Training and Transfer Effects of Real-Time Feedback-Based Response Inhibition Training on Executive Function in Adolescents and Adults

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Abstract

This study employed the Stop Signal paradigm with immediate feedback as the training task to investigate whether three weeks of training would produce training and transfer effects on executive function in adolescents and adults. Training effects were observed in the adolescent experimental group, adult experimental group, and active control group. Both experimental groups demonstrated transfer effects to the response inhibition Go/No-go task; however, only the adolescent experimental group exhibited transfer effects to the interference inhibition Stroop task. The adult experimental group and active control group both showed transfer effects to the 2-back task; yet only the adolescent experimental group displayed transfer effects on both 2- and 3-back tasks. No group achieved transfer to reasoning ability. The study demonstrates that from adolescence through adulthood, immediate feedback-based response inhibition training can produce training and transfer effects on executive function, but transfer is restricted to basic components such as inhibition and working memory, without improving reasoning ability.

Full Text

Training and Transfer Effects of Response Inhibition Training with Immediate Feedback on Executive Function in Adolescents and Adults

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Abstract

This study employed the Stop Signal paradigm with immediate feedback as a training task to examine whether three weeks of training would produce training effects and transfer effects on executive function in both adolescents and adults. The results revealed training effects in both experimental groups and the active control groups for adolescents and adults. Both experimental groups demonstrated transfer effects to the response inhibition Go/No-go task; however, transfer to the interference inhibition Stroop task was observed only in the adolescent experimental group. Both the adult experimental group and adult active control group showed transfer to the 2-back task, while transfer to both 2-back and 3-back tasks was found only in the adolescent experimental group. No group exhibited transfer to reasoning ability. The study demonstrates that from adolescence to adulthood, response inhibition training based on immediate feedback can produce training and transfer effects on executive function, but such transfer is limited to basic components such as inhibition and working memory, with no improvement in reasoning ability.

Keywords: response inhibition training; executive function; adolescents; immediate feedback

Executive function (EF) develops rapidly during adolescence and earlier developmental stages and serves as a strong predictor of both short-term achievements (e.g., academic performance) and long-term outcomes (e.g., health, career success, socioeconomic status), with predictive power that even exceeds traditional intelligence factors (Moffitt et al., 2011). Executive function represents a functional structure essential for problem-solving psychological processes, enabling individuals to coordinate various resources and control systems to complete diverse processing tasks when performing complex cognitive operations (Diamond, 2013). It comprises three main components: inhibition, working memory, and cognitive flexibility (Miyake et al., 2000). Reasoning, planning, and problem-solving are considered higher-level, integrative indicators of executive function (Diamond, 2013). Currently, research on executive function training and its plasticity has gained considerable momentum. Diamond and colleagues reviewed executive function training studies and identified six primary training approaches: computer-based training, computer and non-computer mixed games, martial arts and mindfulness practices, classroom instruction, classroom instruction supplements, and physical exercise (Diamond & Lee, 2011). Among these, computer-based training represents an early-developed and fruitful intervention approach. Studies employing working memory, particularly updating tasks, as training protocols have demonstrated strong transfer effects to executive function and even fluid intelligence (Melby-Lervåg et al., 2017). In contrast, research on inhibition and cognitive flexibility training remains relatively scarce, with inhibition training particularly showing few transfer effects (Enge et al., 2014; Zhao, Chen, & Maes, 2018; Zhao & Jia, 2019).

Some studies have found that both children and adolescents exhibit transfer effects following inhibition training, with no differences between these age groups (Johnstone, Dimoska, Smith, & Barr, 2007). Zhao et al. (2018), however, found that child trainees showed larger transfer effects compared to adult groups. These findings support the compensation model, which posits that cognitive training effects are negatively correlated with individuals' baseline performance levels. Given that training effects have certain thresholds, higher baseline levels typically imply less room for improvement and lower plasticity (Gaultney, Bjorklund, & Goldstein, 1996; Karbach & Kray, 2010). Nevertheless, inferring differential transfer effects between adolescent and adult inhibition function training from these results carries risks, as such comparisons bypass adolescence and directly compare children with adults. From childhood to adolescence, individuals' neural fiber myelination and frontal cortex continue developing (Diamond, 1985; Diamond & Baddeley, 1996; Eriksen & Eriksen, 1974; Stroop, 1935). Although children' s inhibition develops rapidly before age 6, completing most inhibition-related tasks remains difficult for them (Dowsett & Livesey, 2015). This creates a dilemma when directly comparing children and adults: either selecting tasks appropriately difficult for children but producing ceiling effects in adults, or choosing tasks suitable for adults but yielding floor effects in children. Inhibition during childhood primarily involves qualitative changes, such as understanding task rules and concepts, whereas during adolescence it manifests mainly as quantitative changes, such as gradually enhanced effective inhibition (Best & Miller, 2010). By early adulthood, inhibition function matures and stabilizes (Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Therefore, training and transfer tasks for children should be less difficult than those for adolescents and adults, while adolescents and adults can use relatively uniform tasks (Anderson, 2002)—a consideration lacking in existing comparative studies (Johnstone et al., 2007; Zhao & Jia, 2019). Consequently, this study represents the first direct comparison of whether adolescents and adults exhibit training and transfer effects on executive function following inhibition training.

The prerequisite for selecting which inhibition function to train is that this inhibition function shows developmental differences between adolescent and adult stages. However, no consistent conclusion has been reached regarding whether adolescents possess the same response inhibition capacity as children or whether their plasticity approximates that of adults. According to dimensional overlap theory, stimulus conflict refers to similarity between task-relevant and task-irrelevant stimuli, with tasks inhibiting such conflict classified as interference inhibition tasks (e.g., Stroop and Flanker tasks). Response conflict involves similarity between task-relevant stimulus sets and responses (Kornblum, 1992; Kornblum, Hasbroucq, & Osman, 1990; Kornblum, Stevens, Whipple, & Requin, 1999), with tasks inhibiting response conflict classified as response inhibition tasks (e.g., Simon task). Jongen and Jonkman (2008) noted that 6-7-year-old children can complete interference inhibition tasks, whereas 10-12-year-old children still make numerous errors on response inhibition tasks, suggesting that stimulus conflict mechanisms mature earlier than response conflict mechanisms, which may not mature until adolescence or even early adulthood. Another researcher found that 5-year-old children show conflict adaptation effects in Simon and Stroop tasks but not in Flanker tasks (Ambrosi, Lemaire, & Blaye, 2016). Ambrosi, Servant, Blaye, and Burle (2019) further demonstrated through distribution analyses that 5-6-year-old children complete three conflict tasks (Flanker, Simon, Stroop) using mechanisms similar to adults, albeit with different time courses. Liu, Liu, Shangguan, Liu, and Shi (2018) investigated conflict adaptation effects in stimulus and response conflicts among children, finding minimal age-related differences in Flanker task performance across 5-year-olds, 10-year-olds, and college students, whereas 5-year-olds showed significantly smaller conflict adaptation effects in Simon tasks compared to 10-year-olds and college students. This indicates that brain mechanisms for stimulus conflict are relatively mature by age 5, while response conflict mechanisms remain immature during childhood and may not mature until early adulthood. Therefore, comparing the plasticity of interference inhibition capacity between adolescents and adults can help explore the potential maturation stage of interference inhibition ability.

Rueda, Rothbart, Mccandliss, Saccomanno, and Posner (2005) used a training task set including interference control tasks and found that five days of training could transfer to reasoning abilities in 4-6-year-old children. However, such multi-task training studies (Denckla, 1996) cannot determine which training task or cognitive function produces transfer effects. Moreover, multi-task training does not necessarily yield better training or transfer effects. Thorell, Lindqvist, Nutley, Bohlin, and Klingberg (2009) simultaneously used interference inhibition and response inhibition training and found no transfer effects. Increasingly, researchers do not advocate using multiple training tasks or complex training paradigms (Diamond & Ling, 2015; Friedman & Miyake, 2004; Shilling, Chetwynd, & Rabbitt, 2002), as these approaches often result in insufficient dosage of pure inhibition function training, and interactions among multiple tasks and cognitive components make it difficult to identify the source of transfer effects. Currently, studies using single interference inhibition tasks as training protocols are relatively common. For instance, Zhao et al. (2018) found transfer effects from Stroop training to multiple executive function components and reasoning, though some studies have found no transfer effects (Strobach, Salminen, Karbach, & Schubert, 2014). The Stroop task process involves inhibiting dominant responses (semantic information processing) while completing task-relevant information (color) processing (Verbruggen, Liefooghe, & Vandierendonck, 2004), which shares similarities with the process of suppressing dominant responses in the Stop Signal task. Both tasks also share brain regions such as the right dorsolateral prefrontal cortex (right DLPFC) and anterior cingulate cortex (ACC) during response selection stages (Nee, Wager, & Jonides, 2007), providing a basis for transfer from Stroop task training to other inhibition tasks. The inhibitory function of interference inhibition for competing distracting stimuli shares mechanistic consistency with the updating function in working memory N-back tasks (Zhao & Jia, 2019), which may constitute the functional basis for Stroop task transfer to executive function components including working memory and reasoning. However, these conclusions may also lead to an alternative hypothesis: that Stop Signal task training, which shares similar processing with Stroop and Go/No-go tasks in suppressing irrelevant responses, would similarly produce training and transfer effects on executive function.

Logan and Cowan (1984) used the Stop Signal task as a training protocol and found clear training effects after six hours of training but no transfer effects. This conclusion was also verified in training studies with obese populations (Guerrieri, Nederkoorn, & Jansen, 2008). One possible reason for the absence of transfer effects is that during training, stimulus-response associations continuously change, and the negative reinforcement from unsuccessful inhibition trials may hinder the development of automatic inhibition, thereby preventing improvement in inhibition capacity (Spierer, Chavan, & Manuel, 2013). Another possibility is excessive emphasis on response speed at the expense of stop trial accuracy, leading to suboptimal task performance. In fact, accuracy serves as a fundamental indicator ensuring participants attend to stop trial correctness in both stop and go trials. Focusing solely on speed while neglecting accuracy may reflect lower inhibition levels or ineffective inhibition training (Enge et al., 2014). According to reinforcement theory, individuals should be immediately informed whether their responses are correct. If correct, immediate feedback acts as a reinforcer; if incorrect, it serves as a corrective measure. Thus, feedback immediacy can enhance reinforcement effectiveness (Melanko & Larkin, 2013). It can be argued that adding feedback between training trials can efficiently reinforce and solidify associations (Littman & Michael, 2015; Mnih et al., 2015). Additionally, inter-trial immediate feedback helps individuals manage the speed-accuracy tradeoff (Kohls, Peltzer, Herpertz-dahlmann & Konrad, 2010; Leotti & Wager, 2010). Incorporating feedback during training not only helps individuals understand current performance to adjust subsequent response strategies but also functions as a reinforcer, making individuals more inclined to produce correct responses and attend more closely to accuracy. Therefore, this study introduced an immediate feedback step in adolescent and adult training groups while having active control groups train on the Stop Signal task without feedback, examining whether Stop Signal task training with immediate feedback produces training and transfer effects.

In summary, to investigate the training and transfer effects of response inhibition training on executive function from adolescence to adulthood, this study used the immediate feedback-based response inhibition task—Stop Signal paradigm—as the training protocol. We measured whether training and transfer effects occurred in adolescents and adults across executive function components including response inhibition (Go/No-go task), interference inhibition (Stroop task), working memory (N-back task), and reasoning, and whether these effects differed by age.

2.1 Participants

We recruited 150 adult participants and 60 adolescent participants from one university and one middle school in Jilin Province. The adult sample consisted of 65 males and 85 females with a mean age of 20.55 ± 0.79 years. The adolescent sample comprised 34 males and 26 females with a mean age of 15.1 ± 0.30 years. All participants were right-handed with normal or corrected-to-normal vision, had not participated in similar psychological experiments within the past six months, and volunteered for the study. Participants or their guardians signed informed consent forms before the experiment began. All participants received 10 RMB per session or equivalent small stationery items as compensation after completing the experiment. Adult participants were randomly assigned to adult experimental, adult active control, and passive control groups. Sixteen adult participants failed to complete the experiment due to withdrawal or personal reasons (5 from the experimental group, 3 from the active control group, and 8 from the passive control group), resulting in final effective sample sizes of 47 in the adult experimental group, 45 in the adult active control group, and 42 in the passive control group. Adolescent participants were randomly assigned to adolescent experimental (30 participants) and adolescent active control (30 participants) groups.

2.2.1 Stop Signal Task

We adapted the classic Stop Signal task (Verbruggen & Logan, 2008) for use as both the training task and a response inhibition measure. A fixation point (plus sign "+") appeared at the center of the computer screen for 500 ms, followed by a white arrow pointing in any direction as the go stimulus (left and right directions appeared randomly with equal frequency) for 1000 ms. Participants were required to identify the target stimulus type and make a key press response, pressing the "F" key for left-pointing arrows and the "J" key for right-pointing arrows. In stop trials, participants were required to inhibit their impulse to respond when the stop signal (a small blue triangle above the arrow) appeared and withhold any response. All trials within each block were presented in a completely random order. Task difficulty increased adaptively: the time interval between arrow onset and triangle onset (stop signal delay, SSD) adjusted based on performance in the previous stop trial. To ensure stimulus identification effectiveness, the SSD varied between 250–750 ms, increasing by 50 ms following a correct response and decreasing by 50 ms following an incorrect response. The experimental group differed from the active control group in that immediate feedback was added to the experimental group procedure; after each trial, participants' reaction time and response accuracy for that trial were displayed at the center of the screen. The task included 32 practice trials and four experimental blocks, each containing 100 trials. The specific procedure is illustrated in Figure 1 [Figure 1: see original paper]. This study used two indicators to represent task performance: (1) SSRT—calculating the average stop signal delay (SSD) between each response stimulus and stop signal, then subtracting the mean SSD from the go reaction time to obtain each participant' s stop signal reaction time (SSRT). Longer SSRT indicates poorer response inhibition ability. (2) Stop trial accuracy.

2.2.2 Go/No-go Task

This task served as a measure of response inhibition. Task stimuli consisted of white digits (1-9). A fixation point "+" appeared at the center of the computer screen for 500 ms, followed by a randomly selected digit from 1-9 for 1000 ms (the digit "3" and other digits each accounted for 25% and 75% of total presentations, respectively). Participants were instructed to withhold responses when seeing the digit "3" and press the spacebar for all other digits. All trials within each block were presented in a completely random order. The task comprised four blocks, each containing 32 practice trials and 100 experimental trials. This study used three indicators to represent task performance: (1) Go trial reaction time; (2) No-go trial accuracy; and (3) d' .

2.2.3 Stroop Task

This task served as a measure of interference inhibition. Task stimuli consisted of color words ("red," "green," "yellow," "blue") printed in different colors. A white fixation point "+" appeared at the center of the computer screen for 500 ms, followed by a color word for 1000 ms. Participants were required to identify the ink color (press "R" for red, "F" for green, "U" for yellow, and "J" for blue). In congruent trials, the word meaning matched the ink color; in incongruent trials, the word meaning and ink color differed. Congruent and incongruent trials accounted for 75% and 25% of total trials, respectively. The experiment consisted of four blocks, each containing 36 practice trials and 100 experimental trials. This study used the Stroop effect (reaction time difference between incongruent and congruent trials) to represent task performance.

2.2.4 N-back Task

The N-back task served as a measure of working memory updating ability and a far-transfer indicator. Task stimuli consisted of uppercase English letters (A-Z). A fixation point "+" appeared for 500 ms, followed by a randomly presented English letter. Participants were required to judge the current letter based on previously presented letters. In match trials, the currently presented letter matched the letter presented n steps earlier, requiring a "F" key response; in non-match trials, the letters differed, requiring a "J" key response. The task comprised two blocks—2-back and 3-back—requiring participants to judge current letters based on letters presented 2 or 3 steps earlier, respectively. Each block included 20 practice trials and 100 experimental trials. Task performance was represented by accuracy.

2.2.5 Raven’ s Standard Progressive Matrices

We used Raven’ s Standard Progressive Matrices (Raven, Raven, & Court, 2000) as a measure of reasoning ability, representing an integrative indicator of executive function and a far-transfer measure. This non-verbal test requires participants to select the missing portion of a figure from options based on given patterns. The test contains 60 items total, divided into pre-test and post-test versions. The pre-test included odd-numbered items from sets A, C, and E and even-numbered items from sets B and D (30 items total); the post-test included even-numbered items from sets A, C, and E and odd-numbered items from sets B and D (30 items total). Performance was measured by accuracy.

2.3 Procedure

This study consisted of three phases: pre-test, training, and post-test. During pre- and post-test phases, inhibition tasks (Stop Signal, Go/No-go, Stroop), working memory tasks (N-back), and Raven’ s Standard Progressive Matrices were administered in random order. To avoid fatigue effects, testing was divided across two days. During the training phase, experimental and active control groups completed Stop Signal task training three times per week for three weeks. The experimental group received immediate feedback during training, while the active control group did not. Training consisted of eight blocks per session, with each block containing 100 trials.

2.4 Apparatus

We used E-prime 2.0 software to program and run experimental procedures and record participant responses. Task stimuli were presented on a desktop computer with an 18.5-inch Dell E1916HM monitor (screen resolution: 1366$×$768, refresh rate: 60 Hz). Participants were seated approximately 60 cm from the display and completed the experiment individually in a moderately lit, quiet laboratory environment.

2.5 Data Analysis

We conducted data analysis using SPSS 22.0 software. Test scores were standardized, and repeated measures ANOVA was used to explore training improvements and transfer effects. Trials with incorrect responses or reaction times exceeding 4000 ms, as well as trials with reaction times less than 200 ms or exceeding three standard deviations in other tasks, were excluded or replaced with mean values.

3.1 Training Process and Training Effects

Table 1 presents descriptive statistics for daily Stop Signal task training effects across the four training groups. A 9 (training sessions 1–9) × 2 (group: experimental, active control) × 2 (age: adolescent, adult) repeated measures ANOVA revealed significant main effects of age group (SSRT: F(1,43) = 104.05, $p < 0.001$, $p^2 = 0.41$; accuracy: F(1,43) = 27.39, $p < 0.001$, $p^2 = 0.416$), indicating that adults had faster SSRT and higher accuracy than adolescents. The main effect of training session was also significant (SSRT: F(8,405) = 19.78, $p < 0.001$, $p^2 = 0.12$; accuracy: F(8,405) = 91.36, $p < 0.001$, $p^2 = 0.38$), meaning both groups showed improved SSRT and accuracy as training progressed. The three-way interaction among age group, group, and training session was significant (SSRT: F(3,148) = 4.97, $p < 0.05$, $p^2 = 0.33$; accuracy: F(3,148) = 8.04, $p < 0.01$, $p^2 = 0.23$), suggesting that adolescent and adult experimental and active control groups showed different patterns of change across training sessions. Therefore, we conducted separate 9 (training sessions 1-9) × 2 (group: experimental, active control) repeated measures ANOVAs for adolescent and adult groups. In the adult group, a significant interaction emerged (SSRT: F(1,8) = 4.19, $p < 0.05$, $p^2 = 0.04$; accuracy: F(1,8) = 32.37, $p < 0.001$, $p^2 = 0.27$), indicating improvement across training sessions. The adolescent group also showed significant interactions between group and training session (SSRT: F(1,8) = 26.52, $p < 0.001$, $p^2 = 0.31$; accuracy: F(1,8) = 123.49, $p < 0.001$, $p^2 = 0.68$), with no significant performance differences between experimental and active control groups during sessions 1-4, but significant differences emerging during sessions 5-9. Thus, the performance gap between adult experimental and active control groups, as well as between adolescent experimental and active control groups, gradually widened over the training course.

3.2 Transfer Effects

Pre-test and post-test results are detailed in Table 2 . We conducted separate 2 (measurement time: pre-test, post-test) × 5 (group: adolescent experimental, adolescent active control, adult experimental, adult active control, passive control) repeated measures ANOVAs for each task indicator, with results as follows:

3.2.1 Response Inhibition Task–Go/No-go Task We performed repeated measures ANOVAs on Go/No-go task reaction time, accuracy, and d' . Analysis of reaction time revealed a significant main effect of measurement time (F(1,189) = 24.09, $p < 0.001$, $p^2 = 0.11$). Post-hoc comparisons showed shorter reaction times in the post-test phase than in the pre-test phase. The interaction between measurement time and group was significant (F(4,189) = 3.35, $p < 0.05$, $p^2 = 0.66$). Simple effects tests revealed that only the adult experimental group and adolescent experimental group showed improved reaction speed on the Go/No-go task, while the other three groups showed no improvement.

Analysis of accuracy revealed significant main effects of measurement time (F(1,189) = 49.68, $p < 0.001$, $p^2 = 0.21$) and group (F(1,4) = 18.88, $p < 0.001$, $p^2 = 0.29$), with a significant interaction between the two (F(4,189) = 12.34, $p < 0.001$, $p^2 = 0.21$). Simple effects tests indicated that only the adult experimental group and adolescent experimental group showed improved accuracy, with no differences between pre-test and post-test for the other three groups.

Repeated measures ANOVA on d’ also revealed significant main effects of measurement time ($F(1,189) = 16.04$, $p < 0.001$, $p^2 = 0.08$) and group ($F(1,4) = 19.00$, $p < 0.001$, $p^2 = 0.29$), with a significant interaction ($F(4,189) = 22.63$, $p < 0.001$, $p^2 = 0.32$). Further simple effects tests showed that all groups except the adult active control group demonstrated significantly better post-test than pre-test d’ scores.

Collectively, these three indicators demonstrate that response inhibition training with feedback produced clear improvements on Go/No-go task performance for both adults and adolescents.

3.2.2 Interference Inhibition Task–Stroop Task Repeated measures ANOVA on Stroop effects revealed no significant main effect of measurement time or interaction between measurement time and group, but a significant main effect of group ($F(1,4) = 12.17$, $p < 0.001$, $p^2 = 0.21$). Further post-hoc comparisons showed no differences among adult experimental, adult active control, and passive control groups, indicating that training produced no transfer effects on Stroop effects in adult groups. The adolescent experimental group outperformed the adolescent active control group, passive control group, and both adult groups, demonstrating that response inhibition training with feedback produced clear transfer effects on interference inhibition performance only in adolescents.

3.2.3 Working Memory Updating Task–N-back Task We examined accuracy in 2-back and 3-back tasks through repeated measures ANOVA. In the 2-back task, main effects of measurement time ($F(1,189) = 69.90$, $p < 0.001$, $p^2 = 0.27$) and group ($F(1,4) = 53.37$, $p < 0.001$, $p^2 = 0.54$) and their interaction ($F(4,189) = 15.82$, $p < 0.001$, $p^2 = 0.25$) were all significant. Simple effects tests indicated significant pre-test to post-test improvements in the adult experimental group, adult active control group, and adolescent experimental group. Thus, for adults, response inhibition training produced transfer effects on 2-back accuracy regardless of feedback presence, whereas for adolescents, only training with feedback improved their 2-back performance.

In the 3-back task, main effects of measurement time ($F(1,189) = 26.49$, $p < 0.001$, $p^2 = 0.12$) and group ($F(1,4) = 58.25$, $p < 0.001$, $p^2 = 0.55$) were significant, but the interaction was not. Post-hoc comparisons showed significantly better post-test than pre-test performance. No differences emerged among adult experimental, adult active control, and passive control groups, while the adolescent experimental group outperformed all other groups and the adolescent active control group outperformed the passive control group. Thus, in the 3-back task, response inhibition training with feedback produced transfer effects only in adolescents.

3.2.4 Raven' s Standard Progressive Matrices We administered Raven' s Standard Progressive Matrices to adolescents and adults during both measurement sessions and conducted a 2 (measurement time: pre-test, post-test) × 5 (group: adolescent experimental, adolescent active, adult experimental, adult active, passive control) repeated measures ANOVA. No significant effects emerged for measurement time ($F(1,189) = 0.43$, $p = 0.51$, $p^2 = 0.01$), group ($F(1,4) = 2.5$, $p = 0.12$, $p^2 = 0.03$), or their interaction ($F(4,189) = 0.01$, $p = 0.001$, $p^2 = 0.91$), indicating that training produced no transfer to fluid intelligence.

Following 27 sessions of Stop Signal task training over three weeks, this study found that Stop Signal training with immediate feedback produced training effects in both adolescents and adults. Both age groups showed near transfer to the response inhibition Go/No-go task and far transfer to working memory, but no improvement in Raven' s Standard Progressive Matrices accuracy. Adolescents also demonstrated near transfer to the interference inhibition Stroop task, whereas adults showed no transfer on this task. The results support the conclusion that Stop Signal task training can improve executive function (Johnstone et al., 2007), but transfer is influenced by both age-related differences in cognitive plasticity and task characteristics. Performance changes in tasks showing transfer effects are illustrated in Figure 3 [Figure 3: see original paper].

This study demonstrates differential training and transfer effects of inhibition function between adolescents and adults, corroborating indirect conclusions from Johnstone et al. (2007) and Zhao et al. (2018) while partially supporting previous findings of no transfer effects in adults following this training (Enge et al., 2014). These results align with developmental evidence regarding the relationship between prefrontal cortex maturation and inhibition function (Diamond, 1985; Diamond & Baddeley, 1996) and behavioral evidence (Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001). According to Best and Miller' s (2010) analysis, inhibition function development during adolescence occurs as quantitative change, with early adulthood as the turning point. Our results enrich this perspective: the so-called quantitative change is relative to the rapid change rate in childhood, but in fact, the quantitative change in adolescence addresses the effectiveness of inhibition, whereas childhood development addresses the ability to inhibit or not. The continuous development of inhibition function during adolescence directly promotes top-down changes in executive function-related cognitive processes. The results support the compensation model perspective: the adolescent group showed lower baseline accuracy in training tasks than the adult group (see Table 2), and their improvement following training was significantly greater than that of adults (Gaultney, Bjorklund & Goldstein, 1996; Karbach & Kray, 2010).

Following training, we found transfer effects to the Go/No-go task in both adolescents and adults, supporting Enge et al.' s (2014) adult training results. The essence of the Stop Signal task involves competition between processing current task stimuli and stop signal-triggered stopping processes. The comparison between response time for task stimulus processing and the sum of stop signal delay and stop signal reaction time directly determines whether a response is executed or inhibited (Logan, 1984). Combined analysis of training progress and immediate feedback data shows clear improvements in both SSRT and accuracy, indicating that training enhanced individuals' speed-accuracy tradeoff, yielding faster speeds and lower false alarm rates. Such improvement more easily transfers to Go/No-go tasks, which similarly require speed-accuracy tradeoff between two stimulus types. The Go/No-go task requires individuals to respond quickly to Go stimuli while withholding responses to No-go stimuli; thus, shorter Go stimulus reaction times and lower No-go stimulus false alarm rates represent performance improvements, also requiring good speed-accuracy tradeoff. Furthermore, De Jong et al. proposed that peripheral mechanisms associate with rapid, non-selective inhibition tasks like No-go tasks, whereas stop tasks are constrained by central mechanisms (De Jong, Coles, & Logan, 1995). However, Van Boxtel argued that when stop signal delay duration does not exceed threshold, No-go and stop tasks operate under both central and peripheral mechanisms, with both tasks sharing the same mechanism (Van Boxtel, Van, Jennings, & Brunia, 2001). Therefore, transfer from Stop Signal task improvements to Go/No-go tasks operating under the same mechanism is quite straightforward.

Transfer to the Stroop task was found only in the adolescent group. Both Stroop and Stop Signal tasks involve processing stages of inhibiting dominant responses, which can explain the occurrence of transfer effects. However, the adult group showed no transfer, consistent with Enge et al.' s (2014) adult training results and Wilkinson and Yang' s (2012) findings that Stroop training improved Go/No-go performance. This may relate to the Stroop task' s heavy reliance on selective attention. Similar to Flanker tasks, Stroop tasks require filtering irrelevant distractors to complete responses, except that in Stroop tasks, the distractor and target are different attributes of the same stimulus. Because distractors are processed automatically with high priority, Stroop tasks require greater recruitment of selective attention to filter distractors. Selective attention develops from childhood through adolescence and matures only in adulthood (Brodeur & Pond, 2001; Karatekin, 2004). According to the compensation model (Gaultney, Bjorklund & Goldstein, 1996; Karbach & Kray, 2010), adolescents' relatively lower selective attention shows greater improvement through training than adults' , which may partially explain why adolescents exhibited transfer effects to the Stroop task.

Regarding far-transfer effects on working memory and the integrative indicator of reasoning ability, training successfully improved working memory updating function in both adolescents and adults but failed to improve reasoning ability. In executive function training research, near transfer refers to when training significantly affects performance on tasks measuring the same psychological function as the training task. For example, if spatial working memory span training clearly improves performance on verbal working memory span tasks that also measure working memory span, this constitutes near transfer from spatial to verbal working memory span tasks. Thus, near transfer occurs between functionally similar tasks. Conversely, when training improves performance on tasks measuring other psychological functions—such as inhibition training improving working memory, cognitive flexibility, fluid intelligence, or other non-inhibition components—this is considered far transfer. At the neural level, far transfer occurs when training effects cross domains based on shared neural circuits between training and transfer tasks (Dahlin, 2013; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). At the behavioral level, cognitive functions capable of far transfer should share similar cognitive mechanisms with training tasks (Morrison & Chein, 2011). Studies by Conway, Kane, and Engle (2003) and Gray, Chabris, and Braver (2003) support that executive control mechanisms activate when maintaining and processing information to reduce interference, with concurrent activation of prefrontal cortex regions required for working memory tasks. At the behavioral level, both updating and inhibition require suppressing irrelevant information (Maraver, Teresa, & Gomez-Ariza, 2016). Our results support the inference that these functions share neural substrates and cognitive mechanisms. Although response inhibition and reasoning share common cognitive components, whether transfer effects occur remains controversial (Ji, Wang, Chen, Du, Zhan, & Ji, 2016; Loosli, Falquez, Unterrainer, Weiller, Rahm, & Kaller, 2016). Our study found no transfer effects to reasoning in either group, possibly due to the relatively low correlation between response inhibition and reasoning (Bellaj, Salhi, Le Gall, & Roy, 2015).

The addition of immediate feedback did not change training effects in adults, whereas the adolescent group began showing clear improvements from sessions 5-9. Feedback also influenced transfer effects in adults on Go/No-go and 2-back tasks but did not affect Stroop, 3-back, or Raven' s reasoning test performance. In adolescents, feedback produced differential transfer effects on inhibition and working memory components of executive function, but reasoning performance remained unaffected. These results strongly support the view that feedback can improve speed-accuracy tradeoff (Leotti & Wager, 2010; Kohls et al., 2010). Individuals tend to prolong current task reaction time to successfully execute subsequent stop trials (Boehler, Appelbaum, Krebs, Hopf, & Woldorff, 2012), resulting in decreased SSRT, increased stop trial accuracy, and reduced response speed (Leotti & Wager, 2010). Feedback information as a reinforcer can induce immediate emotions, which then regulate subsequent goal-directed behavior through interactions between top-down control systems and approach-avoidance motivational systems (Hare & Casey, 2005). Adolescents are more sensitive to feedback than adults, related to their greater sensitivity to emotional signals in goal-directed attention tasks (Monk et al., 2003), with children and adolescents showing stronger emotional biases toward motivational information. In this study, feedback more readily enabled adolescents to adjust speed-accuracy tradeoff and strategically pursue higher accuracy (see Figure 2, changes in stop trial accuracy during training). This supports Enge' s (2014) inference that the lack of transfer effects in Stop Signal training may result from individuals overly pursuing speed at the expense of accuracy. Consistent with reinforcement theory, immediate feedback provides better reinforcement, strengthening correct responses and allowing timely correction of errors. Therefore, this study added immediate feedback after each trial to increase participants' attention to accuracy, enabling them to monitor their performance after each trial and make better decisions for subsequent responses.

This study used a single training task—the response inhibition Stop Signal paradigm—to compare adolescents and adults performing identical executive function operations, finding that adolescents benefited more from response inhibition training. The results supplement developmental trends in inhibition training effects on executive function, directly verifying the view that adolescence benefits more from inhibition training than adulthood, and demonstrating that the fundamental prerequisite for effective inhibition training is that trainees should be in pre-adult developmental stages. In selecting training tasks, this study chose the response inhibition task with relatively fewer "cognitive components," demonstrating that even training tasks that create conflict and inhibition only at the behavioral level can improve individuals' higher cognitive functions during periods of strong brain plasticity. However, improvements are limited to basic factors such as inhibition and working memory due to similarities in cognitive mechanisms and activated brain structures between training and transfer tasks. For higher-level integrative reasoning ability, the training difficulty remains insufficient. The study demonstrates that both interference inhibition and response inhibition tasks can serve as training protocols, but response inhibition tasks produce relatively narrow transfer effects. The findings that immediate feedback can enhance training and transfer effects demonstrate that motivational and emotional factors play powerful roles in cognitive training, suggesting that future training programs should incorporate immediate feedback as a fundamental component to effectively improve training outcomes.

Several limitations must be acknowledged. First, this study only compared two non-continuous age groups—mid-adolescence and early adulthood—lacking early adolescence (more similar to childhood) and late adolescence (more similar to adulthood) groups, thus lacking developmental continuity. Future research should enrich studies on continuous developmental trends during the transition from adolescence to adulthood. Second, this study did not measure cognitive flexibility. This omission was based on evidence that task switching paradigms, typical measures of cognitive flexibility, strengthen their function by enhancing updating through segmented rehearsal, with their processing heavily recruiting updating functions (Boot, Kramer, Simons, Fabiani, & Gratton, 2008). If updating function improves, this indirectly demonstrates cognitive flexibility improvement; therefore, to shorten measurement time during pre-test, post-test, and follow-up phases, cognitive flexibility measurement was omitted. Future studies should include this measurement when time and participant energy permit. Third, the immediate feedback in this study appeared only after participants completed a trial and disappeared when entering the next trial, failing to achieve real-time (on-line) feedback effects. Video game training represents an ecologically valid executive function training approach with excellent transfer effects, one of whose prominent advantages is that immediate feedback during gameplay appears continuously alongside tasks through progress bars, timers, and score displays, providing uninterrupted reinforcement. Future research could 借鉴 video game training methods by presenting not only post-trial feedback but also cumulative average reaction times and accuracy for completed trials within each trial, potentially further enhancing training effects.

In conclusion, Stop Signal training with immediate feedback can produce training effects during adolescence and adulthood. Transfer effects are influenced by both age-related differences in cognitive plasticity and task characteristics. Both adolescent and adult groups showed transfer to the response inhibition Go/No-go task and working memory, but no transfer to reasoning ability. Transfer to the interference inhibition Stroop task occurred only in the adolescent group. This study provides recommendations for improving inhibition training research, demonstrating that adding immediate feedback to computerized training can effectively enhance training and transfer effects. The findings supplement developmental trends in inhibition training effects on executive function, directly verifying that adolescence benefits more from inhibition training than adulthood, and suggesting that inhibition training has more formative effects on pre-adult age stages.

References

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology, 8*(2), 71-82.

Anderson, V. A., Anderson, P., Northam, E., Jacobs, R., & Catroppa, C. (2001). Development of executive functions through late childhood and adolescence in an Australian sample. *Developmental Neuropsychology, 20*(1), 385-406.

Ambrosi, S., Lemaire, P., & Blaye, A. (2016). Do young children modulate their cognitive control?: sequential congruency effects across three conflict tasks in 5-to-6 year-olds. *Experimental Psychology, 63*(2), 117-126.

Ambrosi, S., Servant, M., Blaye, A., & Burle, B. (2019). Conflict processing in kindergarten children: new evidence from distribution analyses reveals the dynamics of incorrect response activation and suppression. *Journal of Experimental Child Psychology, 177*(1), 1-18.

Bellaj, T., Salhi, I., Le Gall, D., & Roy, A. (2015). Development of executive functioning in school-age Tunisian children. *Child Neuropsychology, 22*(8), 1-36.

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development, 81*(6), 1641-1660.

Boehler, C. N., Appelbaum, L. G., Krebs, R. M., Hopf, J. M., & Woldorff, M. G. (2012). The influence of different stop-signal response time estimation procedures on behavior-behavior and brain-behavior correlations. *Behavioural Brain Research, 229*(1), 123-130.

Boot, W. R., Kramer, A. F., Simons, D. J., Fabiani, M., & Gratton, G. (2008). The effects of video game playing on attention, memory, and executive control.

Acta Psychologica, 129(3), 387-398.

Brodeur, D. A., & Pond, M. (2001). The development of selective attention in children with attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology, 29*(3), 229-239.

Conway, A. R. A., Kane, M. J., & Engle, R. W. (2003). Working memory capacity and its relation to general intelligence. *Trends in Cognitive Sciences, 7*(12), 547-552.

Dahlin, K. I. E. (2013). Working memory training and the effect on mathematical achievement in children with attention deficits and special needs. *Journal of Education & Learning, 2*(1), 118-133.

De Jong, R., Coles, M. G. H., & Logan, G. D. (1995). Strategies and mechanisms in nonselective and selective inhibitory motor control. *Journal of Experimental Psychology: Human Perception and Performance, 21*(3), 498-511.

Denckla, M. B. (1996). A theory and model of executive function: a neuropsychological perspective. In G. R. Lyon & N. A. Krasnegor (Eds.), *Attention, memory, and executive function* (pp. 263-278). Baltimore, MD: Paul H. Brookes Publishing.

Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on AB. *Child Development, 56*(4), 868-883.

Diamond, A., & Baddeley, A. (1996). Evidence for the importance of dopamine for prefrontal cortex functions early in life [and discussion]. *Philosophical Transactions of the Royal Society B: Biological Sciences, 351*(1346), 1483-1494.

Diamond, A., & Lee, K. (2011). Interventions shown to aid executive function development in children 4 to 12 years old. *Science, 333*(6045), 959-964.

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*(1), 135-168.

Diamond, A., & Ling, D. S. (2015). Conclusions about interventions, programs, and approaches for improving executive functions that appear justified and those that, despite much hype, do not. *Developmental Cognitive Neuroscience, 18*(4), 34-48.

Dowsett, S. M., & Livesey, D. J. (2015). The development of inhibitory control in preschool children: effects of "executive skills" training. *Developmental Psychobiology, 36*(2), 161-174.

Enge, S., Behnke, A., Fleischhauer, M., Küttler, L., Kliegel, M., & Strobel, A. (2014). No evidence for true training and transfer effects after inhibitory control training in young healthy adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(4), 987-1001.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics,* *16*(1), 143-149.

Friedman, N. P., & Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *Journal of Experimental Psychology: General, 133*(1), 101-135.

Gaultney, J. F., Bjorklund, D. F., & Goldstein, D. (1996). To be young, gifted, and strategic: advantages for memory performance. *Journal of Experimental Child Psychology, 61*(1), 43-66.

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience, 6*(3), 316-322.

Guerrieri, R., Nederkoorn, C., & Jansen, A. (2008). The interaction between impulsivity and a varied food environment: its influence on food intake and overweight. *International Journal of Obesity, 32*(4), 708-714.

Hare, T. A., & Casey, B. J. (2005). The neurobiology and development of cognitive and affective control. *Brain and Cognition, 57*(3), 273-286.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences, 105*(19), 6829-6833.

Ji, Y., Wang, J., Chen, T., Du, X., Zhan, Y., & Ji, Y., et al. (2016). Plasticity of inhibitory processes and associated far-transfer effects in older adults. *Psychology and Aging, 31*(5), 415-429.

Johnstone, S. J., Dimoska, A., Smith, J. L., & Barry, R. J. (2007). The development of stop-signal and Go/No-go response inhibition in children aged 7-12 years: performance and event-related potential indices. *International Journal of Psychophysiology, 63*(1), 25-38.

Jongen, E. M. M., & Jonkman, L. M. (2008). The developmental pattern of stimulus and response interference in a color-object Stroop task: An ERP study. *BMC Neuroscience, 9*(1), 1-24.

Karatekin, C. (2004). Development of attentional allocation in the dual task paradigm. *International Journal of Psychophysiology, 52*(1), 7-21.

Karbach, J., & Kray, J. (2010). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science, 12*(6), 978-990.

Kohls, G., Peltzer, J., Herpertz-dahlmann, B., & Konrad, K. (2010). Differential effects of social and non-social reward on response inhibition in children and adolescents. *Developmental Science, 12*(4), 614-625.

Kornblum, S. (1992). Dimensional overlap and dimensional relevance in stimulus-response and stimulus-stimulus compatibility. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 743-777). Amsterdam: North-Holland.

Kornblum, S., Stevens, G. T., Whipple, A., & Requin, J. (1999). The effects of irrelevant stimuli: the time course of stimulus-stimulus and stimulus-response consistency effects with Stroop-like stimuli, Simon-like tasks, and their factorial combinations. *Journal of Experimental Psychology: Human Perception and Performance, 25*(3), 688-714.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility—a model and taxonomy. *Psychological Review, 97*(2), 253-270.

Leotti, L. A., & Wager, T. D. (2010). Motivational influences on response inhibition measures. *Journal of Experimental Psychology: Human Perception and Performance, 36*(2), 430-447.

Littman, K. L., & Michael, L. (2015). Reinforcement learning improves behaviour from evaluative feedback. *Nature, 521*(7553), 445-451.

Liu, X., Liu, T., Shangguan, F., Liu, Q., & Shi, J. (2018). Neurodevelopment of conflict adaptation: evidence from event-related potentials. *Developmental Psychology, 54*(7), 1347-1362.

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: a theory of an act of control. *Psychological Review, 91*(3), 295-327.

Loosli, S. V., Falquez, R., Unterrainer, J. M., Weiller, C., Rahm, B., & Kaller, C. P. (2016). Training of resistance to proactive interference and working memory in older adults: a randomized double-blind study. *International Psychogeriatrics, 28*(3), 453-467.

Maraver, M. J., Teresa, B. M., & Gomez-Ariza, C. J. (2016). Training on working memory and inhibitory control in young adults. *Frontiers in Human Neuroscience, 10*(11), 1-18.

Melanko, S., & Larkin, K. T. (2013). Preference for immediate reinforcement over delayed reinforcement: relation between delay discounting and health behavior. *Journal of Behavioral Medicine, 36*(1), 34-43.

Melby-Lervåg, M., Redick, T. S., & Hulme, C. (2016). Working memory training does not improve performance on measures of intelligence or other measures of "far transfer" : evidence from a meta-analytic review. *Perspectives on Psychological Science, 11*(4), 512-534.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49-100.

Mnih, V., Kavukcuoglu, K., Silver, D., Rusu, A., Veness, J., Bellemare, M., … Hassabis, D. (2015). Human-level control through deep reinforcement learning. *Nature, 518*(7540), 529-533.

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., ···Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences, 108*(7), 2693–2698.

Monk, C. S., Mcclure, E. B., Nelson, E. E., Zarahn, E., Bilder, R. M., Leibenluft, E., ···Pine, D. S. (2003). Adolescent immaturity in attention-related brain engagement to emotional facial expressions. *Neuroimage, 20*(1), 420–428.

Morrison, A. B., & Chein, J. M. (2011). Does working memory training work? the promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin & Review, 18*(1), 46–60.

Nee, D. E., Wager, T. D., & Jonides, J. (2007). Interference resolution: insights from a meta-analysis of neuroimaging tasks. *Cognitive, Affective & Behavioral Neuroscience, 7*(1), 1–17.

Raven, J., Raven, J. C., & Court, J. H. (2000). *Standard progressive matrices.* Oxford: Psychology Press.

Rueda, M. R., Rothbart, M. K., Mccandliss, B. D., Saccomanno, L., & Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the National Academy of Sciences, 102*(41), 14931–14936.

Shilling, V. M., Chetwynd, A., & Rabbitt, P. M. A. (2002). Individual inconsistency across measures of inhibition: an investigation of the construct validity of inhibition in older adults. *Neuropsychologia, 40*(6), 605–619.

Soveri, A., Antfolk, J., Karlsson, L., Salo, B., & Laine, M. (2017). Working memory training revisited: a multi-level meta-analysis of n-back training studies. *Psychonomic Bulletin and Review, 24*(4), 1077–1096.

Spierer, L., Chavan, C. F., & Manuel, A. L. (2013). Training-induced behavioral and brain plasticity in inhibitory control. *Frontiers in Human Neuroscience, 7*, 1–9.

Strobach, T., Salminen, T., Karbach, J., & Schubert, T. (2014). Practice-related optimization and transfer of executive functions: a general review and a specific realization of their mechanisms in dual tasks. *Psychological Research, 78*(6), 836–851.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology: General, 121*(1), 15–23.

Thorell, L. B., Lindqvist, S., Nutley, S. B., Bohlin, G., & Klingberg, T. (2009). Training and transfer effects of executive functions in preschool children. *Developmental Science, 12*(1), 106–113.

Van Boxtel, G. J. M., Van der Molen, M. W., Jennings, J. R., & Brunia, C. H. M. (2001). A psychophysiological analysis of inhibitory motor control in the stop-signal paradigm. *Biological Psychology, 58*(3), 229–262.

Verbruggen, F., Liefooghe, B., & Vandierendonck, A. (2004). The interaction between stop signal inhibition and distractor interference in the flanker and stroop task. *Acta Psychologica, 116*(1), 21-37.

Verbruggen, F., & Logan, G. D. (2008). Automatic and controlled response inhibition: associative learning in the go/no-go and stop-signal paradigms. *Journal of Experimental Psychology: General, 137*(4), 649-672.

Wilkinson, A. J., & Yang, L. X. (2012). Plasticity of inhibition in older adults: Retest practice and transfer effects. *Psychology and Aging, 27*(3), 606-615.

Zhao, X., Chen, L., & Maes, J. H. R. (2018). Training and transfer effects of response inhibition training in children and adults. *Developmental Science, 21*(1), e12511.

Zhao, X., & Jia, L. (2019). Training and transfer effects of interference control training in children and young adults. *Psychological Research, 83*(7), 1519-1530.

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