Mullane et al., 2011). It is worth mentioning that studies using the ANT task demonstrated a double dissociation of attentional systems, especially between the control of attention and the orienting system. As described in the next section, research on the orienting system in ADHD has found intact orienting mechanisms in the patients while their functions for attentional control are revealed to be impaired (e.g., Konrad et al., 2006; Mullane et al., 2011). Such findings thus indicates that the three domains of attentional processes suggested in this review are independent from each other, as indicated in double dissociations of deficits in ADHD among the three attentional mechanisms.

In addition to the paradigms targeting the process of conflict resolution, impaired attentional control to allocate attentional resources has been revealed in ADHD in a study with visual oddball paradigm (Lopez et al., 2006). Specifically, Lopez et al. (2006) explored the distribution of attentional resources in children with ADHD using a double-oddball visual task. Previous researchers demonstrated that examining the amplitude of early and late ERP components could reflect resource allocation in visual spatial tasks (Luck et al., 1996; Mangun & Hillyard, 1990). Based on such evidence, Lopez and colleagues compared the amplitudes of P1 (the first positive component after about 80-100 ms of the stimulus onset), N1 (the first negative component after about 150-200 ms of the stimulus onset), and P300 (the positive component after 300 ms of the stimulus onset) components generated by ADHD children to those generated by neurotypical counterparts. Participants were asked to pay attention to the stimulus inside of a frame on the center of the screen while ignoring other stimuli outside of the frame. Stimuli used in this task were faces of male (i.e., standard stimuli) or female (i.e., target stimuli), and the task was to mentally count how many female faces appeared inside of the frame in each block. The ERP was time-locked to each stimulus presented inside or outside of the frame. There were four different stimulus types in terms of their location and identity, namely S1 (a standard stimulus inside of the frame), T1 (a target inside of the frame), S2 (a standard stimulus outside of the frame), and T2 (a target stimulus outside of the frame). With this task, the researchers found that the later distribution of attentional res ources was deviant in ADHD children, while their initial allocation of attention indexed by P1 and N1 was intact. In particular, the researchers found that the control group produced a significant P300 only for the target stimuli inside of the frame, whereas the ADHD group failed to show reduced P300 for peripheral stimuli, which were supposed to be ignored. Further, the researchers found that, only in the ADHD group, P300 amplitudes were determined by stimulus type. That is, a significantly graded P300 amplitude increase was found in following order among children with ADHD: S1 < S2 < T2 < T1. Such finding indicates redistribution of attentional resources according to the stimulus type among ADHD children although they seemed to be able to suppress irrelevant stimuli at the initial stage (Lopez et al., 2006). The authors thus concluded that ADHD children showed an intact initial selection processing when focusing attention over a task-relevant area, but they revealed impaired allocation of attention at the later stage, showing later reassignment of attentional resources.

Overall, previous studies have demonstrated that children with ADHD are suffering from deficits in attentional control. Their abnormalities are revealed in impairments in allocating attentional resources to task-relevant dimension (Barkley, 1997; Bush et al., 1999; Carter et al., 1995; Kilic et al., 2007; Seidman et al., 2000), in conflict resolution (Bush et al., 1999; Konrad et al., 2006; Mullane et al., 2011), and in deviant distribution patterns of attentional resources (Lopez et al., 2006). While it would be valuable to investigate attentional control mechanism in ADHD by its subtypes (e.g., ADHD/I, ADHD/H, and ADHD/C), most of the studies introduced in this review tested attentional control processing in ADHD combined type (e.g., Albrecht et al., 2008; Kilic et a.,, 2007; Lopez et al., 2006). Only a study by Mullane and colleagues (2011) compared ability of conflict resolution between ADHD/I and ADHD/C, and found that the impairments on conflict resolution did not significantly differ between the two subtypes of ADHD. Future study including all three subtypes of ADHD can address an issue that whether the deficits in attentional control processing is specific to one type of ADHD (e.g., ADHD/C) or general impairments in ADHD regardless of its subtypes. Finally, it is noteworthy that the deficits in conflict resolution in ADHD evident in studies using Stroop tasks or a flanker paradigm do not seem to be due to impairments in response inhibition in ADHD (e.g. Albrecht et al., 2008; Bush et al., 1999; Carter et al., 1995). Although the Stroop interference effect can be elicited due to response conflict, response conflict and its resolution is not identical concept to response inhibition. Further, the impaired performance in such task in abovementioned studies was resulted in longer response time, rather than prompt and inaccurate responses in children with ADHD. Findings in neuroimaging studies also support that the processing of conflict resolution is abnormal in individuals with ADHD independent from their deficits in response inhibition, as shown in decreased neural activation in ACC and frontal circuits for conflict resolution in children with ADHD compared to their neurotypical counterparts (e.g., Konrad et al. 2006; Mullane et al., 2011). Taken together, it is reasonable to conclude that children with ADHD have specific deficits in conflict resolution and attentional control to assigning cognitive resources to take-relevant dimension, although whether the deficit in attentional control is general or specific to a certain type of ADHD remains unspecified.

**Alerting, Orienting and Disengagement of attention** The most commonly used paradigm to investigate the attentional orienting network is Posner's covert orienting of visuospatial attention paradigm, the so-called *Posner's cueing paradigm* (Posener, 1980; Posner & Peterson, 1990). Before I move into findings on attentional orienting systems in ADHD, I will first explain this covert orienting task. The covert orienting indicates orienting attention toward a location, which is not foveated. In the covert orienting task, participants are asked to detect a target presented inside of the left or right peripheral box, while they fixate their eyes on the center of the screen. The target, usually a simple visual stimulus (e.g., an asterisk), is preceded by a cue in most of the trials. The cue can either be centrally presented indicating one direction (e.g., right/left arrows; or a green circle for the left direction and a red for the right) or appear in the location of peripheral boxes (e.g., a sudden flash of one of the boxes). Depending on the cue type, a certain aspect of orienting system can be measured. Using a central cue, endogenous/voluntary orienting can be measured, as people must use their top-down mechanism to determine meaning of the cues and orient their attention accordingly. In contrast, the peripheral cues are used to measure involuntary or automatic orienting because the sudden appearance of the peripheral stimulus can draw one's attention to that location automatically (i.e., exogenous orienting). When the location indicated by either type of cue is congruent with the area where a following target appears (i.e., a valid condition), participants perform a given task faster and more accurately than when those two locations are incongruent (i.e., an invalid condition). According to Posner and colleagues (1980; 1990), the beneficial effect of the valid cue reflects an efficient orienting and engaging system, while the cost of the invalid cue indicates an inefficiency of disengagement system, which is the system to disengage attention from the misdirected area and reorient it to the target location.

The covert orienting task can not only test the efficiency of orienting and re-orienting systems, but can also provide information on the vigilance and alerting systems in attentional mechanism (Fan et al., 2002). Vigilance is often referred to as sustained attention, the ability to maintain a tonic state of alertness during prolonged and sustained mental activity (Mirksy & Duncan, 2001; Weinberg & Harper, 1993). The deficits in alertness or vigilance can be reflected as slow response times on attention tasks. This vigilance and alerting processing have been measured with so-called “double cue” or “neutral cue” conditions, where both of the peripheral boxes are simultaneously cued. This condition is often compared to the condition without any preceding cues to determine the efficiency of alerting system.

Previous researchers have used the Posner’s cueing paradigm to determine whether any of the attentional orienting systems are impaired in ADHD. Whereas studies on other aspects of attention have provided relatively convergent findings, the reports on attentional orienting system using Posner’s paradigm are somewhat contradictory. For this reason, I will separately review evidence on the attentional orienting system in ADHD in following topics: 1) findings suggesting deficits in alerting network in ADHD, 2) findings suggesting intact functions in all of the orienting networks in ADHD, and 3) findings suggesting deficits in disengaging systems in ADHD.

**Evidence on deficits in alerting networks.** Several researchers provided evidence on impaired alerting system in individuals with ADHD despite intact functions in orienting and disorienting networks. For example, Nigg et al. (1997) demonstrated that children with ADHD showed normal benefits and costs by peripheral cues during a cover orienting task. They also found that children with ADHD revealed normal reduction of response times (RT) when the duration between cue and target increased. The authors found, however, a significant RT asymmetry on the no cue trials in the ADHD group. Children with ADHD were slower to respond to the target in the left visual field than to the target in the right visual field after no cue at 100 ms. This RT asymmetry in ADHD was also evident in other research (e.g., McDonald et al., 1999), and the researchers suggested a specific deficit in the right lateralized alerting process among individuals with ADHD.

A study using an attention network task (ANT) has also reported similar findings (Oberlin et al., 2005). As introduced earlier, the ANT consists of both Posner ’s cueing paradigm and the flanker task to determine functions of each of the attentional networks. With a typical ANT, Oberlin and colleagues compared separated attentional systems in ADHD children to those in the normal controls. Surprisingly, the researchers did not find any behavioral deficits in orienting network in ADHD children. What they did find, however, was that individuals with ADHD combined type showed significantly slower RTs in the non-spatial cue conditions (i.e. double cue) compared to those of the normal controls or to those with ADHD inattentive type, indicating a limited function of alerting system in children with ADHD/C. A recent research with ANT supported the notion that children with ADHD would show weaker alerting system than their neurotypical counterparts (Mullane et al., 2011), but they did not find significant group differences in alerting system between ADHD/C and ADHD/I.

**Evidence on intact orienting networks in ADHD.** A number of studies with the covert orienting paradigm tried to find abnormalities in the orienting system in ADHD. However, not all of them succeeded. For example, Aman et al. (1998) used a Posner's cueing task with peripheral/exogenous cues to test orienting systems in children with ADHD. They varied duration between the onset of a cue and the onset of a target (i.e. SOA) to be 100 ms or 500 ms. Although the researchers found abnormalities in other attentional tasks in ADHD (e.g., inhibitory control and planning), they failed to find deviant functions in the orienting system in ADHD. That is, children with ADHD revealed a typical pattern of the validity effect, showing faster RTs in the valid conditions and slower RTs in the invalid condition. The effect size of this validity effect and overall RTs were also similar in ADHD participants and the controls.

Studies with ERPs also demonstrated normal functions in attentional orienting in individuals with ADHD. Using both peripheral and central cues, Novak et al. (1995) found that children with ADHD showed typical validity effects with both types of cues. Moreover, the researchers reported that the early and late ERP components related to attentional orienting seemed to be normal in the ADHD group. In detail, the P1 and N1 amplitudes were greater for the validly cued target than for the invalidly cued one in both ADHD and normal children. Similarly, the latency and amplitude of P300 was equivalent for both groups, showing longer latency and greater amplitude of P300 elicited by invalidly cued targets than validly cued ones (Novak et al., 1995). A study by Perchet et al. (2001) also supports the claim that children with ADHD show normal patterns of orienting mechanisms. Specifically, the researchers used ERPs with a covert orienting paradigm, and demonstrated that behavioral performance in children with ADHD and normal controls was equivalent in terms of their validity effect. Moreover, although the amplitude of the early

ERP component elicited by validly cued target (i.e. P1) was somewhat decreased in the ADHD group, the pattern of the P1 amplitude gradient was similar in both groups. That is, the amplitude was largest to the validly cued target followed by the one to the invalidly cued target, then to the targets without a preceding cue. This amplitude gradient was also found in the late positive complex (e.g., P3) in both normal and ADHD groups. Similarly, a review on visuospatial orienting in ADHD also concluded that the orienting system tended to be intact in ADHD though the authors emphasize that testing the visuospatial orienting system in different ADHD subtypes is necessary to clarify specific attentional deficits in each subtype (Huang-Pollock & Nigg, 2003). In sum, abovementioned studies suggest that children with ADHD have normal functioning of orienting networks.

**Evidence on deficits in orienting and re-orienting networks.** Although several researchers suggested intact functioning of orienting systems in patients with ADHD, others have claimed that those networks are impaired in ADHD. For example, a recent ERP study reported poor performance in a visuospatial orienting task in children with ADHD combined type, when state regulation is impaired during the preparatory stage (Ortega et al., 2013). Further, the target-related ERP components in the ADHD group was found to be abnormal, reflecting a abnormal allocation of attentional resources in ADHD after a valid cue.

In fact, a number of studies suggest an abnormality in disengaging system despite their intact orienting mechanism (Carter et al., 1995; Epstein et al., 1997; Swanson et al., 1991; Wood et al., 1999). That is, previous studies found abnormal patterns of costs of invalid cues in individuals with ADHD. For instance, the first study of covert orienting mechanism in ADHD (Swanson et al., 1991) used an exogenous cue paradigm with peripheral cues. The researchers controlled the predictability of the cue to be 80:20 for valid trials and invalid trials, respectively. Also, the researchers manipulated the SOAs to be either 800 ms or 100 ms. With this paradigm, the researchers found that both ADHD and control children showed faster RTs on the validly cued targets compared to RTs in the no cue condition in both SOAs. Also, the RTs on all targets in 800 ms SOA condition were delayed compared to those in the 100 ms SOA condition in both groups. These findings suggest that children with ADHD have normal processing of visual cues as well as an intact function of orienting. However, the researchers found an abnormal pattern of disengagement of attention in children with ADHD. That is, in the longer SOA condition, the ADHD group showed increased costs in detecting invalidly cued targets presented in the right visual field, whereas they revealed decreased costs in detection of invalidly cued left visual field targets. The researchers suggested that this asymmetry indicated a right hemisphere deficit in children with ADHD when disengaging their attention from the left visual field (the invalidly cued location).

After this first report, several researchers provided supportive evidence on the brain asymmetry in disengagement process among individuals with ADHD. For example, Carter et al. (1995) used both peripheral and central cues and replicated the results from Swanson et al. (1991). The researchers recruited 20 ADHD children and 20 matched-controls, and compared their performance on covert orienting task. Again, Carter et al. (1995) found normal validity effects by both cue types in ADHD children. However, the researchers found that children with ADHD showed an asymmetrical performance deficit characterized by more costs on voluntarily orienting to the invalidly cued right visual field targets. This finding is consistent with other reports on adults ADHD (Epstein et al., 1997), suggesting right hemispheric deficits in disengaging attention from the left to right visual field.

Abnormality in disengaging process in ADHD has also been evident in studies using slightly different task paradigms. Wood et al. (1999) used exogenous cueing paradigm with 150 ms and 350 ms SOAs to investigate orienting and reorienting mechanisms in children with ADHD. They found that the control group showed typical reaction time advantages conferred by increasing SOAs in both valid and invalid trials. Such advantage was, however, not evident in the ADHD group for invalid trials. As a result, the cost from the invalid cue at 350 ms SOA were significantly larger in the ADHD group than in the control group, whereas the size of the cost was similar in both groups at shorter SOA. It has been suggested that orienting attention to peripheral cues at longer SOAs required more voluntary control over attentional systems (Maruff, Hay, et al., 1995; Rafal & Henik, 1994). Based on this suggestion, Wood et al. (1999) concluded that increased costs of invalid cues at the longer SOA in the ADHD group indicated a difficulty in disengaging attention when voluntary control is required.

Finally, a study with a voluntary cueing paradigm provides additional evidence that children with ADHD present difficulties in reorienting attention to the goal-relevant location (McDonald et al., 1999). They used voluntary orienting cues to impose more needs for controlled attentional processing during the task. In comparison between normal and ADHD children, the researchers found that children with

ADHD generated greater RT benefits and costs by the central cues. That is, those children tended to super attend to the cued location and did not appear to reorient attention as quickly as children without ADHD. This finding supports the idea that individuals with ADHD have deficits in disengaging and reorienting their attention from the unwanted area to the goal-relevant location.

In sum, research on covert orienting systems has provided somewhat diverging evidence on those systems in people with ADHD. Some studies suggest intact functions in all of the orienting network, whereas others claimed abnormal functions in certain aspects of the network (e.g., alerting or disengaging systems). Closer look at the functions in attentional orienting systems in ADHD will be able to provide precise information on deficits in those aspects of attention in ADHD. For example, convergent evidence of behavioral and neuroimaging data may better classify the deficits in the attentional orienting networks in people with ADHD. In fact, a recent neuroimaging study with ANT revealed significant abnormalities in the neuronal functions of all the three networks (Konrad et al., 2006). Although the researchers failed to find subnormal behavioral functions in ADHD on the alerting and orienting/disorienting networks, they demonstrated deviant neural activities associated with each of the network. This finding suggests that neural examination can be a sensitive tool to investigate functions and dysfunctions in separate orienting systems. Thus, thoroughly designed studies with combined methods will be able to answer the question about which aspects of the attentional orienting systems are impaired in individuals with ADHD. Finally, whether the orienting network is deferentially affected by each subtype of ADHD should also be considered. Although some research found deviant alerting system in the ADHD combined type only (e.g., Oberlin, 2005), others found no significant differences in alerting system bewteen each subtype of ADHD (e.g., Mullane, 2011). Testing covert orienting system in each subtype of ADHD will be helpful to determine which aspect of orienting system is impaired in each subtype, which can in turn lead to appropriate cognitive intervention for each subtype in ADHD.

**Conclusions and further directions** In summary, patients with ADHD show deficits in various dimensions of attentional mechanism. Individuals with ADHD show major deficits in response inhibition and attentional control, especially in conflict resolution. Studies also suggest that individuals with ADHD seem to suffer from deficits in the alerting and disengaging systems, although evidence on orienting system is not very well-converged for ADHD. Neuroimaging and electrophysiological studies on patients with ADHD support the claim that a variety of attentional functions are deviant in those patients, and provide evidence that the dysfunctions in frontal areas of brain might be the most responsible for the attentional deficits in this disorder.

Despite the converged results from behavioral, electrophysiological, and neuroimaging data, several issues must be considered to interpret attentional deficits in these patients. First, most of ADHD studies in this review examined children with ADHD. Although ADHD is most prevalent among children, it would be useful to know the developmental trajectories of attentional functions in these patients. Examining how the development deviates from the normal developmental trajectory beyond simple gross differences could provide very essential knowledge on fundamental attentional dysfunctions in people with ADHD.

Further, a gender effect on attentional processing might be of interest when testing attentional deficits in ADHD. In fact, a male-to-female ratio of ADHD is revealed to be 3:1 in population based studies (Barkley, 2006; Gaub & Carlson, 1997) and between 5:1 to 9:1 in clinical samples (Gaub & Carlson, 1997; Sandberg, 2002). As a result, most of the studies in this review included more male than female participants, thus the attentional functions and dysfunctions in ADHD found in the reviewed studies might be biased to those of males. However, all of the studies also included gender-matched healthy control counterparts to minimize possible effects of gender on cognitive processing. Moreover, as male ADHD is more common than female ADHD, studies with more male participants perhaps more naturally represent the ADHD population. Of note, recent studies on gender differences revealed no or little gender differences in cognitive functions (Martel, 2013; Skogli et al., 2013). Thus, it is likely that gender may not be a critical factor influencing attentional functions in ADHD, although future research on gender effect in each of attention system can be helpful to elucidate whether gender plays a crucial role in attentional processing in ADHD.

Third, the results from the neuroimaging data should be considered with caution. Since the individuals are already suffering from their own deficits, their brain structures are not ne cessarily the same as the standard structure. Further, should not only the level of activity in each brain area but also the connection between them be considered to determine deviant attentional functions and their neural networks in those patient groups. In fact, recent techniques, such as diffusion tensor imaging (DTI), will allow researchers to track connectivity in fronto-striatal and parietal areas and to assess differences in the neural connectivity among normal individuals and individuals with ADHD. The converged evidence from neuroimaging and from those techniques of functional connectivity could help to further understand the attentional deficits in patients with ADHD.

Finally, attentional functions associated with other domains of cognition (e.g., working memory, language) or emotions are not covered in this review due to its original purpose being to determine basic attentional dysfunctions in ADHD. However, previous studies on attention suggest that attentional function interacts with other domains of cognition and emotions. Thus, studies on such interactions can further clarify understanding of the attentional functions in individuals with ADHD in their everyday lives.

In conclusion, as its name infers, individuals with ADHD suffer from attentional deficits. This review have provided evidence that response inhibition and conflict resolution are most significantly affected in children with ADHD. Accumulated knowledge on deficits in different aspects of attention in ADHD can be used as a guideline to develop cognitive intervention for children with ADHD. For example, intervention to improve response inhibition and conflict resolution would be more critical than intervention for spatial attention or attentional orientation for ADHD patients to improve their every ability. Importantly, research on attentional deficits in each subtype of ADHD should be encouraged in order to develop appropriated cognitive intervention and treatment for different subtypes of ADHD. Convergent knowledge from clinical trials and evidence from research in cognitive science on subsystems of cognition (e.g., attention) will help to understand pathology of ADHD, which in turn will help to predict treatment outcomes of various cognitive intervention in patients with ADHD.

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# 주의력결핍 및 과다행동장애(ADHD)에서 나타나는 주의기능 장애

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주의력결핍 및 과다행동장애 (ADHD)는 주의가 산만하고 과다활동, 충동성과 학습장애를 보이는 소아청소년기의 장애이다. 명칭에서 나타나듯이, ADHD를 가진 환자들은 여러 가지 주의기능에서 장애를 나타냄이 밝혀져 왔다. 하지만, 주의 기제는 한 가지 구성요소로만 이루어진 단일 기제가 아니기 때문에, ADHD의 주의 장애에 관한 연구들은 서로 다른 주의기제에 대한 단편적인 결론만을 제시하여왔다. 본 논문에서는 주의기제를 세 가지 영역 (반응 억제, 주의 조절, 정향주의 시스템)으로 나누고, 현재까지 발표된 연구결과들을 총괄하여, ADHD 환자들에게 특히 나타나는 주의 장애가 무엇인지에 대해 개관하였다.

주요어 : 주의력결핍 및 과다행동장애, 반응 억제, 주의 조절, 정향주의 시스템