Development of Inhibitory Control in Children With Attention Deficit/Hyperactivity Disorder by the Modified Stop-Signal Task

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ADHD is known well as a developmental disorder characterized by behavioral inhibition. The present study aimed to investigate developmental changes and characteristics of inhibitory control in children with ADHD. For this purpose, we used a stop-signal task, modifying the procedure in order to determine the timing of the stop delay so that the timing was related to individual response speed. Participants, elementary-school-age children with ADHD (N = 18) and without ADHD (controls; N = 64), were divided into 2 groups, younger and older. The children with ADHD had variable reaction time; the rate of their errors was high compared to the control children. Their reactions to go signals were inefficient; there were no differences between the 2 ADHD groups on the inhibition. Some children with ADHD were able to inhibit the response to go signals and used waiting strategies, as did the control children. However, the change in their inhibitory control with increasing age was slow in comparison with the control children. We found that how the strategies were used was related to inhibitory control.

Key Words: stop-signal task, attention deficit/hyperactivity disorder (ADHD), inhibitory control, elementary school children with ADHD

Introduction

Attention-deficit/hyperactivity disorder (ADHD) is a developmental disorder mainly characterized by inattention, hyperactivity, and impulsivity (DSM-IV; American Psychiatric Association, 1994). It is often difficult for children with ADHD to control their behavior. Barkley (1997) proposed a hybrid neuropsychological model of self-control in ADHD. In Barkley's model, behavioral inhibition plays an essential role in working the executive function, and the difficulty of behavioral inhibition causes the lack of self-control.

Over the last decades, researchers have attempted to investigate the behavioral control of children with ADHD by using various tasks, such as the go/no-go task (e.g., Trommer, Hoeppner, Lorber, & Armstrong, 1988), the continuous performance test (e.g., Okazaki, Hosokawa, Kawakubo, Ozaki, Maekawa, & Futakami, 2004), and
the stop-signal task (e.g., Oosterlaan, Logan, & Sergeant, 1998).

The stop-signal task, developed by Logan and Cowan (1984), measures the inhibition of ongoing prepotent responses to go signals. In the stop-signal task, participants are required to stop ongoing responses to a go signal when the stop signal is presented. This task is similar to the circumstances when children are told by their teacher to stop some behavior. The stop-signal task is based on a “race model”; it can explain the response processing of the go and stop signals dynamically. The race model accounts for the response inhibition in the stop-signal task. It assumes the existence of two independent processes, a go process and a stop process. Inhibition depends on a race between these two (Logan, 1994).

Research using the stop-signal task has shown that children with ADHD have significant difficulty with response inhibition, in comparison with children without ADHD (Jennings, van der Molen, Pelham, Debski, & Hoza, 1997; Rubia, Oosterlaan, Sergeant, Brandeis, & van Leeuwen, 1998; Schachar & Logan, 1990) and children with other psychopathological disorders such as learning disorders, conduct disorders, and emotional disorders (Oosterlaan et al., 1998; Schachar & Logan, 1990). Therefore, the stop-signal task is a suitable task for investigating the inhibitory control of ADHD.

In the stop-signal task, the timing of the onset of stop signal has an essential influence on inhibitory control. For instance, when a stop signal is presented immediately after the onset of a go signal, it is easy for participants to inhibit their responses. On the other hand, when the interval between the onset of the go and the stop signals is sufficiently long, it is difficult for them to stop their responses. That is, how the timing is set is a crucial factor in the experiment.

In a typical experiment (Logan, 1994), the timing of the onset of stop signals in a block is set in relation to the individual mean reaction time to go signals in a previous block. Mean reaction time is the average latency of responding to go signals on successful trials in which no stop signal was presented.

Rubia et al. (1998) conducted modified stop-signal task to examine the contingency of timing of the stop signals. They employed two different methods to determine the timing: one was the typical one; the other was based on the onset of the go signal. In the latter setting, the children without ADHD showed a high probability of inhibition. In their experiment, the children with ADHD were less efficient at inhibition than the children without ADHD in both versions of this task. These results (Rubia et al., 1998) suggest that change in the timing of the stop signals has a great effect on response inhibition in the stop-signal task.

Perchet, Revol, Fournieret, Mauguire, and Garcia-Larrea (2001) reported that children without ADHD did not have problems predicting the onset of a cue and utilizing the cue adequately in other tasks such as the Posner paradigm. This paradigm requires participants to react with a motor response to a target presented to the left or right visual field after the onset of a cue stimulus that could be either valid or invalid. Perchet et al. (2001) found that children with ADHD had a deficit in anticipatory control.
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In the present study, we used a modified stop-signal task, which was based on the original stop-signal task (Logan, 1994), except for the method of determining the timing of the stop signals. The participants first performed a choice reaction time task that consisted only of go signals. The reaction time measured in this task was called their choice reaction time, and was used to determine the timing of the stop signal in the stop-signal task. That is, the timing of the stop signal did not change through all the blocks in the experiment. By using each individual's mean reaction time on the choice reaction time task, we intended to take individual differences in reaction speed into account. Since the timing of the stop signal was fixed throughout the experiment, the participants were able to predict the onset of the stop signals and prepare for them.

Our primary hypothesis for the present study is that children with ADHD would be deficient in inhibition of go signals and in the anticipatory mechanism of the onset of the stop signals. We presumed that the difference in the timing of the stop signal reflects individual's ability to accomplish go-signal processing. We investigated the difficulty that children with ADHD have in predicting the onset of the stop signals and preparing their responses. We show that novel evidence of the characteristics of ADHD includes preparation for signals.

It has been reported that the ability to inhibit and execute responses changes throughout childhood. Six- to 12-year-old children without ADHD showed remarkable improvement with age in the stop-signal task (Bedard, Nichols, Barbosa, Schachar, Logan, & Tannock, 2002; Schachar & Logan, 1990; Williams, Ponesse, Schachar, Logan, & Tannock, 1999) and a continuous performance test (Brocki & Bohlin, 2004; Okazaki et al., 2004). The symptoms of ADHD change with age; in particular, the syndromes of disinhibition in DSM-IV (American Psychiatric Association, 1994) seem to decline (Hart, Lahey, Loeber, Applegate, & Frick, 1995).

The developmental changes in response inhibition in children with ADHD are well known. For example, Jennings et al. (1997) showed that older children with ADHD inhibited more successfully in the stop-signal task than did younger children with ADHD. There is little research supporting this, however. Therefore, we investigated developmental changes in performance related to inhibition on this task.

Method

Participants

Participants were 18 children with combined-type ADHD, ranging in age from 6 to 12 years old; 16 of the 18 children were males. The children were referred to a hospital pediatrician, including for psychiatric or psychoeducational assessment of learning or behavioral disorder. The children were to be free of methylphenidate for more than 24 hours prior to participating in this experiment. The control group consisted of 64 children from 6 to 12 year-old without ADHD.

The children with and without ADHD were divided into two age groups each, a younger and an older group. In the younger group of children with ADHD, there...
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were 7 males and 1 female (mean age, 8.1 years; age range, 6.7–8.8); in the older group, there were 9 males and 1 female (mean age, 10.3 years; age range, 9.1–12.8).

In the younger group of children without ADHD, there were 7 males and 17 females (mean age, 7.8 years; age range, 6.6–8.9), and in the older group, 21 males and 19 female (mean age, 10.8 years; age range, 9.3–12.4).

Prior to the experiment, all participants were informed of the experimental design, and permission to participate was obtained from the parents of the children.

Task

The stimuli for the stop-signal task were made by REAL basic, and were presented on a notebook computer. The computer was equipped with two large switches for responding to the stimuli.

The go signal for this task was a dog in Cairo font (4.5 cm × 5 cm, 5.2° × 4.7° of visual angle), which appeared in the center of the screen for 1,000 ms and then was extinguished. Each trial started with presentation of the dog in side view either to the right or the left. Participants responded as quickly as possible without making mistakes on either of two buttons or keys, using the hand corresponding to the direction that the dog was facing.

The two directions that the dog could face occurred with equal frequency in all blocks. A fixation point, which appeared randomly in the center of the screen, preceded each go signal, and appeared for 700, 750, 800, or 850 ms. The stop signal was a 100-ms 1000 Hz pure tone generated by two speakers. On 30% of the trials, a stop signal followed the dog in one of three conditions, occurring equally often at each condition. Participants were required to stop their response when a stop signal occurred. It was emphasized that they should respond to the go signals as quickly as possible. The inter-trial interval varied randomly among 2,250 ms, 2,500 ms, 2,750 ms, 3,000 ms, and 3,250 ms.

Procedure

The children with ADHD were tested in the same way as those without ADHD, except that the children with ADHD were tested at a hospital, and the children without ADHD were tested at their school. All children participated individually. The experimenter remained in the room throughout.

The children were seated in front of a computer screen in a quiet room, and instructed about the task. First, they completed the choice reaction time task, which consisted of a practice block of 10 trials, followed by a test block of 50 trials. In this task, only go signals appeared, and individual mean reaction time was measured for the test block (see Fig. 1).

Second, the children completed 3 blocks of 50 trials in the stop task. In this task, stop signals appeared with equal probability 250 ms, 100 ms, and 0 ms before each participant’s individual mean reaction time from the choice reaction time task. After 3 blocks, participants had a break; then they were given 1 block of the choice reaction time task and 3 blocks of the stop task.
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**FIG. 1** The Series of Stimuli in the Choice Reaction Time Task (upper panel) and Stop Task (bottom panel)
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**Analysis of Data**

The independent variables were the 3 stop signal conditions in the stop task.

The dependent variables were: mean reaction time for trials in the choice reaction time task and the stop task in which stop signals were not presented, the standard deviation (SD) of their mean reaction time, the rate of errors of commission (pressing the right button when dog was pointed to the left, or vice versa) and of errors of omission (not pressing either button when the go signal occurred), the probability of inhibition in the 3 stop signal conditions, the difference in mean reaction time between the choice reaction time task and the stop task, and the relation between the difference in mean reaction time and the probability of inhibition.

We conducted an analysis of variance (ANOVA) with repeated measures on the mean reaction times, the SD of the mean reaction times, and the rate of errors of commission or omission between tasks in both groups. An ANOVA with repeated measures across conditions was performed on the probability of inhibition. For measures in which the F values were significant, post hoc Turkey-Kramer tests (5%) were conducted to check on differences between the groups. A multivariate analysis of covariance (MANCOVA) with the differences in mean reaction time as covariates was performed, in order to compare the probability of inhibition between the children with and without ADHD in each stop signal condition.

**Results**

Group comparisons of the measures in the younger and older children with and without ADHD are shown in Table 1.

**Mean Reaction Time in the Choice Reaction Time Task and the Stop Task**

The repeated ANOVA conducted on mean reaction time revealed a significant main effect for age \( F(1, 78) = 19.659, p < .01 \) and tasks \( F(1, 78) = 82.868, p < .01 \). In the choice reaction time task, the mean reaction time of the younger groups was significantly longer than that of the older groups in the children both with and without ADHD. Mean reaction time on the stop task was significantly longer than that on the choice reaction time task in both groups, regardless of age.

**SD of Mean Reaction Time in the Choice Reaction Time Task and Stop Task**

The repeated ANOVA conducted on the SD revealed a significant main effect for age \( F(1, 78) = 13.019, p < .01 \) and an interaction of task with group \( F(1, 78) = 6.891, p < .05 \). In addition, the SD of the younger groups was significantly larger than that of the older groups.

On the choice reaction time task, the SD of the children with ADHD was significantly larger than that of the children without ADHD in both the younger and older groups. On the stop task, the SD of the children with ADHD was significantly larger than that of the children without ADHD in the older group. The SD of the younger children without ADHD was significantly larger than that of the older group.
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<table>
<thead>
<tr>
<th>Measure</th>
<th>Children with ADHD</th>
<th>Children without ADHD</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>Younger 6-8 10.3</td>
<td>Older 9-12 8.1</td>
<td></td>
</tr>
<tr>
<td>Mean age (years)</td>
<td>Younger 7.8</td>
<td>Older 10.8</td>
<td></td>
</tr>
<tr>
<td>Number of participants</td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>n.s.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 1** Group Comparisons for Choice Reaction Time Task and Stop Task

<table>
<thead>
<tr>
<th>Measure</th>
<th>Children with ADHD</th>
<th>Children without ADHD</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRT for correct responses (ms)</td>
<td>582.87 488.41</td>
<td>524.70 441.28</td>
<td>n.s.</td>
</tr>
<tr>
<td>Mean SD of MRT (ms)</td>
<td>181.96 148.93</td>
<td>114.85 87.58</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>rate of commissions (%)</td>
<td>9.25 9.20</td>
<td>2.34 1.43</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>rate of omissions (%)</td>
<td>1.38 0.70</td>
<td>0.27 0.21</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>younger, older: ADHD&gt;controls</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>younger, elder: ADHD&gt; controls</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Choice reaction time task

**Note.** RT= reaction time; SD= standard deviation; MRT= mean reaction time.

As a significant difference between tasks, the SD for the stop task was larger than that for the choice reaction time task in the older group of children with ADHD, as well as the younger and older groups of children without ADHD.

**Rate of Errors of Commission and Omission**

The ANOVA conducted on the rate of errors of commission on both tasks revealed a significant main effect for group \( F(1, 78)=49.053, p<.01 \) (Fig. 2). The rate of errors of commission in the group of children with ADHD was higher than that of the children without ADHD. The ANOVA conducted on rate of errors of omission on both tasks showed a significant main effect for group \( F(1, 78)=12.146, \)
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The rate of errors of omission by the children with ADHD was higher than that of the children without ADHD. Multiple comparison tests revealed that errors of omission on the stop task were significantly greater than on the choice reaction time task in the younger groups; the younger group made more errors of omission on the stop task than did the older group.

**Probability of Inhibition**

The ANOVA conducted on the probability of inhibition revealed a significant main effect for age \([ F(1, 78)=3.968, \ p<.05] \) and condition \([ F(2, 156)=107.315, \ p<.01] \), and an interaction of age with condition \([ F(2, 156)=3.326, \ p<.05] \) (Fig. 3).

Multiple comparison tests showed the following results: The probability of inhibition of the older groups was significantly higher than that of the younger groups in the condition of 250 ms and 100 ms before the mean reaction time on the choice reaction time task. In the younger and older groups, the probability of inhibition on 250 ms was significantly higher than for 0 ms. In the older group, the

![Diagram](image-url)

**Fig. 2** Rate of Errors of Commission, Comparing Children With and Without ADHD on Both Tasks
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probability of inhibition in the 250 ms condition was significantly higher than for 100 ms, and the probability of inhibition for 100 ms was higher than for 0 ms. However, there were no differences between the children with and without ADHD, regardless of ages.

Relation Between the Differences in Mean Reaction Time and Probability of Inhibition

The result of the MANCOVA indicated a significant difference in the mean reaction time [Wilks lambda, $F=89.275$, $p<.01$], and an interaction between group and the difference in mean reaction time [Wilks lambda, $F=4.411$, $p<.01$].

Discussion

The present study revealed developmental changes and characteristics of children with ADHD, using the stop-signal task with a modified procedure for determining the timing of the stop signal.

Developmental Changes

We investigated whether the performance of the children with ADHD changed with age compared to children without ADHD. The mean reaction time to a go signal in the groups of children with ADHD decreased with age, as did the control children in the choice reaction time task. On the other hand, the variability in mean reaction

**FIG. 3** Probability of Inhibition, Comparing Children With and Without ADHD on Each Condition of Onset of the Stop Signal

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time was large in the group of children with ADHD, and most of the children with ADHD did not respond constantly. Also, the children with ADHD were not able to respond correctly, overlooked the go signals, and made many errors regardless of age. The number of errors of omission in both groups increased in the stop task. We assume that many of these errors were related to impulsivity and inattention on the choice reaction time task without stop signals. This finding was indicated by an analysis of the errors on the continuous performance test (e.g., Corkum & Siegel, 1993), and was characterized as part of the ADHD syndrome. When participants were instructed to stop their response to go signals, some of them forgot to push the buttons, deliberately ceased from responding to the go signals, or missed the go signals.

The children, particularly in the groups with ADHD, had difficulty responding to go signals correctly when they were presented go and stop signals concurrently on the stop task. These results might be related to the following findings: children with ADHD have difficulty in inhibiting responses to irrelevant stimuli (Brodeur & Pond, 2001), and have problems with motor control that is concerned with orienting attention to distinguish the relevancy of stimuli (Brandeis, van Leeuwen, Rubia, Vitacco, Steger, Pascual-Marqui, & Steinhausen, 1998; Okazaki et al., 2004). Thus, the difficulty in executing responses, which appeared as errors of commission and omission, may result from the dysfunction in orienting attention that is associated with ADHD.

According to the results on the probability of inhibition, the children with ADHD had difficulty in inhibiting their responses compared to same-age controls. Furthermore, developmental changes in inhibitory control in children with ADHD are slower than that in children without ADHD.

Thus, we suggest that the response inhibition of children with ADHD improves with age, the same as it does in children without ADHD. However, the children with ADHD did show more low performances than the controls participants from six to twelve years of age. These results suggest that it is necessary to examine not only developmental changes but also other components.

**Performance on the Modified Stop-Signal Task**

On the modified stop-signal task, the timing of the stop signal was determined by the individual mean reaction time. The following two points are the characteristics of this task. First, the interval of the onset of the go and stop signals was shorter than in the original stop-signal task. In the original stop-signal task, it has been evident that children with ADHD have difficulty in stopping their responses (Oosterlaan et al., 1998; Rubia et al., 1998). Our results did not correspond with these previous studies; that is, the children with ADHD inhibited the response just as the children without ADHD did. We assume that this result was related to the timing of the stop signal. In this task, it was easy for participants to stop their responses because the intra-individual timing was constant, and the interval between the onset of the go and stop signals was short. As for the effect of the interval, Logan (1994) indicated that
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the probability of inhibition is high when the interval is short.

Second, in our task, the timing of the stop signals was based on individual reaction times and related to the speed of their responses. As participants were able to predict the occurrence of the stop signals by using their reaction time, we suppose that they were able to stop their response to the go signals by waiting for the onset of the stop signals. According to the reports from the participants, many of the children without ADHD waited for the onset of the stop signal as a strategy.

We attempted to relate inhibitory control to these strategies. However, we found that many children with ADHD were not able to effectively use the strategy of waiting for the stop signal. That is, children with ADHD, who have an inhibitory control deficit, were not able to predict the onset of the stop signals and had difficulty in inhibiting their responses. Schachar and Logan (1990) indicated that the development of inhibitory control results from increasing awareness of strategies.

It is said that children with ADHD are not good at planning the next behavior or at using anticipation effectively. Children with ADHD are not able to use effectively the anticipatory function (Perchet et al., 2001). However, we suggest that some of children, including those with ADHD, were able to use deliberate waiting strategies to stop their response to the go signals under particular conditions. By their awareness of the timing of the stop signals, they might prepare their response to the signals and inhibit prepotent responses.

Thus, it is important to clarify in more detail the relation between inhibitory control and strategies in this stop-signal task. If we know how children with ADHD can utilize waiting strategies, we can give them appropriate instructions for effective timing in their daily life.

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References


Brandeis, D., van Leeuwen, T. H., Rubia, K., Vitacco, D., Steger, J., Pascual-Marqui, R.
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