Brain and Cognition 84 (2014) 44–62

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Inhibitory control gains from higher-order cognitive strategy training ☆

Michael A. Motes [a,*], Jacquelyn F. Gamino [a], Sandra B. Chapman [a], Neena K. Rao [a], Mandy J. Maguire [a,b], Matthew R. Brier [d], Michael A. Kraut [e], John Hart Jr. [a,c]

[a] Center for BrainHealth, School of Behavioral & Brain Sciences, University of Texas at Dallas, United States
[b] Callier Center for Communication Disorders, School of Behavioral & Brain Sciences, University of Texas at Dallas, United States
[c] Department of Neurology, University of Texas Southwestern Medical Center at Dallas, United States
[d] Medical Scientist Training Program and Program in Neuroscience, Washington University in St. Louis, United States
[e] Department of Radiology, Johns Hopkins University School of Medicine, United States

ARTICLE INFO

Article history:
Accepted 26 October 2013
Available online 25 November 2013

Keywords:
Cognitive strategy training
Inhibition
Inhibitory control
Cognitive control
Executive function
Reasoning
Comprehension
Transfer

ABSTRACT

The present study examined the transfer of higher-order cognitive strategy training to inhibitory control. Middle school students enrolled in a comprehension- and reasoning-focused cognitive strategy training program and passive controls participated. The training program taught students a set of steps for inferring essential gist or themes from materials. Both before and after training or a comparable duration in the case of the passive controls, participants completed a semantically cued Go/No-Go task that was designed to assess the effects of depth of semantic processing on response inhibition and components of event-related potentials (ERP) related to response inhibition. Depth of semantic processing was manipulated by varying the level of semantic categorization required for response selection and inhibition. The SMART-trained group showed inhibitory control gains and changes in fronto-central P3 ERP amplitudes on inhibition trials; whereas, the control group did not. The results provide evidence of the transfer of higher-order cognitive strategy training to inhibitory control and modulation of ERPs associated with semantically cued inhibitory control. The findings are discussed in terms of implications for cognitive strategy training, models of cognitive abilities, and education.

Published by Elsevier Inc.

1. Introduction

Formal education requires balancing teaching subject content and teaching more general cognitive and learning strategies (Conley, 2008; Dansereau, 1985; Pressley et al., 1990; Rosenshine & Meister, 1992; Weinstein & Mayer, 1986, 1991; Weinstein, Ridley, Dahl, & Weber, 1989). On the one hand, teaching subject content is necessary for students to develop subject knowledge and competence with subject-specific learning and problem-solving strategies. On the other hand, teaching general cognitive and learning strategies is necessary to facilitate student learning and problem-solving in novel situations, particularly in situations where an expert is not immediately available. Teaching higher-order cognitive strategies aimed at improving reasoning, problem-solving, and comprehending, however, also has the potential to exercise and improve supporting core executive processes. As a test of this broader hypothesis that higher-order cognitive strategy training can improve associated executive processes, the present study examined the transfer of a higher-order, reasoning-based, cognitive strategy training program to an untrained measure of inhibitory control.

The Strategic Memory Advanced Reasoning Training (SMART©) program (Chapman & Gamino, 2008; Gamino, Chapman, Hull, & Lyon, 2010) was used as the higher-order cognitive strategy training program in the present study. SMART is a general cognitive strategy program that teaches a hierarchical sequence of steps designed to facilitate inferring essential gist from materials. The findings from a randomized control study have provided validation for SMART as a method for improving the ability to infer essential gist from materials (Gamino et al., 2010). In that study, middle-school students were randomly assigned to either receive SMART, mnemonic training, or lectures about the teen brain. The analysis of summaries written before and after the training showed that the SMART group, but not the other two control groups, made significant gains in inferring overall messages from texts and inferring connections between overall messages and more general world knowledge. The efficacy of SMART for improving the ability to infer the essential gist from materials also has been shown in healthy

☆ This research was supported by Texas Legislature appropriated ARRA Funding for the Middle School Brain Years Program (2009–2011), and ongoing research on SMART is supported by funding from the Texas Legislature and AT&T. A United States patent application has been filed to protect the Strategic Memory Advanced Reasoning Training program (Publication #US20120282578 A1) with the University of Texas System Board of Regents, Dr. Chapman, and Dr. Gamino as the assignees.

* Corresponding author. Address: Center for BrainHealth, School of Behavioral & Brain Sciences, University of Texas at Dallas, 2200 W. Mockingbird Lane, Dallas, TX 75235, United States. Fax: +1 214 905 3026.
E-mail address: michael.motes@utd.edu (M.A. Motes).

0278-2626/$ - see front matter Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.bandc.2013.10.007

elderly adults (Anand et al., 2011) and adults who had suffered traumatic brain injuries (Vas, Chapman, Cook, Elliott, & Keebler, 2011).

SMART steps and activities were developed based on models of comprehension and reasoning and were designed to foster the use of comprehension and reasoning processes to facilitate inferring essential gist from studied materials. SMART consists of seven hierarchical steps: (1) identifying and deleting irrelevant information, (2) organizing the remaining relevant information, (3) inferring unstated meanings from the organized information, (4) paraphrasing, (5) synthesizing important information, (6) inferring an overall message or messages, and (7) inferring analogous relationships between the newly inferred message(s) and general world knowledge (e.g., adages, themes, morals). From models of comprehension, these steps were designed to foster the use of processes mediating the transformation of studied materials into more global, abstract representations forming a topic (Brown & Day, 1983; Kintsch & van Dijk, 1978; van Dijk, 1977), including suppressing topic-irrelevant information, substituting superordinate representations (e.g., substituting gardening for weeding, mowing, and trimming), and inserting inferred global facts (e.g., inferring that tools were used in gardening). From models of reasoning, the steps were designed to foster the use of processes mediating inferring relationships between parts of studied materials, including identifying attributes and inferring and comparing relationships between attributes (Green & Kluever, 1991; Pellegrino & Glaser, 1979; Sternberg & Gardner, 1983; van der Ven & Ellis, 2000). Furthermore, the steps were designed to foster the use of more cognitively demanding *inductive inferencing* or making assertions about relationships between information not explicitly present in the studied materials (Klauer & Phye, 2008).

The present study explored the effects of SMART on inhibitory control, an executive process that should be recruited and exercised during SMART but that was not directly addressed by the training. Inhibitory control has been proposed to affect a range of higher-order cognitive processes (Dempster, 1991; Dempster & Corkill, 1999). In comprehension, inhibitory control mechanisms have been said to eliminate or suppress extraneous encoded information and retrieved inappropriate meanings and inferences (Cain, 2006; Chiappe, Siegel, & Hasher, 2000; De Beni & Palladino, 2000; Gernsbacher & Faust, 1991; Gernsbacher & Robertson, 1995; Just & Carpenter, 1992; Kintsch & van Dijk, 1978; Pimperton & Nation, 2010). Additionally, in reasoning, inhibitory control mechanisms have been proposed to also eliminate or suppress extraneous encoded information (Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004) and to eliminate or suppress retrieved strategies, beliefs, examples, memories, and prepotent responses deemed inaccurate (De Neys & Everaerts, 2008; De Neys, Schaeken, & d'Ydewalle, 2005; Handley, Capon, Beveriddge, Dennis, & Evans, 2004; Houdé, 2000; Houdé et al., 2000; Moutier, Angeard, & Houde, 2002; Moutier & Houdé, 2003; Robin & Holyoak, 1995). Thus, by engaging comprehension and reasoning processes while working through SMART, students also should engage and exercise inhibitory control mechanisms.

Inhibitory control in the present study was measured using a Go/No-Go task (e.g., Luria, 1959; Simpson & Riggs, 2006). Go/No-Go tasks involve building preparatory or anticipatory cognitive and motor responses through frequent and temporally regular presentations of stimuli to which participants are to respond and then involve the attenuation, circumvention, or some kind of "control" of these prepotent responses when shown a less frequently presented No-Go stimulus (Simpson & Riggs, 2006). Thus, the proportion of correct rejections on No-Go trials serves as an index of inhibitory control, and the proportion of correct rejections has been shown to provide a reliable and relatively pure index of inhibitory control (Perner, Lang, & Kloo, 2002; Simpson & Riggs, 2006).

Research suggests that a general inhibitory control mechanism mediates correct rejections on Go/No-Go tasks (Brocki & Bohlin, 2004; Friedman & Miyake, 2004; Miyake et al., 2000; but see Eagle, Bari, & Robbins, 2008; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Shilling, Chetwynd, & Rabbitt, 2002). Inhibitory control often has been operationalized using motor control measures like stopping a planned or prepotent response (Barkley, 1997; Bedard et al., 2002; Brocki & Bohlin, 2004; Eagle et al., 2008; Rubia et al., 2001; Schachar et al., 2007; Verbruggen & Logan, 2008, 2009; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). However, latent variable analyses have provided convergent and discriminant evidence for the presence of a general inhibitory control mechanism (Brocki & Bohlin, 2004; Friedman & Miyake, 2004; Friedman et al., 2006; Miyake et al., 2000). Latent variable analyses have revealed correlations between a range of measures of response inhibition (i.e., stopping planned, prepotent, or automatic motor responses) and of distractor interference (i.e., avoiding the influence of irrelevant distractors), providing convergent evidence for a common inhibitory control mechanism. Latent variable analyses also have shown distinctions in the associations between measures of inhibitory control and prospective memory interference, providing discriminant evidence for involvement of an inhibitory control mechanism in response inhibition and distractor interference but not resistance to memory intrusions (Friedman & Miyake, 2004).

The Go/No-Go task used in the present study also allowed for the examination of the effects of SMART on semantically cued inhibitory control (Brier et al., 2010; Maguire, White, & Brier, 2011; Maguire et al., 2009). Research on semantically cued inhibitory control has shown the sensitivity of fronto-central (Fz) EEG markers of response inhibition to requirements of deeper semantic processing (Brier et al., 2010; Maguire et al., 2009). Go/No-Go tasks, in general, have been found to elicit changes in the N2 and P3 ERP components, with the N2 occurring approximately 150–300 ms after the stimulus onset and the P3 occurring approximately 300–600 ms after the stimulus onset (e.g., Hillman et al., 2012; Maguire et al., 2009; Simson, Vaughan, & Ritter, 1977). For both components, greater signal change has been observed on successful No-Go trials (i.e., correct rejections) compared to successful Go trials (e.g., Donkers & van Boxtel, 2004; Maguire et al., 2009). However, there has been debate over which component, N2 or P3, over which location actually indexes inhibitory control (Bruin, Wijers, & van Staveren, 2001; Donkers & van Boxtel, 2004; Falkenstein, Hoormann, & Hohnsbein, 1999; Kopp, Mattler, Goertz, & Rist, 1996; Smith, Johnstone, & Barry, 2007). Among young adults, both N2 and P3 inhibitory control effects have been observed over fronto-central electrodes (e.g., Donkers & van Boxtel, 2004; Maguire et al., 2009). However, among young adults, deeper semantic processing requirements have been shown to attenuate fronto-central (Fz) P3 amplitudes and increase P3 peak latencies on No-Go trials (Maguire et al., 2009). Deeper semantic processing requirements also have been shown to decrease EEG frontal theta-band power changes and increase frontal theta-band peak latencies on No-Go trials (Brier et al., 2010).

In addition to showing sensitivity to deeper semantic processing, research on semantically cued inhibition has provided evidence for the sensitivity of P3 to developmental change (Maguire et al., 2011). A developmental study of groups of children 10–11 years of age and 7–8 years of age showed depth of semantic processing modulation of the P3 over parieto-central (Pz) electrodes. The 10–11 year old group showed attenuation of the P3 amplitude at Pz on No-Go trials with increases in the depth of semantic processing requirements, but the younger group showed increases in the P3 amplitude at Pz on Go trials with increases in the depth of semantic processing requirements. These results suggest that there is a shift in the modulatory effect of deeper

semantic processing on P3 at Pz as children develop from middle to late childhood. Then when compared with the results from young adults (Maguire et al., 2009), there appears to be another shift toward fronto-central mediated semantically cued inhibitory control.

The present study was conducted to evaluate the transfer of SMART to inhibitory control using the semantically cued Go/No-Go task (Brier et al., 2010; Maguire et al., 2009, 2011). Participants in the SMART group were recruited from a pool of students enrolled in a broader, in-school administration of the SMART program (see Fig. 1). Thus, importantly, the training was provided in normal school classrooms during school hours. Providing the training in a relevant educational context, rather than a lab setting, increased ecological validity of the study. Ecological validity has been an oft-raised issue regarding generalization of cognitive, cognitive neuroscience, and in particular, cognitive training findings to relevant educational contexts (e.g., Varma, McCandliss, & Schwartz, 2008). A pre-post, quasi-experimental design, including a historical control group, was used (Campbell & Stanley, 1966). The semantically cued Go/No-Go task allowed for the assessment of the transfer of SMART to inhibitory control, the specificity of the transfer to inhibitory control (i.e., as compared to selection), and the effect of SMART on the potential modulatory effects of deeper semantic processing in inhibitory control.

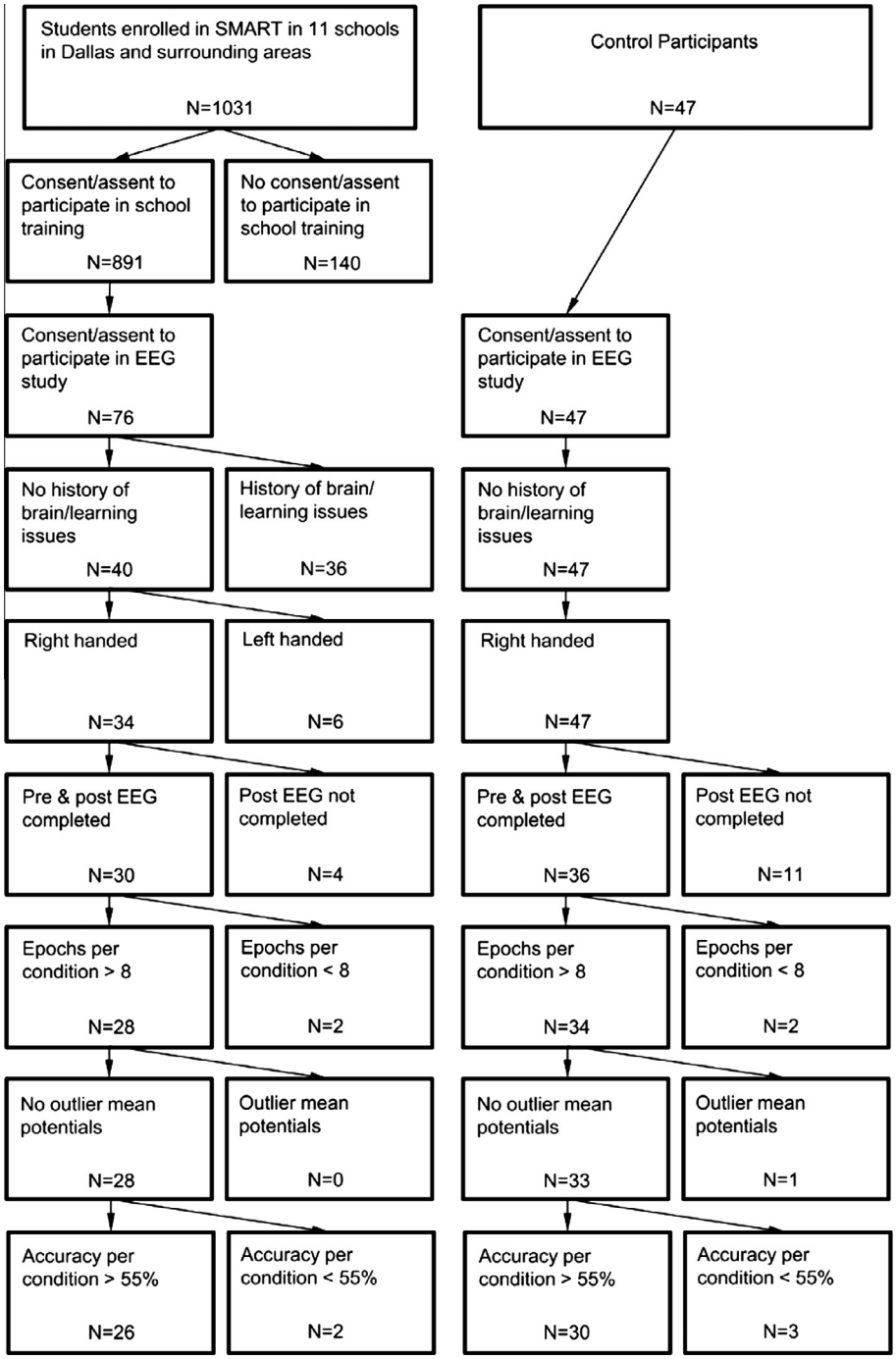

Fig. 1. Diagram illustrating participant and data flow through to the final datasets analyzed.

2. Materials and methods

2.1. Participants

2.1.1. Demographics

The data for 26 participants (M = 13.19 years; 16 males; 11 White, 8 Hispanic, 6 African-American, and 1 Native American) in the SMART group and 30 participants (M = 13.07 years; 14 males; 21 White, 4 Hispanic, and 5 African-American) in the control group were analyzed. All were right-handed adolescents between 12 and 15 years of age. Full scale IQ scores (based on WAIS Matrix Reasoning and Vocabulary tests; Wechsler, 1999) were obtained for both groups.[1] The mean full scale IQ was significantly higher for the control group (M = 105.57, SEM = 2.40) than the SMART group (M = 94.16, SEM = 2.36), $t(53) = 3.36$, $p < .001$.

This experiment was approved by the Institutional Review Board for the University of Texas at Dallas, and the experiment was conducted according to the principles expressed in the Declaration of Helsinki. Informed written assent and consent were obtained from participants and legal guardians, respectively, at the beginning of the study for participation in the in-school SMART program. For both SMART and control groups, informed written assent and consent were obtained at the beginning of each session of the inhibitory control sub-study. For the SMART group, participation in the inhibitory control sub-study was optional and did not affect the participation in the in-school SMART program. Participants received $15.00 in restaurant gift cards for participating in the in-school SMART program, and participants in the SMART and control groups each received $40 per session for participating in the EEG sessions.

2.1.2. Recruitment

Participants in the SMART group were recruited from a larger pool of students enrolled in a broader, in-school administration of the SMART program. The in-school training was provided during normal school hours to students in 11 middle schools in Dallas and the surrounding area. The administration of SMART to children in these schools was coordinated through the districts, school administrators, and teachers. Cumulatively, 1031 students were initially offered the opportunity to participate in the SMART program being administered in the 11 schools, and 891 students and their parents provided written assent and consent, respectively, to participate in the in-school training (see Fig. 1). The program was provided to all students enrolled in the classes made available by the district and school administrators. The schools had diverse SES and ethnicity demographics (e.g., SES ranged from 6% to 96% of the student population receiving free lunch; ethnicity ranges varied from 61–1% White, 78–12% Hispanic, 68–4% African American, and 26–0% Asian).

The students enrolled in the in-school administration of SMART were recruited to participate in the present inhibitory control sub-study through open-house meetings with parents and students or through printed advertisements distributed to students enrolled in the in-school SMART program. As per agreements with the schools, participation in the inhibitory control sub-study was open to all students who had agreed (i.e., provided written informed consent/assent) to participate in the in-school SMART program. Parent report questionnaires, addressing participant histories of brain injury, learning disabilities, neurodevelopmental disorders, and placement in special education courses, were used to prescreen SMART participants for use in the analysis of data reported in this inhibitory control sub-study. Participants reporting a history of brain injury, neurodevelopmental disorders, learning disabilities, or placement in remedial, resource, or special education courses and participants who were left-handed were allowed to participate in the inhibitory control sub-study, as per agreements with the schools. Of the 11 schools, three made the program available only to students enrolled in resource/remedial classes. However, for the present analysis, all participants were right-handed adolescents between 12 and 15 years of age, and they did not report histories of brain injury, neurodevelopmental disorders, or placement in remedial, resource, or special education courses.

Participants in the control group in the present study were recruited through printed advertisements distributed within schools, libraries, and recreation centers in Dallas and the surrounding area. Forty-seven participants originally volunteered. Of the data analyzed and reported in the present study, some of the participants (N = 17) in the control group were recruited during the summer of 2010, while the data on the SMART group were collected from the winter of 2010 through the summer of 2011. Some of the participants (N = 13) in the control group were recruited from the same schools as those in the SMART group, and those data were then collected over the same time period as the students in the SMART group from those schools. Missing data and data quality control led to reduction in the number of datasets used for both groups (see Fig. 1 and descriptions below).

2.2. The SMART Cognitive strategy training program

The SMART program (Gamino et al., 2010) consisted of seven steps administered to students during normal school hours, in 10 sessions over a one-month period, with 45–50 min per session. Trained teachers from the University of Texas at Dallas' Center for BrainHealth administered SMART to students.

SMART participants were taught six steps to facilitate inferring the essential gist from materials:

- Step 1: Deleting irrelevant information. Participants engaged in discussion and activities aimed at learning to distinguish extraneous details and repeated information presented in text from information that is important for understanding a topic (e.g., main characters, important facts, and important actions). The main activities involved deleting words, phrases, and sentences from short texts that contained repeated information or extraneous details.
- Step 2: Organizing important information. Participants engaged in discussion and activities aimed at learning the value of organizing important information based on episode changes (e.g., topic, event, or activity). The main activities involved developing episode-based outlines of important information in texts.
- Step 3: Inferring unstated meanings. Participants engaged in discussion and activities aimed at learning to infer meaning from texts. The activities progressed from inferring the meaning of words from context within sentences to inferring unstated meaning and psychological attributes (e.g., motivation) from brief paragraphs and essays.
- Step 4: Paraphrasing. Participants engaged in discussion and activities aimed at learning to restate key information from texts in more familiar terms while retaining meaning. The activities progressed from rating the quality of paraphrased versions of sentences (from *verbatim with a few word changes* to *well transformed with preserved meaning*) to paraphrasing sentences and evaluating the quality of the paraphrasing.
- Step 5: Synthesizing important information. Participants engaged in discussion and activities aimed at learning to infer succinct paraphrasing of episodes of key information from texts. The initial activities progressed from rating the quality of succinct, one-sentence paraphrases of brief paragraphs (from *too*

[1] Full-scale IQ for one participant in the SMART group could not be computed, because the participant did not want to complete the Vocabulary test. This participant's raw Matrix Reasoning score was 29, falling within the normal range.

terse to *concise with preserved meaning and detail*) to producing and self-rating succinct, one-sentence paraphrases of brief paragraphs. The final activities involved using all of the learned strategies to produce succinct paraphrases of episodes from two short texts.

- Steps 6 and 7: Inferring an overall message. Participants engaged in discussion and activities aimed at learning to infer an overall lesson from materials, and in particular, to infer a message that would generalize to other contexts and situations (i.e., general knowledge like adages, themes, morals, etc.). The activities progressed from evaluating the quality of provided lessons inferred from familiar stories (e.g., from *Little Red Riding Hood*, a lower-level lesson was "Red Riding Hood should have listened to her mom", and a higher-level lesson was "evil is not a match for those who have good hearts") to producing and self-evaluating lessons from familiar fairy tales. The final activity involved using all of the learned steps and producing overall lessons linked to general knowledge for episodes derived from novel short stories.

2.3. Go/No-Go task materials and apparatus

The Go/No-Go response inhibition task has been used and described in previously published research (Brier et al., 2010; Maguire et al., 2009, 2011). The stimuli were black-line drawings from the Boston Naming Test (Rosenshine & Meister, 1992), the Snodgrass and Vanderwart standardized set of easily nameable pictures (Snodgrass & Vanderwart, 1980), or were drawings by visual artists that were stylistically consistent with stimuli from the standardized sets (for examples, see Fig. 2). Three stimulus-sets were used to vary the semantic level of categorization during the task (Collins & Quillian, 1969; Rosch, Mervis, Gray, Johnson, & Boyesbraem, 1976). For the Single Basic-Level categorization condition, the Go stimulus was a single car, and the No-Go stimulus was a single dog. For the Multiple Basic-Level categorization condition, Go stimuli consisted of 40 drawings of different cars (e.g., SUVs, trucks, convertibles) and their left–right mirrored images repeated twice throughout the run, and No-Go stimuli consisted of 10 different drawings of dogs (e.g., beagle, great dane, and retriever) and their left–right mirrored images repeated twice throughout the run. For the Superordinate-Level categorization condition, Go stimuli consisted of drawings of 40 food items, 40 cars, 20 clothing items, 20 kitchen items, 20 body parts, and 20 tools, and No-Go stimuli consisted of 40 drawings of animals of varying typicality (e.g. dogs, spider, worms, lobster, and dolphins). None of the animals used were drawn in threatening positions. Although some of the animals might elicit a negative reaction in some small portion of the general population, the number of such stimuli constituted a small portion of the animals used (i.e., one spider and one shark). Additionally, none of the participants reported negative reactions or problems otherwise with the stimuli, and none of them showed negative reactions during testing.

The images were shown to participants on a 52 cm LCD monitor. A chair was positioned 90 cm from the monitor so that the Go and No-Go stimuli subtended approximately 18° of visual angle. A button box was placed on the right arm of the chair, and it interfaced with the Stim2 (Compumedics, Inc.) software to record the responses and RTs.

Continuous EEG data were recorded using a Neuroscan Quickcap, Neuroscan SynAmps2 amplifier, and Scan 4.5 software (Compumedics, Inc.). The Neuroscan Quickcap was an elastic cap that contained 64 silver/silver-chloride electrodes, and it was placed on the participant's head so that the electrodes were positioned according to the International 10–20 electrode placement standard. Blinks and eye movements were monitored via two electrodes, one mounted above the left eyebrow and one below the left eye. The edge of the front of the cap was three to five cm superior to the nasion. The online reference electrode was located near the vertex, and the APZ electrode served as the ground electrode. The impedance for each electrode was adjusted to less than 10 kΩ at the beginning of each run, and the EEG data were sampled at a rate of 1000 Hz.

2.4. Go/No-Go task procedure

For each categorization condition, there were 200 trials, consisting of 160 (80%) Go trials and 40 No-Go trials. Participants were instructed "to press the response button for a car (*all cars/all objects*) but not to press the button for a dog (*any dogs/any animals*)." All stimuli were presented for 300 ms followed by fixation point (+) for 1700 ms. Although both fixed and varied intervals have been used in previous Go/No-Go studies (e.g., Donkers & van Boxtel,

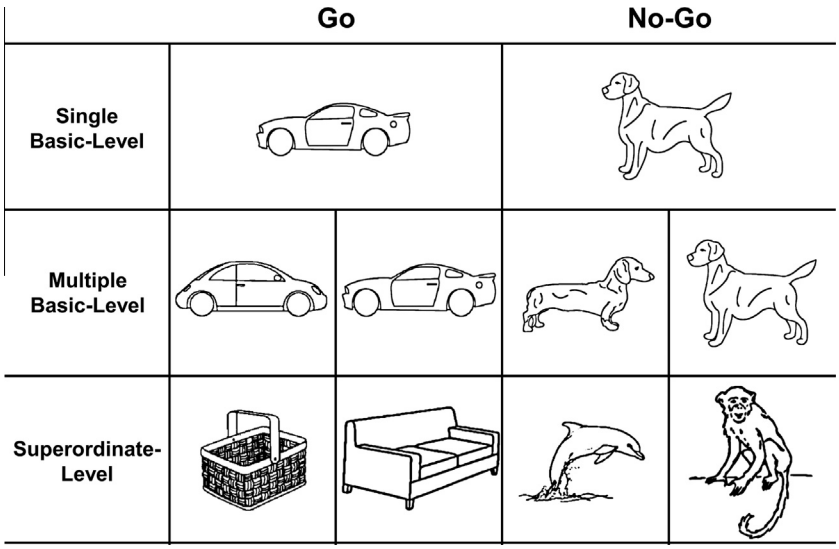

Fig. 2. Examples of Go and No-Go stimuli from the stimulus-sets constructed to affect the depth of semantic processing. Examples from the stimulus-sets are shown in the rows, with examples of stimuli to which the participants were to respond (i.e., Go stimuli) and were not to respond (i.e., No-Go stimuli) separated into columns.

2004; Johnstone et al., 2007; Pfefferbaum & Ford, 1988), varying the ITI has been shown to lead to better performance on No-Go trials, that is, to lead to improvements in inhibitory control on go/no-go tasks (Ryan, Martin, Denckla, Mostofsky, & Mahone, 2010; Wodka, Simmonds, Mahone, & Mostofsky, 2009), and fixed ITIs have been shown to increase readiness to respond (Poulton, 1950). Participants were instructed to respond as quickly and accurately as possible, although responses for a given trial were recorded and scored up to the onset of the next stimulus. To minimize stimulus specific effects, six versions of the single basic-level condition were constructed each with a different Go and No-Go stimulus. To minimize stimulus order effects, six different random orders for each categorization condition were created, and the order in which the categorization condition stimulus-sets were administered was counterbalanced across participants. RT was measured from the onset of a trial stimulus to the response. A time marker for each stimulus onset and response was recorded in the continuous EEG data file.

2.4.1. Go/No-Go task behavioral measures

Correct rejection rate for No-Go trials served as the measure of inhibitory control. However, hit rate for Go trials also allowed for the evaluation of whether SMART-related inhibitory control gains were associated with improved discrimination or response strategy shifts. Signal-detection statistics for response sensitivity (d'), bias ($ln(\beta)$), and criterion (c) were calculated for each participant based on Stanislaw and Todorov (1999). For a Go/No-Go task, signal detection theory analysis assumes that responding depends on a cognitive decision index. When the decision index exceeds a response criterion during a trial, the participant responds. For the present study, the sensitivity index, d', was calculated by subtracting the z-standardized false-alarm rate from the z-standardized hit rate. The sensitivity index provides an estimate of the difference between the mean of the signal distribution (i.e., Go stimuli) and the mean of the noise distribution (i.e., No-Go stimuli). With this calculation, $d' = 0$ indicates no discrimination between the signal and the noise, and higher values of d' indicate better discrimination. Negative d' values were possible, indicating possible response confusion, but none were found for the current data. The index of bias, $ln(\beta)$, was calculated by subtracting the squared, z-standardized hit rate from the squared, z-standardized false-alarm rate and dividing by two, yielding the natural logarithm of β for statistical comparisons rather than β proper which is based on a likelihood ratio. With this calculation, $ln(\beta) = 0$ indicates no bias, $ln(\beta) < 0$ indicates a Go bias, and $ln(\beta) > 0$ indicates a No-Go bias. The criterion index, c, was calculated by multiplying the average of the z-standardized hit rate and the z-standardized false-alarm rate by negative one. With this calculation, $c = 0$ indicates that the criterion was at a point where no bias existed (i.e., $ln(\beta) = 0$), $c < 0$ indicates the criterion was set toward Go, and $c > 0$ indicates the criterion was set toward No-Go.

RT on Go trials also allowed for the evaluation of whether SMART-related gains were specific to response inhibition or resulted from more general gains. Indeed, in latent variable analyses, Go RT and accuracy have been observed to load on a separate factor from No-Go accuracy, and different developmental trajectories have been observed for measures of response inhibition and response execution (Bedard et al., 2002; Brocki & Bohlin, 2004; Johnstone et al., 2007). Although No-Go accuracy serves as an index of inhibitory control, Go accuracy and RT have been considered measures of general processing speed or arousal (Bedard et al., 2002; Brocki & Bohlin, 2004). Additionally, RTs per trial allowed for the calculation of the coefficient of variation (CV), that is, processing time variability while controlling for linear relationships between the mean and standard deviation (Wagenmakers & Brown, 2007). CV then allowed for the assessment of SMART-related shifts in the structure of the processes leading to a response (Segalowitz & Frenkiel-Fishman, 2005) compared to a shift in overall processing speed.

2.4.2. Go/No-Go task EEG preprocessing

Data were preprocessed to remove artifacts prior to calculating ERPs. The data were visually inspected for time-series segments containing muscle artifacts and for poorly functioning electrodes and both were excluded from further analyses. Eye movement artifacts were removed from the remaining data using a single value decomposition spatial filtering algorithm designed to preserve the background EEG data (via Neuroscan, Compumedics, Inc.). The corrected continuous EEG data were band-pass filtered from 0.15 to 30 Hz and then segmented into 1600 ms epochs, spanning 100 ms before and 1500 ms after the onset of the trial. Next, the data were re-referenced to the average potential over the entire head to eliminate the effect of the vertex-located reference electrode used during data acquisition attenuating the signal amplitude of neighboring electrodes. Additionally, to reduce a slight bias in the electrode-based average reference (Junghöfer, Elbert, Tucker, & Braun, 1999), spherical splines were fitted to the data and used to compute a new average for referencing (Ferree, 2006; Perrin, Pernier, Bertrand, & Echallier, 1989). For participants with fewer than five bad electrodes, the splines also were used to interpolate the time-series for those electrodes.

2.4.3. Go/No-Go task ERP calculation

ERPs were calculated for each electrode for each of the 12 Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go) conditions. For each electrode, each epoch was linearly detrended and then baseline corrected by subtracting the mean potential (μV) of the prestimulus interval (−100 ms to 0 ms) from the potential measured at each time point (Duncan et al., 2009; Woodman, 2010). Epochs with potentials exceeding ±70 μV, epochs in which incorrect responses were given, and epochs in which RT exceeded 2.5 SDs from the participant's mean RT (i.e., outlier RTs) were excluded from further analyses. The assessment of epochs with data points exceeding ±70 μV was done per electrode. A minimum of 8 epochs was required for each ERP (for the full analysis, Fz epochs $M_{go} = 99.46$, $SEM_{go} = 2.68$, $M_{no\text{-}go} = 24.86$, $SEM_{no\text{-}go} = 0.55$; and Pz epochs $M_{go} = 99.04$, $SEM_{go} = 2.66$, $M_{no\text{-}go} = 24.76$, $SEM_{no\text{-}go} = 0.57$), and the data for any participant not meeting this criterion for any condition were excluded from further analysis (see Fig. 1). The data were evaluated for outlier mean potentials across conditions, and the data for one participant showing a large number of outlier mean potentials (i.e., for 13 conditions across Fz and Pz N2 and P3 means exceeding ±2.5 SDs from the mean for the sample) were excluded (see Fig. 1). Most other participants did not have any means exceeding the ±2.5 SDs. Additionally, the data were excluded from further analysis due to performance for one or more of the Time × Response conditions (i.e., proportion correct ⩽.50; see Fig. 1). For the remaining participants (SMART group $N = 26$; Control group $N = 30$), ERPs were calculated by averaging data at corresponding time-points across the remaining trial epochs for the condition. Based on prior research on semantically cued inhibitory control (Brier et al., 2010; Maguire et al., 2009, 2011) and other Go/No-Go tasks (Donkers & van Boxtel, 2004; Hillman et al., 2012; Simson et al., 1977) and on visual inspection of the data (see Figs. 5–7), mean amplitude estimates for each condition were obtained for intervals corresponding to midline frontal (Fz), central (Cz), and parietal (Pz) electrode N2 and P3 components. For each participant, mean amplitudes for each condition were obtained by averaging over data points within the intervals of 100–300 ms post-stimulus onset for the Fz N2, 300–600 ms post stimulus onset for the Fz P3, 150–250 ms post-stimulus onset for the Cz N2, 250–600 ms

post-stimulus onset for the Cz P3, 100–200 ms post-stimulus onset for the Pz N2, and 200–600 ms post stimulus onset for the Pz P3.

3. Results

The primary aim of the study was to evaluate training-related effects on inhibitory control. Therefore, for all analyses the Group (SMART; Control) × Time (Pre; Post) and higher order interaction effects involving Group (SMART; Control) × Time (Pre; Post) are reported below, and in the interest of full reporting, the ANOVA tables for all main and interaction effects appear in Appendices A and B. All ANOVAs used Type III sums of squares yielding more conservative estimates of effects when samples sizes differed, potentially affecting estimates of the marginal means. Post hoc follow-up tests for significant effects were based upon marginal means estimated for the data entered for that particular follow-up test, or cell means in the case of comparisons between just two conditions, rather than being based on the marginal means used in the omnibus tests. The means reported in the text are for the means used in the specific follow-up test, and the reported effect-size estimates for the follow-up tests are also based on the means used in the follow-up tests. Modest differences were present only in cases where the marginal means involved averaging across the groups (i.e., where the *N*s for the cell means differed), but the patterns of the effects were comparable for the cell and marginal mean estimates. None of these comparisons, however, were relevant to evaluating training-related effects.

3.1. Behavioral data analysis

Hit and false alarm rates, signal detection statistics, RT, and CV were evaluated for training-related effects. For each participant, the mean RT for the Go response for each Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) condition was calculated after discarding RTs for incorrect responses and outliers (RTs < −2.5 and RTs > 2.5 SDs from a participant's mean). For each participant, the CV for each Time × Categorization condition was calculated by dividing the participant's RT SD by the participant's mean RT for that condition.

3.1.1. Hit and false alarm rates

A Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go) mixed-model ANOVA was used to examine the mean hit and correct rejection rates (i.e., Go and No-Go accuracy, respectively) for evidence of training-related changes (see Fig. 3). The ANOVA yielded a significant Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go) interaction, $F(1,54) = 8.74$, $p = .005$, *partial* $\eta^2 = 0.139$. The training-related Group (SMART; Control) × Time (Pre; Post) and the other higher-order interactions involving Group (SMART; Control) × Time (Pre; Post) effects were not statistically significant (see Appendix A Table A1).

Interaction follow-up tests for the Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go) interaction revealed differences in the pretest to post-test changes in correct rejection rate for the SMART and control groups, but the follow-up tests did not reveal group differences in the changes in the hit rate. The interaction follow-up tests showed a significant Time (Pre; Post) × Trial-Type (Go; No-Go) interaction for the SMART group, $F(1,25) = 6.285$, $p = .019$, *partial* $\eta^2 = 0.201$, but not for the control group, $F(1,29) = 2.15$, $p = n.s.$, *partial* $\eta^2 = 0.069$. For the SMART group, the correct rejection rate significantly increased from pretest ($M = 0.730$, $SEM = 0.026$) to post-test ($M = 0.787$, $SEM = 0.027$), $F(1,25) = 6.28$, p=.019, *partial* $\eta^2 = 0.201$, but the hit rate did not significantly differ from pretest ($M = 0.900$, $SEM = 0.013$) to post-test ($M = 0.853$, $SEM = 0.026$), $F(1,25) = 3.71$, $p = n.s.$, *partial* $\eta^2 = 0.129$. Thus, participation in SMART led to improved inhibitory control evidenced by a specific reduction in commission errors or inhibition failures, with the SMART group showing greater success in withholding responses on No-Go trials following training without showing increased omission errors on Go trials but similar performance improvements not observed in the control group.

Given the observed IQ differences between the groups, the data were analyzed using a Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go) mixed-model ANCOVA with full-scale IQ entered as a covariate. The Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go) interaction remained significant even while statistically controlling for variability in IQ, $F(1,52) = 6.60$, $p = .013$, *partial* $\eta^2 = 0.113$. The correct rejection rate gains for the SMART group (adjusted $M_{post\text{-}pre} = 0.054$, $SE = 0.023$) were significantly greater than those for the control group (adjusted $M_{post\text{-}pre} = -0.014$, $SE = 0.020$), $F(1,52) = 4.57$, $p = .037$, *partial* $\eta^2 = 0.081$.

To control for potential influences of pretest correct rejection rate, the group differences in correct rejection rate gains also were analyzed with an ANCOVA with pretest correct rejection rate entered as a covariate. While controlling for pretest correct rejection rate, the correct rejection rate gains shown by the SMART group (adjusted $M_{post\text{-}pre} = .050$, $SE = 0.02$) were significantly greater than those shown by the control group (adjusted $M_{post\text{-}pre} = -0.010$, $SE = 0.18$), $F(1,53) = 4.956$, $p = .03$, *partial* $\eta^2 = 0.086$.

An examination of the mean correct rejection rate (i.e., averaging across categorization conditions) revealed that approximately 65% ($N = 17$) of the participants in the SMART group showed gains ($M = 0.13$; Min = 0.03; Max = 0.22). The other participants in the SMART group did not show change ($N = 1$) or showed decreases in the correct rejection rate ($N = 8$; $M = -0.08$; Min = −0.25; Max = −0.02). The majority of the control group (63%), on the other hand, showed no change ($N = 2$) or decreases in the correct rejection rate ($N = 17$; $M = -0.08$; Min = −0.17; Max = −0.01), and the others showed more modest gains ($N = 11$; $M = 0.08$; Min = 0.02; Max = 0.19).

3.1.2. Signal detection statistics

Initially, separate Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) mixed-model ANOVAs were used to examine the signal detection statistics for evidence of training-related changes (see Fig. 4A–C). The ANOVAs revealed a significant Group (SMART; Control) × Time (Pre; Post) interaction only for *c*, $F(1,54) = 7.53$, $p = .008$, *partial* $\eta^2 = 0.122$. The training-related Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) interaction effect was not statistically significant, and the training-related Group (SMART; Control) × Time (Pre; Post) and Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) interaction effects were not statistically significant for d' or $\ln(\beta)$ (see Appendix A Tables A2–A4).

Interaction follow-up tests revealed differences in changes in *c* from pretest to the post-test for the SMART and control groups (see Fig. 4C). Interaction follow-up tests showed that *c* significantly increased from pretest ($M = -0.383$, $SEM = 0.07$) to post-test ($M = -0.156$, $SEM = 0.06$) for the SMART group, $F(1,25) = 7.39$, p=.012, *partial* $\eta^2 = 0.228$, but *c* did not significantly change from pretest to post-test for the control group, $F(1,29) = 1.05$, $p = n.s.$, *partial* $\eta^2 = 0.035$. Thus, SMART also associated produced a shift in the decision criterion from a Go bias toward No-Go bias, regardless of the depth of processing requirements.

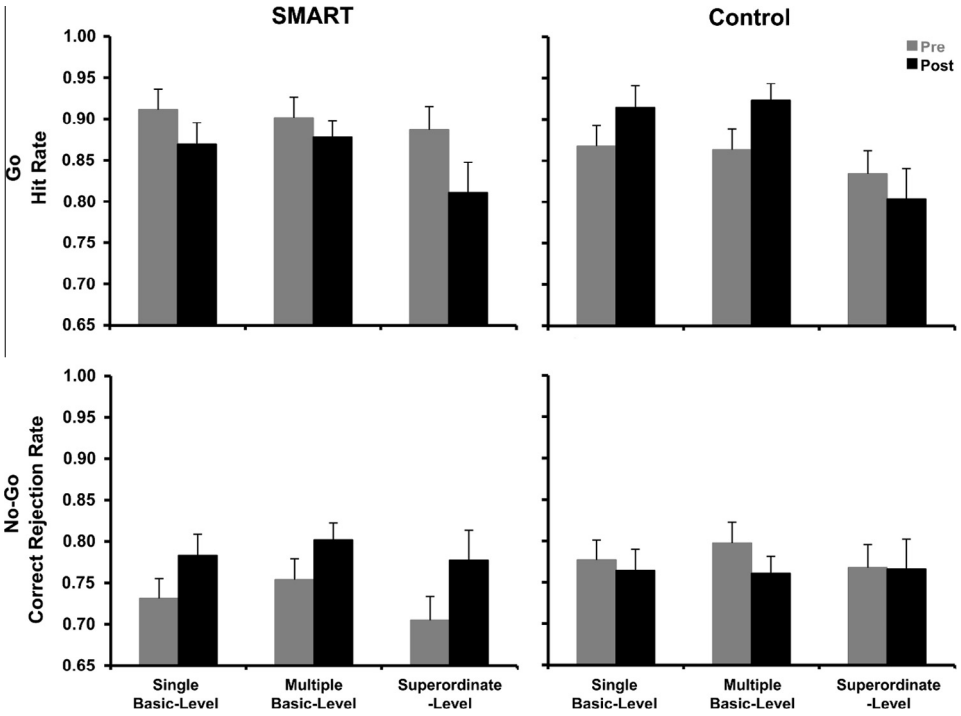

Fig. 3. Mean correct rejection and hit rates as functions of group, time, categorization, and trial-type. Data for the pretest session are shown in gray, and data for the post-test session are shown in black. Data for the Go trial-types are shown in the upper graphs, and data for the No-Go trial-types are shown in the lower graphs. Data for the SMART group are shown in the graphs on the left, and data for the control group are shown in the graphs on the right. Bars depict 1 SEM.

3.1.3. RT and CV

Initially, separate Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) mixed-model ANOVAs were used to examine RT and CV for evidence of training-related changes (see Fig. 4D and E). However, the training-related Group (SMART; Control) × Time (Pre; Post) and Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) interaction effects were not statistically significant for RT or CV (see Appendix A Tables A5 and A6).

3.2. ERP data analysis

Initial analyses of the Fz, Cz, and Pz effects using separate Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go) mixed-model ANOVAs yielded significant training-related effects for P3 at Fz (Fig. 5) but not for N2 at Fz or for either N2 or P3 at Cz or Pz (Figs. 6 and 7, respectively, and Appendix B, Tables B1–B6). Therefore, only the training-related effects for P3 at Fz are reported below.

3.2.1. Fz P3

Initially, a Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go) mixed-model ANOVA was used to examine the mean potential changes corresponding to P3 at Fz (see Fig. 5). The 4-way mixed-model ANOVA yielded a significant a significant Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go) interaction, $F(1,54) = 4.22$, $p = .045$, *partial* $\eta^2 = 0.073$. The training-related Group (SMART; Control) × Time (Pre; Post) and the other higher-order interactions involving Group (SMART; Control) × Time (Pre; Post) were not statistically significant (see Appendix B, Table B1).

Interaction follow-up tests showed differences in No-Go P3 at Fz from the pretest to the post-test for the SMART group but not for the control group (see Fig. 8). There was a significant Time (Pre; Post) × Trial-Type (Go; No-Go) interaction for the SMART group, $F(1,25) = 11.03$, $p = .003$, *partial* $\eta^2 = 0.306$, but not for the control group, $F(1,29) = 1.44$, $p = n.s.$, *partial* $\eta^2 = 0.047$. For the SMART group, No-Go P3 amplitude was significantly greater at pretest ($M = 1.877$, $SEM = 0.704$) than at posttest ($M = -0.360$, $SEM = 0.729$), $F(1,25) = 6.02$, $p = .021$, *partial* $\eta^2 = 0.194$. However, Go P3 amplitude did not significantly differ from pretest ($M = -0.593$, $SEM = 0.433$) to posttest ($M = -0.847$, $SEM = 0.412$), $F(1,25) < 1.00$, $p = n.s.$, *partial* $\eta^2 = 0.010$. Thus, SMART led to attenuation of the P3 inhibitory control signal not the selection signal, with the SMART group showing a reduction in the No-Go P3 amplitude, but not the Go P3 amplitude and the control group not showing comparable reductions.

4. Discussion

4.1. Training-related inhibitory control gains

The results provided evidence that higher-order cognitive strategy training can lead to increased inhibitory control. Overall, the group of students who completed the SMART program was more successful at inhibiting prepotent responses after the training, regardless of the depth of semantic categorization required, than the control group. Furthermore, although inhibitory control increased, the group of students who completed the SMART program showed a decision criterion shift from a criterion biased toward responding to a more neutral criterion, but the control group did not show a comparable decision criterion shift. However, the results did not reveal evidence of the inhibitory control gains being due to strategy shifts toward refraining from responding, trading speed for accuracy, or general processing speed gains (i.e., were not accompanied by response bias shifts or slower RTs).

The SMART-related inhibitory control gains on the untrained Go/No-Go task support a model in which engaging in comprehension and inductive reasoning activities leads to the recruitment, exercise, and subsequent improvement of supporting domain-general inhib-

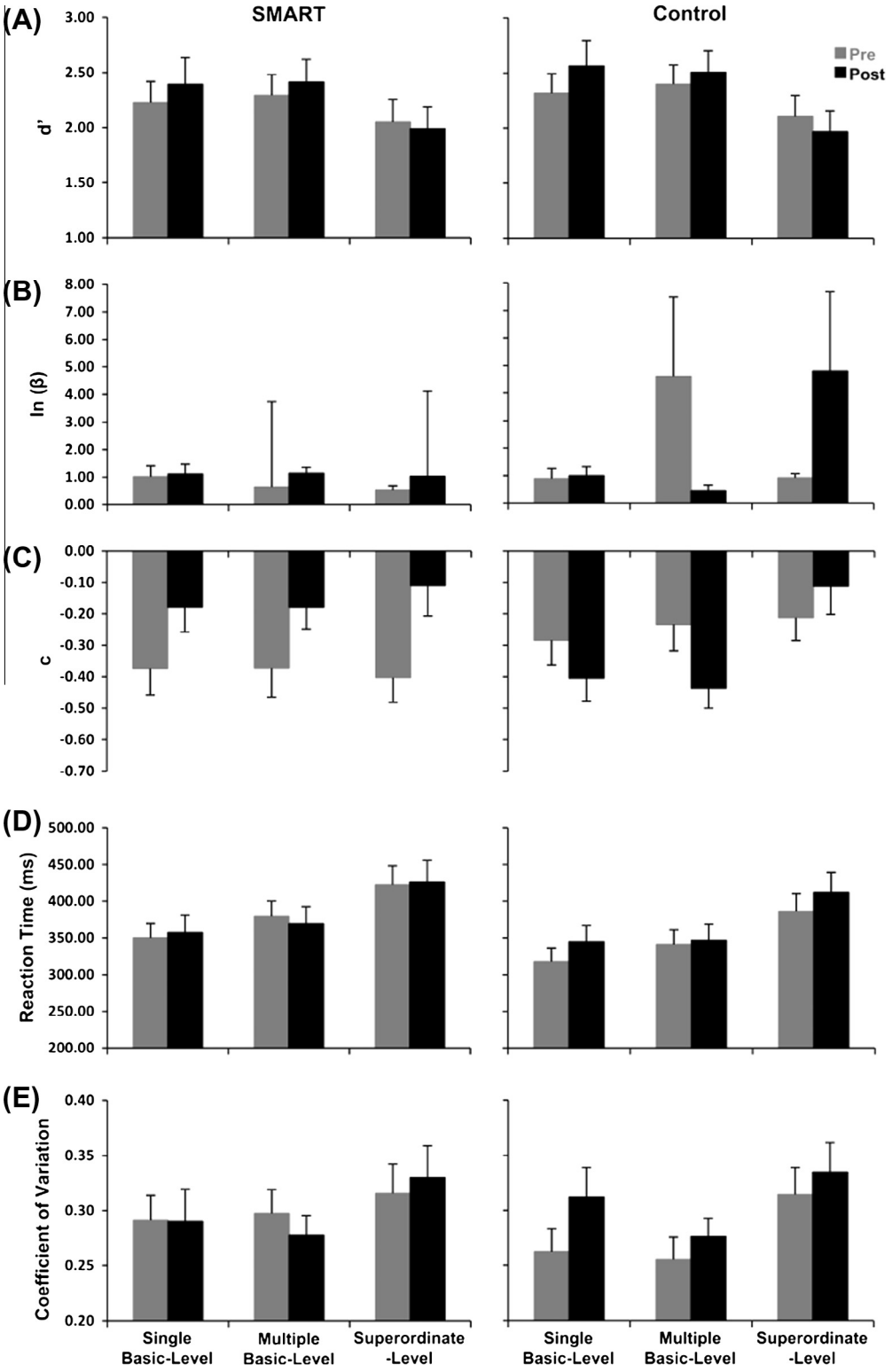

Fig. 4. Mean (A) sensitivity (d'), (B) bias ($ln\beta$), (C) decision criterion (c), (D) reaction time, and (E) coefficient of variation as functions of group, time, and categorization. Data for the pretest session are shown in gray, and data for the post-test session are shown in black. Data for the SMART group are shown on the left, and data for the control group are shown on the right. Bars depict 1 SEM.

itory control processes. SMART emphasized the use of sets of comprehension and inductive reasoning processes to facilitate inferring the essential gist or abstracted meanings from materials. In models of comprehension, inhibitory control processes have been hypothesized to eliminate or suppress extraneous encoded information and retrieved inappropriate meanings and inferences (Cain, 2006; Chiappe et al., 2000; De Beni & Palladino, 2000; Gernsbacher & Faust, 1991; Gernsbacher & Robertson, 1995; Just & Carpenter, 1992; Kintsch & van Dijk, 1978; Pimperton & Nation, 2010), and similarly, in models of reasoning, inhibitory control processes have been hypothesized to eliminate or suppress extraneous encoded information and inaccurate retrieved strategies, beliefs, examples, memories, and

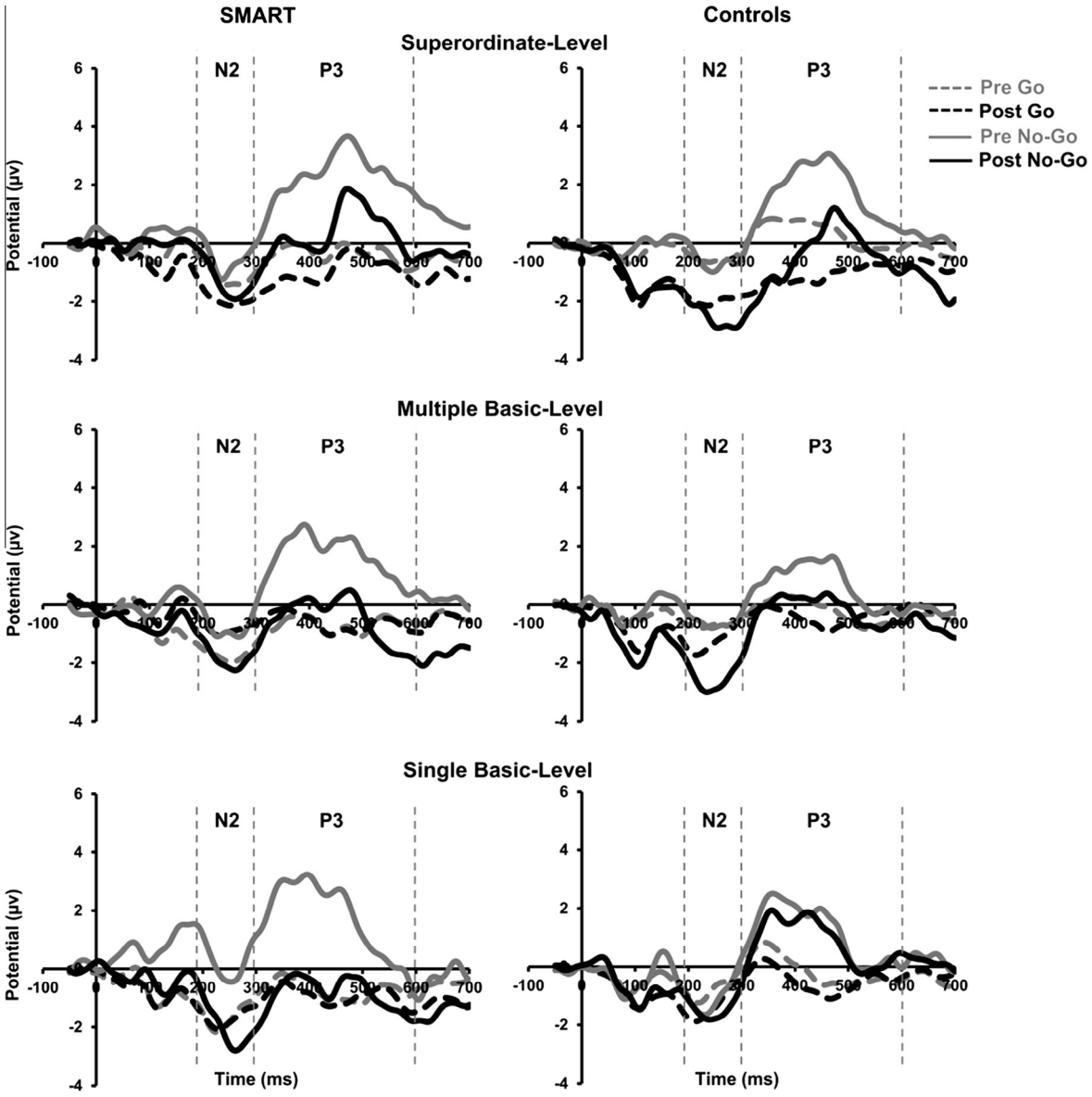

Fig. 5. ERP (μV) at Fz as a function of group, time, categorization, and trial-type. Data for the pretest session are shown in gray, and data for post-test session are shown in black. Data for the Go trial-types are depicted with dashed lines, and data for the No-Go trial-types are depicted with solid lines. Data for the SMART group are shown on the left, and data for the control group are shown on the right. Data for the superordinate-level categorization condition are shown in the upper row; data for the multiple basic-level categorization condition are shown in the center row; and data for the single basic-level categorization condition are shown in the lower row. Vertical black dashed lines indicate temporal ranges for the N2 and P3.

prepotent responses (De Neys & Everaerts, 2008; De Neys, Schaeken, & d'Ydewalle, 2005; Handley et al., 2004; Houdé, 2000; Houdé et al., 2000; Moutier & Houdé, 2003; Moutier et al., 2002; Robin & Holyoak, 1995; Viskontas et al., 2004). The observed transfer of SMART to inhibitory control then supports the prediction that higher-order cognitive strategy training aimed at improving reasoning, problem-solving, and comprehending has the added potential of exercising supporting inhibitory control processes and provides further evidence supporting models in which inhibitory control processes support comprehension and reasoning (Cain, 2006; Chiappe et al., 2000; De Beni & Palladino, 2000; De Neys, Schaeken, & d'Ydewalle, 2005; Gernsbacher & Faust, 1991; Handley et al., 2004; Houdé, 2000; Just & Carpenter, 1992; Kintsch & van Dijk, 1978; Pimperton & Nation, 2010; Robin & Holyoak, 1995; but see Friedman et al., 2006).

Although inhibitory control was the primary outcome measure in the present study, the results also provide support for the broader prediction that higher-order cognitive strategy training aimed at improving reasoning, problem-solving, and comprehending has the potential to improve executive function, in general. Executive function has been defined and operationalized in a host of ways (see Gilbert & Burgess, 2008; Miyake et al., 2000; Salthouse, Atkinson, & Berish, 2003). However, confirmatory factor analysis has provided evidence that executive function is composed of separable but interrelated processes (Miyake et al., 2000). Separable but correlated factors for inhibition, mental set shifting, and information updating and monitoring have been reliably observed in studies on young adults and children (Bull & Scerif, 2001; Friedman et al., 2006, 2008; Miyake et al., 2000). Thus, on the one hand, the observed gains in inhibitory control in the present study could be indicative of broader gains in a range of executive processes. In fact, previous research on SMART with elderly adults and adults who had experienced traumatic brain injury showed transfer of training to working memory, cognitive switching, verbal fluency, and reasoning processes (Anand et al., 2011; Vas et al., 2011), and research with elderly adults also has shown transfer of

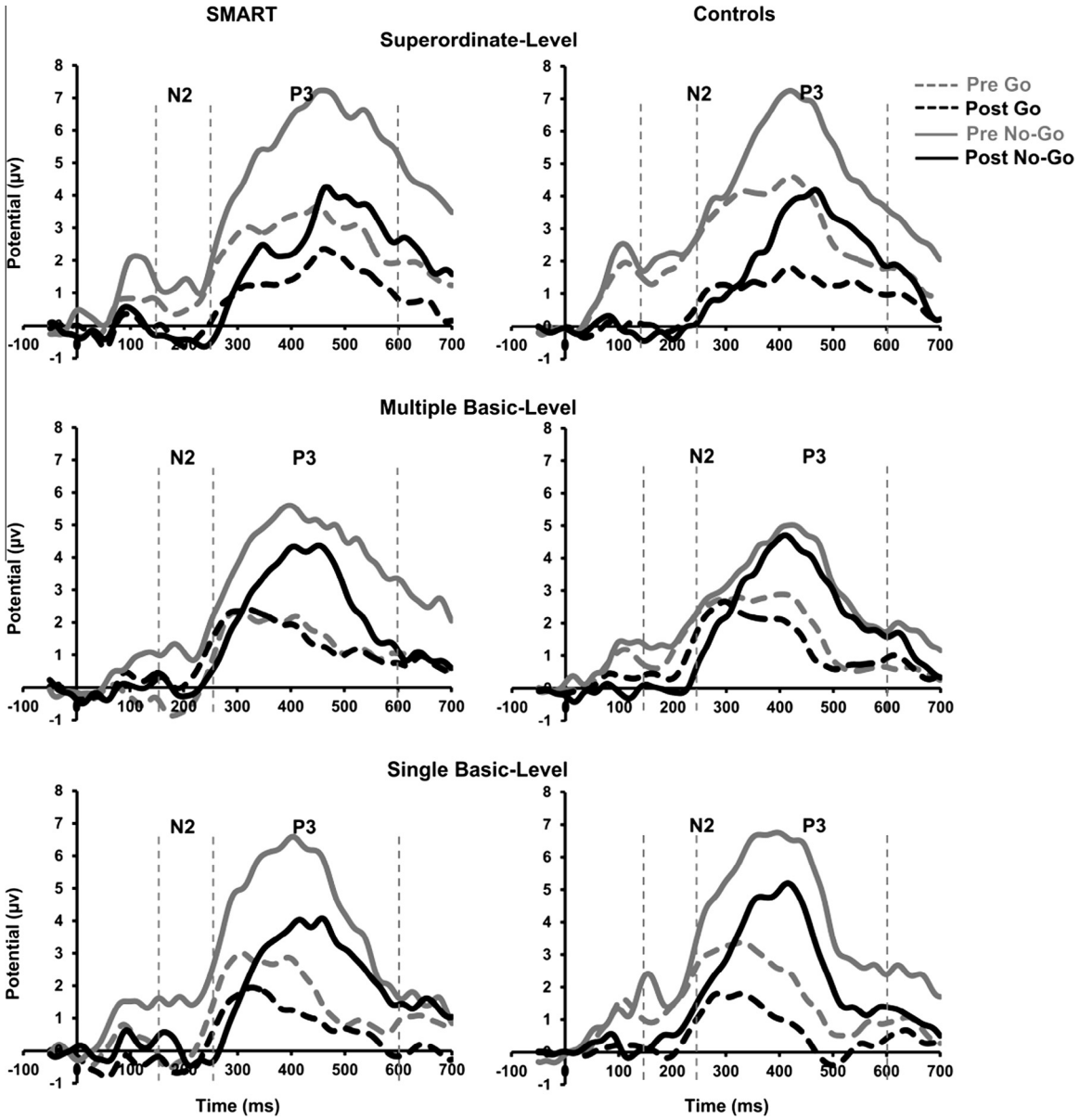

Fig. 6. ERP (μV) at Cz as a function of group, time, categorization, and trial-type. Data for the pretest session are shown in gray, and data for post-test session are shown in black. Data for the Go trial-types are depicted with dashed lines, and data for the No-Go trial-types are depicted with solid lines. Data for the SMART group are shown on the left, and data for the control group are shown on the right. Data for the superordinate-level categorization condition are shown in the upper row; data for the multiple basic-level categorization condition are shown in the center row; and data for the single basic-level categorization condition are shown in the lower row. Vertical black dashed lines indicate temporal ranges for the N2 and P3.

strategy-based video game training to working memory, cognitive switching, and reasoning processes (Basak, Boot, Voss, & Kramer, 2008). On the other hand, the observed gains in inhibitory control could have resulted from exercising integrated executive processes. Studies on working memory and executive function training have shown transfer of the training both to more distally related tasks and to higher-order tasks when working memory training involved exercising executive processes (see Morrison & Chein, 2011) and when executive function training involved variability in the scheduling of the recruitment of executive processes during training (Craik et al., 2007; Kramer, Hahn, & Gopher, 1999).

4.2. Training-related electrophysiological changes

When considered in the context of previously published results on the effects of deeper semantic processing on inhibitory control (Brier et al., 2010; Maguire et al., 2009), the present results suggest that SMART-related inhibitory controls gains might be due to a generalized engagement in deeper semantic processing. Given that increased depth of semantic processing leads to reductions in fronto-central P3 amplitude and theta-band power and increases in fronto-central P3 peak latency and theta-band power on No-Go trails (Brier et al., 2010; Maguire et al., 2009), the P3 results from the present study suggest a generalization of the influences of training-related deeper semantic processing to conditions typically requiring only shallower feature-oriented processing. SMART-related reductions in the inhibition-related fronto-central P3 observed in the single basic-level or shallowest semantic processing condition and SMART-related increases in inhibitory control (i.e., increases in correct rejection rates) were observed. Thus, the present results support the transfer of comprehension/reasoning training to inhibitory control, and the P3 effects suggest the enhanced inhibitory control is related to a generalized engagement in deeper semantic processing.

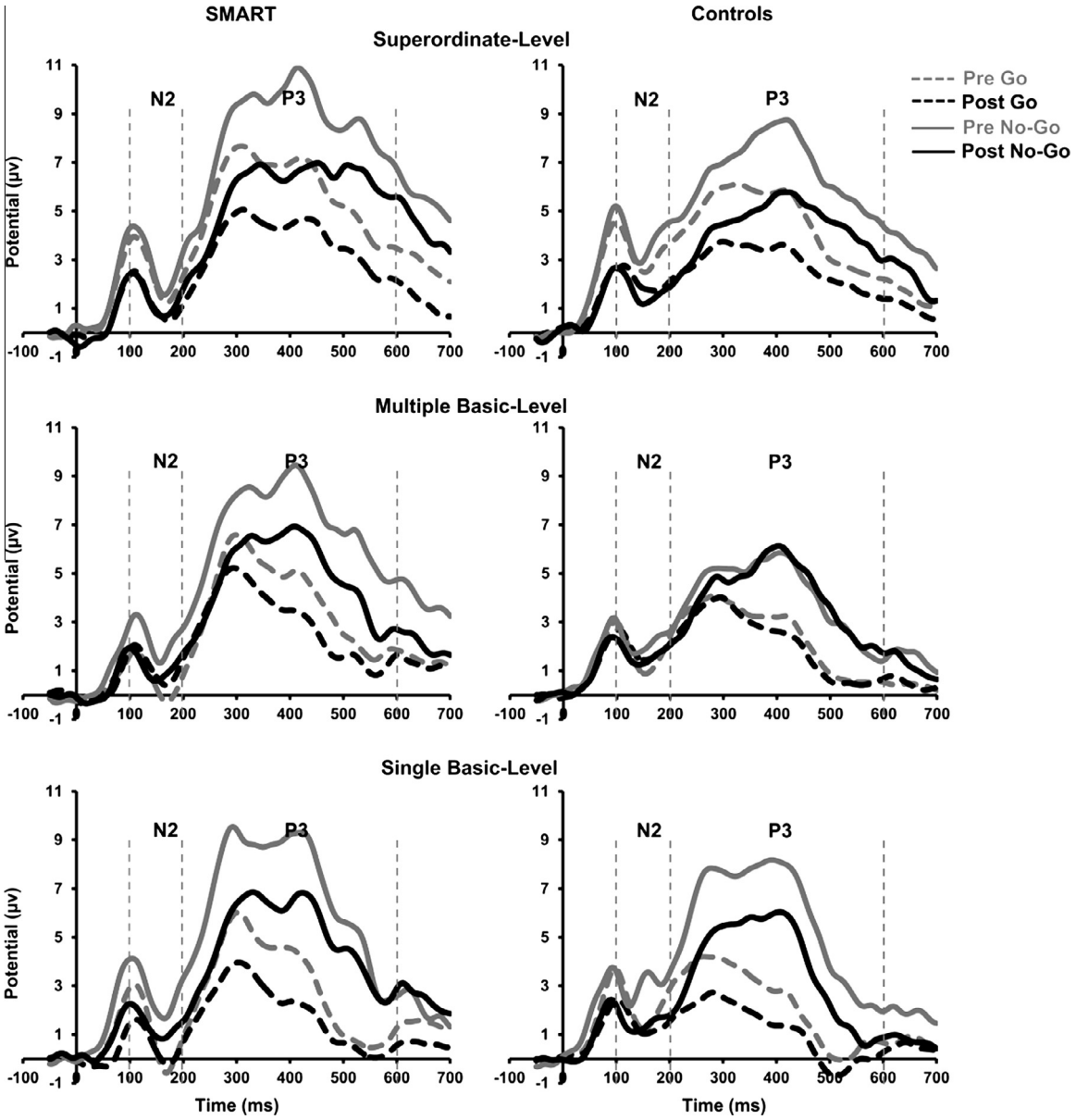

Fig. 7. ERP (μV) at Pz as a function of group, time, categorization, and trial-type. Data for the pretest session are shown in gray, and data for post-test session are shown in black. Data for the Go trial-types are depicted with dashed lines, and data for the No-Go trial-types are depicted with solid lines. Data for the SMART group are shown on the left, and data for the control group are shown on the right. Data for the superordinate-level categorization condition are shown in the upper row; data for the multiple basic-level categorization condition are shown in the center row; and data for the single basic-level categorization condition are shown in the lower row. Vertical black dashed lines indicate temporal ranges for the N2 and P3.

Although previous Go/No-Go inhibitory control studies have examined and observed inhibition-related P3 effects at Fz and averages over fronto-central electrodes (e.g., Donkers & van Boxtel, 2004; Hillman et al., 2012), questions have been raised about processes indexed by N2 and P3 across electrode cites. Greater P3 amplitude at Fz has been observed for No-Go trials compared to Go trials in several studies (e.g., Bruin & Wijers, 2002; Maguire et al., 2009; Nakata, Sakamoto, & Kakigi, 2010; Nakata et al., 2004). Additionally, EEG source localization analyses have suggested anterior-posterior distinctions between No-Go and Go signal generators, with No-Go generators having a more anterior localization (Bokura, Yamaguchi, & Kobayashi, 2001); MEG findings have suggested localization of inhibitory control signals to fronto-central regions (Sasaki, Gemba, Nambu, & Matsuzaki, 1993); and cortical recordings in monkeys have shown No-Go specific (i.e., versus Go) potentials generated in frontal cortices (Gemba, 1993; Gemba & Sasaki, 1990; Sasaki, Gemba, & Tsujimoto, 1989). However, P3 amplitude also has been observed to be greater for 'oddball' trials in oddball-type paradigms (e.g., Duncan-Johnson & Donchin, 1977; Polich & Bondurant, 1997; Polich, Ellerson, & Cohen, 1996), suggesting that P3 amplitude might index deviance- or novelty-related processes versus inhibitory control processes in Go/No-Go paradigms. Indeed, even in Go/No-Go paradigms, P3 amplitude at Fz, Cz, and Pz (and N2; Bruin & Wijers, 2002) has been observed to vary with the proportion of No-Go to Go trials, with P3 amplitude inversely related to the proportion of trial-types regardless of whether the lower proportion trial-type is the Go or No-Go trials (Banquet, Renault, & Lesevre, 1981; Bruin & Wijers, 2002; Eimer, 1993; Pfefferbaum & Ford, 1988). Thus, greater P3 amplitudes observed for No-Go trials relative to Go trials might index deviance- or novelty-related processing (i.e., processing less frequently presented stimuli) rather than inhibitory control processes, *per se*,

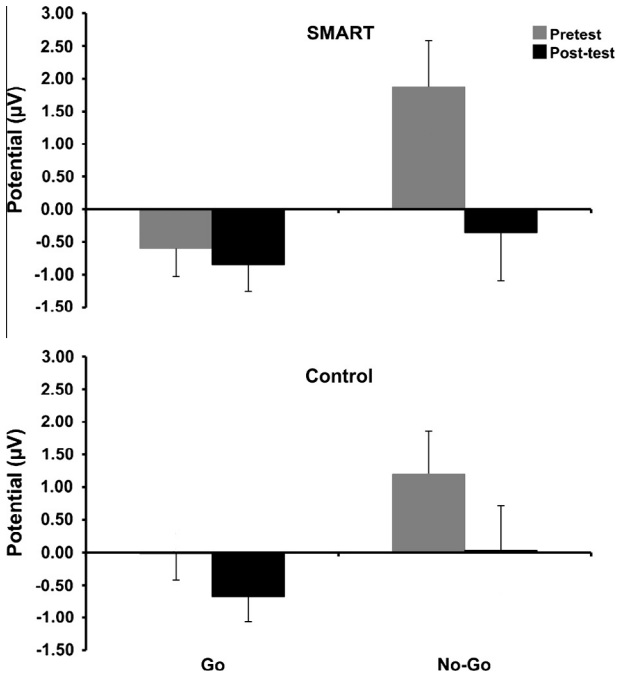

Fig. 8. Mean P3 signal change (μV) at Fz as a function of group, time, and trial-type. P3 signal-change was calculated by averaging the signal from 300 ms to 600 ms post-stimulus onset. Data for the pretest session are shown in gray bars, and data for the post-test session are shown in black bars. Data for the Go trial-types are shown on the left, and data for the No-Go trial-types are shown on the right. Data for the SMART group are shown in the upper graph, and data for the control group are shown in the lower graph. Bars depict 1 SEM.

because of the differences in the proportion of Go to No-Go trials used in typical studies.

However, evidence from multi-Go/No-Go (Donkers & van Boxtel, 2004) and cued Go/No-Go (Randall & Smith, 2011; Smith, 2011; Smith et al., 2007) studies provides support that fronto-central P3 on No-Go trials indexes inhibitory control processes. In a multi-Go/No-Go study, Donkers and van Boxtel (2004) had participants work through a Go/No-Go task and a Go/*GO* task, in which *GO* trials required a more forceful response than on Go trials. P3 amplitude was greater on No-Go trials than on go trials over Fz and Cz; P3 amplitude was greater on *GO* trials than on Go trials over Fz, Cz, and Pz; and P3 amplitude was greater on No-Go trials than on *GO* trials over Fz, Cz, and Pz. Thus, the findings suggest that the P3 component is affected by response switching (i.e., Go versus *GO*) and response inhibition (i.e., Go versus No-Go and *GO* versus No-Go).

Findings from the cued Go/No-Go studies have provided further evidence that the fronto-central P3 component on No-Go trials indexes inhibitory control-related processing (Randall & Smith, 2011; Smith, 2011; Smith et al., 2007). For example, Smith (2011) systematically varied cue symbol (No-Go, Go Left, and Go Right) and target symbol pairings. Manipulation of the cue-target pairings allowed for examining N2 and P3 amplitudes when (1) target responses were expected (i.e., No-Go, Go Left, or Go Right cues were followed by corresponding targets on 60% of the trials); (2) target responses were expected but the target symbol was unexpected (i.e., No-Go cue paired with a less frequently presented alternate No-Go target, or a Go Left or Right cue paired with a less frequently presented alternate Go Left or Right target); (3) the target response was switched from the cued response (i.e., Go Left preceded by a Go Right cue and vice versa); (4) the target response was unexpected (i.e., No-Go cue paired with a Go target); and (5) a cued response had to be inhibited (i.e., Go cue paired with a No-Go target). For No-Go trials, compared to validly cued No-Go trials and cued No-Go trials in which the No-Go symbol changed, greater P3 amplitudes were observed across Fz, FCz, Cz, CPz and Pz electrodes for trials requiring the inhibition of a cued response, providing evidence that the greater No-Go P3 amplitude indexes processes mediating inhibition rather than the processing of low frequency or novel stimuli. Additionally, for Go trials, greater P3 amplitudes were observed across the central electrodes when the required response did not match the expected response than in all other Go conditions. This greater amplitude P3 also was said to index the inhibition of the expected response, because the P3 amplitude was greater for trials requiring this response switch than trials requiring a switch to respond after being cued not to respond (i.e., a No-Go cue followed by a Go target).

4.3. Considerations

As with many cognitive training and educational studies, particularly those conducted within the context of a school setting, design issues must be considered when interpreting and evaluating the results (Morrison & Chein, 2011). On the one hand, the SMART program was administered within the school classrooms during normal school hours, thus increasing the ecological validity of the study (Varma et al., 2008). On the other hand, the present study was quasi-experimental (Campbell & Stanley, 1966). Participants were not randomly assigned to the trained and control groups, both groups were self-selected in that they were enrolled in the inhibitory control sub-study after responding to recruitment advertisements, and the control group was a passive, historical control group. The motivation of the SMART group who participated in this inhibitory control sub-study might have differed from those who did not participate, and the motivation of the SMART group might have differed from the passive control group. However, the demographic background of the SMART group was diverse, coming from a range of academic, family, and ethnic backgrounds, and in a previous study in which middle school students were randomly assigned to SMART or active control groups, SMART-related cognitive benefits were observed (Gamino et al., 2010). Although there were IQ and pretest correct rejection rate differences between the SMART and control groups, the SMART-related inhibitory control gains were observed after statistically controlling for IQ and pretest correct rejection rate. Furthermore, the observed changes in the SMART group were specific to the No-Go condition, where differences across conditions would not be expected for placebo or other general motivational factors. Finally, techniques for improving statistical power like prescreening data for quality and participants for histories of potentially confounding demographic/health/learning issues limit the generalization of the present finding. Thus, caution must be exercised when considering the generalization of the present results, particularly to students requiring remedial education, but future research might reveal the benefits of comprehension- and reasoning-based training for these students as well.

One additional consideration is that SMART could have affected pre-stimulus anticipatory processes and related electrical potential changes. If so, baseline correction using the mean potential over part of the prestimulus interval could have affected the calculation of the ERPs. The ITI for the present Go/No-Go task was fixed, and fixed ITIs have been shown to increase anticipatory processing and readiness to respond (Poulton, 1950). Additionally, the amplitude of the readiness potential (i.e., slow-wave negative potential change occurring prior to stimulus onsets) has been shown to increase with lower target frequencies and with the number of non-targets preceding a target (Starr, Sandroni, & Michalewski, 1995). However, to examine whether SMART affected the pre-stimulus potentials used in the calculation of the baseline, a Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic;

Table A1
ANOVA table examining hit and correct rejection rates as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.010	0.00††
Group (SMART; Control) × Time (Pre; Post)	1,54	0.003	0.0††
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.200	0.004
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	0.405	0.007
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	0.901	0.016
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.438	0.008
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	8.742*	0.139
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.292	0.005
Time (Pre; Post)	1,54	0.347	0.006
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.416	0.026
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	1.562	0.028
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	5.070*	0.086
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	17.813**	0.248
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	2.314	0.041
Trial-Type (Go; No-Go)	1,54	37.40**	0.409

* $p < .05$.
** $p < .001$.
†† *Partial* $\eta^2 < 0.001$.

Table A2
ANOVA table examining sensitivity (d') as a function of group, time, and categorization.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.121	0.002
Group (SMART; Control) × Time (Pre; Post)	1,54	0.00†	0.0††
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.289	0.005
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.115	0.002
Time (Pre; Post)	1,54	0.775	0.014
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.716	0.031
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	14.114**	0.207

** $p < .001$.
† $F < 0.001$.
†† *Partial* $\eta^2 < 0.001$.

Table A3
ANOVA table examining response bias ($ln(\beta)$) as a function of group, time, and categorization.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.675	0.012
Group (SMART; Control) × Time (Pre; Post)	1,54	2.260	0.040
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.935	0.017
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.921	0.017
Time (Pre; Post)	1,54	1.228	0.022
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.916	0.017
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.545	0.010

Table A4
ANOVA table examining decision criterion (c) as a function of group, time, and categorization.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.023	0.0††
Group (SMART; Control) × Time (Pre; Post)	1,54	7.530*	0.122
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.844	0.033
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.868	0.016
Time (Pre; Post)	1,54	1.948	0.035
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	3.716*	0.064
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	2.946	0.052

* $p<.05$.
†† *Partial* $\eta^2 << 0.001$.

Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go) mixed-model ANOVA was used to examine the mean potential changes corresponding to the baseline (i.e., the −100 ms to 0 ms prestimulus interval) at Fz, and none of the training-related effects (i.e., Group [SMART; Control] × Time [Pre; Post] and higher order interaction effects involving Group [SMART; Control] × Time [Pre; Post]) were significant, all $Fs(1,54) \leqslant 2.52$ and $Fs(2,108) \leqslant 1.62$, ps = *n.s.* Thus, there was not any evidence that SMART affected prestimlus baseline potentials at Fz. Although SMART might affect anticipatory processing, the present Go/No-Go task might not have been amenable to the detection of such effects. Readiness potentials, in particular, have been associated with preparing to *execute* motor responses rather than preparing to engage cognitive processes (Starr et al., 1995), with amplitudes being larger when making motor responses to targets compared to counting targets aloud and being absent when counting targets silently.

Table A5
ANOVA table examining reaction time as a function of group, time, and categorization.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.747	0.014
Group (SMART; Control) × Time (Pre; Post)	1,54	1.172	0.021
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.128	0.002
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.047	0.001
Time (Pre; Post)	1,54	1.256	0.023
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.650	0.030
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	45.979**	0.460

** $p < .001$.

Table A6
ANOVA table examining the reaction-time variability (CV) as a function of group, time, and categorization.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.105	0.002
Group (SMART; Control) × Time (Pre; Post)	1,54	1.950	0.035
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.401	0.007
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.527	0.010
Time (Pre; Post)	1,54	1.472	0.027
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.585	0.011
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	6.418*	0.106

* $p < .05$.

Table B1
ANOVA table for the N2 potential changes at Fz as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.001	0.0††
Group (SMART; Control) × Time (Pre; Post)	1,54	0.224	0.004
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.236	0.004
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	4.456*	0.078
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	0.190	0.004
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.621	0.029
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	1.094	0.020
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	2.626	0.046
Time (Pre; Post)	1,54	3.656	0.063
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.576	0.011
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	6.690*	0.110
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	2.667	0.047
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.182	0.003
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	1.544	0.028
Trial-Type (Go; No-Go)	1,54	0.001	0.0††

** $p < .001$
* $p < .05$.
†† *Partial* $\eta^2 < 0.001$.

Table B2
ANOVA table for the P3 potential changes at Fz as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.036	0.001
Group (SMART; Control) × Time (Pre; Post)	1,54	0.174	0.003
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.938	0.017
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	0.760	0.014
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	1.213	0.022
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.381	0.025
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	4.222*	0.073
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.616	0.011
Time (Pre; Post)	1,54	7.432*	0.121
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.359	0.025
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	12.030**	0.182
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.204	0.004
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.403	0.007
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	1.603	0.029
Trial-Type (Go; No-Go)	1,54	17.081**	0.240

* $p < .05$.
** $p < .001$.

Table B3
ANOVA table for the N2 potential changes at Cz as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	2.804	0.049
Group (SMART; Control) × Time (Pre; Post)	1,54	1.308	0.024
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.747	0.031
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	0.008	0.0[††]
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	0.379	0.007
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.911	0.017
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	0.018	0.0[††]
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.431	0.008
Time (Pre; Post)	1,54	14.722[**]	0.214
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	9.046[**]	0.143
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	0.017	0.0[††]
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	1.893	0.034
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	3.562[*]	0.062
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.979	0.018
Trial-Type (Go; No-Go)	1,54	3.328	0.058

[*] $p < .05$.
[**] $p < .001$.
[††] *Partial* $\eta^2 < 0.001$.

Table B4
ANOVA table for the P3 potential changes at Cz as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.0[†]	0.0[††]
Group (SMART; Control) × Time (Pre; Post)	1,54	0.004	0.0[††]
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.469	0.009
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	0.408	0.007
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	0.001	0.0[††]
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.095	0.020
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	0.008	0.0[††]
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.292	0.005
Time (Pre; Post)	1,54	13.898[**]	0.205
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	7.900[*]	0.128
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	1.562	0.028
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	3.643[*]	0.063
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	30.454[**]	0.361
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	3.543[*]	0.062
Trial-Type (Go; No-Go)	1,54	41.043[**]	0.432

[*] $p < .05$.
[**] $p < .001$.
[†] $F < 0.001$.
[††] *Partial* $\eta^2 < 0.001$.

Table B5
ANOVA table for the N2 potential changes at Pz as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	0.847	0.015
Group (SMART; Control) × Time (Pre; Post)	1,54	0.028	0.001
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.205	0.004
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	3.678	0.064
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	0.712	0.013
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.239	0.004
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	0.039	0.001
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.924	0.017
Time (Pre; Post)	1,54	9.759[*]	0.153
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	4.671[*]	0.080
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	17.164[**]	0.241
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.454	0.008
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	10.020[**]	0.157
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	2.631	0.046
Trial-Type (Go; No-Go)	1,54	13.008[*]	0.194

[*] $p < .05$.
[**] $p < .001$.

4.4. Conclusion

Both higher education and the work-place have increasingly demanded that students emerge from secondary schools with greater critical thinking skills (Conley, 2008), creating a challenge for educators to incorporate domain-general cognitive strategies in their teaching (Conley, 2008; Pressley et al., 1990; Rosenshine & Meister, 1992). The present results provide evidence that curricula that

Table B6
ANOVA table for the P3 potential changes at Pz as a function of group, time, categorization, and trial-type.

Effect	*df*	*F*	*Partial* η^2
Group (SMART; Control)	1,54	1.659	0.030
Group (SMART; Control) × Time (Pre; Post)	1,54	0.350	0.006
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	0.665	0.012
Group (SMART; Control) × Trial-Type (Go; No-Go)	1,54	0.933	0.017
Group (SMART; Control) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type Trial-Type (Go; No-Go)	2,108	0.217	0.004
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	1.185	0.021
Group (SMART; Control) × Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	0.440	0.008
Group (SMART; Control) × Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.912	0.017
Time (Pre; Post)	1,54	12.345*	0.186
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	3.902*	0.067
Time (Pre; Post) × Trial-Type (Go; No-Go)	1,54	3.788	0.066
Time (Pre; Post) × Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	0.141	0.003
Categorization (Single-Basic; Multiple-Basic; Superordinate)	2,108	20.561**	0.276
Categorization (Single-Basic; Multiple-Basic; Superordinate) × Trial-Type (Go; No-Go)	2,108	7.096*	0.116
Trial-Type (Go; No-Go)	1,54	74.044**	0.578

* $p < .05$.
** $p < .001$.

include higher-order cognitive strategy training aimed at engaging students in inductive reasoning or inferencing, even brief training with subject-specific content, can strengthen supporting inhibitory control processes. The strengthening of inhibitory control processes then has the potential to facilitate learning and problem-solving across a range of domains (Dempster, 1991; Dempster & Corkill, 1999). Various forms of reasoning training, in fact, have been shown to improve performance on broader assessments of academic achievement and intelligence (Klauer, Willmes, & Phye, 2002; Luria, 1959). The present results suggest that such improvements could be due, at least in part, to strengthening supporting executive processes.

Acknowledgments

The authors would like to thank the SMART teachers for administering the program to the students; the SMART data entry and administrative teams; Tiffani Jantz, Monique Salinas, Diane Ogiela, Shreya Goyal, Timothy Meyers, and Monica Yagle for their help with data collection and processing; Ilana Bennett, Ehsan Shokri-Kojori, and Jeffrey Spence for constructive discussions and comments on drafts of this manuscript; and the teachers and administrators at the participating schools for their time and support of the study and the SMART program.

Appendix A

See Tables A1–A6.

Appendix B

See Tables B1–B6.

References

Anand, R., Chapman, S. B., Rackley, A., Keebler, M., Zientz, J., Hart, J. Jr. et al. (2011). Gist reasoning training in cognitively normal seniors. *International Journal of Geriatric Psychiatry, 26*, 961–968.

Banquet, J. P., Renault, B., & Lesevre, N. (1981). Effect of task and stimulus probability on evoked potentials. *Biological Psychology, 13*, 203–214.

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin, 121*, 65–94.

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychology and Aging, 23*, 765–777.

Bedard, A. C., Nichols, S., Barbosa, J. A., Schachar, R., Logan, G. D., & Tannock, R. (2002). The development of selective inhibitory control across the life span. *Developmental Neuropsychology, 21*, 93–111.

Bokura, H., Yamaguchi, S., & Kobayashi, S. (2001). Electrophysiological correlates for response inhibition in a Go/NoGo task. *Clinical Neurophysiology, 112*, 2224–2232.

Brier, M. R., Ferree, T. C., Maguire, M. J., Moore, P., Spence, J., Tillman, G. D., et al. (2010). Frontal theta and alpha power and coherence changes are modulated by semantic complexity in Go/NoGo tasks. *International Journal of Psychophysiology, 78*, 215–224.

Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental Neuropsychology, 26*, 571–593.

Brown, A. L., & Day, J. D. (1983). Macrorules for summarizing texts: The development of expertise. *Journal of Verbal Learning and Verbal Behavior, 22*, 1–14.

Bruin, K. J., & Wijers, A. A. (2002). Inhibition, response mode, and stimulus probability: A comparative event-related potential study. *Clinical Neurophysiology, 113*, 1172–1182.

Bruin, K. J., Wijers, A. A., & van Staveren, A. S. J. (2001). Response priming in a go/nogo task: Do we have to explain the go/nogo N2 effect in terms of response activation instead of inhibition? *Clinical Neurophysiology, 112*, 1660–1671.

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology, 19*, 273–293.

Cain, K. (2006). Individual differences in children's memory and reading comprehension: An investigation of semantic and inhibitory deficits. *Memory, 14*, 553–569.

Campbell, D., & Stanley, J. (1966). *Experimental and quasi-experimental designs for research*. Boston: Houghton Mifflin Company.

Chapman, S. B., & Gamino, J. F. (2008). *Strategic memory and reasoning training (SMART)*. Dallas, TX: Center for BrainHealth.

Chiappe, P., Siegel, L., & Hasher, L. (2000). Working memory, inhibitory control, and reading disability. *Memory & Cognition, 28*, 8–17.

Collins, A. M., & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior, 8*. 240–&.

Conley, M. (2008). Cognitive strategy instruction for adolescents: What we know about the promise, what we don't know about the potential. *Harvard Educational Review, 78*, 84–106.

Craik, F. I. M., Winocur, G., Palmer, H., Binns, M. A., Edwards, M., Bridges, K., et al. (2007). Cognitive rehabilitation in the elderly: Effects on memory. *Journal of the International Neuropsychological Society, 13*, 132–142.

Dansereau, D. F. (1985). Learning strategy research. In J. W. Segal, S. F. Chipman, & R. Glaser (Eds.). *Thinking and learning skills: Relating instruction to research* (Vol. 1, pp. 209–239). Hillsdale, NJ: Erlbaum.

De Beni, R., & Palladino, P. (2000). Intrusion errors in working memory tasks: Are they related to reading comprehension ability? *Learning and Individual Differences, 12*, 131–143.

De Neys, W., & Everaerts, D. (2008). Developmental trends in everyday conditional reasoning: The retrieval and inhibition interplay. *Journal of Experimental Child Psychology, 100*, 252–263.

De Neys, W., Schaeken, W., & d'Ydewalle, G. (2005). Working memory and everyday conditional reasoning: Retrieval and inhibition of stored counterexamples. *Thinking & Reasoning, 11*, 349–381.

Dempster, F. N. (1991). Inhibitory processes: A neglected dimension of intelligence. *Intelligence, 15*, 157–173.

Dempster, F. N., & Corkill, A. (1999). Interference and inhibition in cognition and behavior: Unifying themes for educational psychology. *Educational Psychology Review, 11*, 1–88.

Donkers, F. C. L., & van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition, 56*, 165–176.

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology, 14*, 456–467.

Duncan, C. C., Barry, R. J., Connolly, J. F., Fischer, C., Michie, P. T., Näätänen, R., et al. (2009). Event-related potentials in clinical research: Guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400. *Clinical Neurophysiology, 120*, 1883–1908.

Eagle, D., Bari, A., & Robbins, T. (2008). The neuropsychopharmacology of action inhibition: Cross-species translation of the stop-signal and go/no-go tasks. *Psychopharmacology, 199*, 439–456.

Eimer, M. (1993). Effects of attention and stimulus probability on ERPs in a Go/Nogo task. *Biological Psychology, 35*, 123–138.

Falkenstein, M., Hoormann, J., & Hohnsbein, J. (1999). ERP components in Go/Nogo tasks and their relation to inhibition. *Acta Psychologica, 101*, 267–291.

Ferree, T. (2006). Spherical splines and average referencing in scalp electroencephalography. *Brain Topography, 19*, 43–52.

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

Friedman, N. P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science, 17*, 172–179.

Friedman, N. P., Miyake, A., Young, S. E., DeFries, J. C., Corley, R. P., & Hewitt, J. K. (2008). Individual differences in executive functions are almost entirely genetic in origin. *Journal of Experimental Psychology: General, 137*, 201–225.

Gamino, J. F., Chapman, S. B., Hull, E. L., & Lyon, R. (2010). Effects of higher-order cognitive strategy training on gist reasoning and fact learning in adolescents. *Frontiers in Psychology, 1*, 188. http://dx.doi.org/10.3389/fpsyg.2010.00188.

Gemba, H. (1993). Changes in cortical field potentials during learning processes of go/no-go reaction time hand movement with tone discrimination in the monkey. *Neuroscience Letters, 159*, 21–24.

Gemba, H., & Sasaki, K. (1990). Potential related to no-go reaction in go/no-go hand movement with discrimination between tone stimuli of different frequencies in the monkey. *Brain Research, 537*, 340–344.

Gernsbacher, M. A., & Faust, M. E. (1991). The mechanism of suppression: A component of general comprehension skill. *Journal of Experimental Psychology: Learning Memory and Cognition, 17*, 245–262.

Gernsbacher, M. A., & Robertson, R. R. W. (1995). Reading skill and suppression revisited. *Psychological Science, 6*, 165–169.

Gilbert, S. J., & Burgess, P. W. (2008). Executive function. *Current Biology, 18*, R110–R114.

Green, K. E., & Kluever, R. C. (1991). Structural properties of Raven's Coloured Progressive Matrices for a sample of gifted children. *Perceptual and Motor Skills, 72*, 59–64.

Handley, S. J., Capon, A., Beveriddge, M., Dennis, I., & Evans, J. S. B. T. (2004). Working memory, inhibitory control and the development of children's reasoning. *Thinking & Reasoning, 10*, 175–195.

Hillman, C. H., Pontifex, M. B., Motl, R. W., O'Leary, K. C., Johnson, C. R., Scudder, M. R., et al. (2012). From ERPs to academics. *Developmental Cognitive Neuroscience, 2*(Suppl. 1), S90–S98.

Houdé, O. (2000). Inhibition and cognitive development: Object, number, categorization, and reasoning. *Cognitive Development, 15*, 63–73.

Houdé, O., Zago, L., Mellet, E., Moutier, S., Pineau, A., Mazoyer, B., et al. (2000). Shifting from the perceptual brain to the logical brain: The neural impact of cognitive inhibition training. *Journal of Cognitive Neuroscience, 12*, 721–728.

Johnstone, S. J., Dimoska, A., Smith, J. L., Barry, R. J., Pleffer, C. B., Chiswick, D., et al. (2007). The development of stop-signal and Go/Nogo response inhibition in children aged 7–12 years: Performance and event-related potential indices. *International Journal of Psychophysiology, 63*, 25–38.

Junghöfer, M., Elbert, T., Tucker, D. M., & Braun, C. (1999). The polar average reference effect: A bias in estimating the head surface integral in EEG recording. *Clinical Neurophysiology, 110*, 1149–1155.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*, 122–149.

Kintsch, W., & van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review, 85*, 363–394.

Klauer, K. J., & Phye, G. D. (2008). Inductive reasoning: A training approach. *Review of Educational Research, 78*, 85–123.

Klauer, K. J., Willmes, K., & Phye, G. D. (2002). Inducing inductive reasoning: Does it transfer to fluid intelligence? *Contemporary Educational Psychology, 27*, 1–25.

Kopp, B., Mattler, U., Goertz, R., & Rist, F. (1996). N2, P3 and the lateralized readiness potential in a nogo task involving selective response priming. *Electroencephalography and Clinical Neurophysiology, 99*, 19–27.

Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: Explorations of executive control processes in the task switching paradigm. *Acta Psychologica, 101*, 339–378.

Kramer, A. F., Humphrey, D. G., Larish, J. F., Logan, G. D., & Strayer, D. L. (1994). Aging and inhibition: Beyond a unitary view of inhibitory processing in attention. *Psychology and Aging, 9*, 491–512.

Luria, A. R. (1959). The directive function of speech in development and dissolution. *Word, 15*, 314–464.

Maguire, M. J., Brier, M. R., Moore, P. S., Ferree, T. C., Ray, D., Mostofsky, S., et al. (2009). The influence of perceptual and semantic categorization on inhibitory processing as measured by the N2–P3 response. *Brain and Cognition, 71*, 196–203.

Maguire, M. J., White, J., & Brier, M. R. (2011). How semantic categorization influences inhibitory processing in middle-childhood: An event related potentials study. *Brain and Cognition, 76*, 77–86.

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*, 49–100.

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

Moutier, S., Angeard, N., & Houde, O. (2002). Deductive reasoning and matching-bias inhibition training: Evidence from a debiasing paradigm. *Thinking & Reasoning, 8*, 205–224.

Moutier, S., & Houdé, O. (2003). Judgement under uncertainty and conjunction fallacy inhibition training. *Thinking & Reasoning, 9*, 185–201.

Nakata, H., Inui, K., Nishihira, Y., Hatta, A., Sakamoto, M., Kida, T., et al. (2004). Effects of a go/nogo task on event-related potentials following somatosensory stimulation. *Clinical Neurophysiology, 115*, 361–368.

Nakata, H., Sakamoto, K., & Kakigi, R. (2010). Characteristics of No-go-P300 component during somatosensory Go/No-go paradigms. *Neuroscience Letters, 478*, 124–127.

Pellegrino, J. W., & Glaser, R. (1979). Components of inductive reasoning. In R. E. Snow, P. A. Federico, & W. E. Montague (Eds.), *Aptitude, learning, and instruction: Cognitive process analyses of aptitude* (pp. 177–218). Hillsdale, NJ: Erlbaum.

Perner, J., Lang, B., & Kloo, D. (2002). Theory of mind and self-control: More than a common problem of inhibition. *Child Development, 73*, 752–767.

Perrin, F., Pernier, J., Bertrand, O., & Echallier, J. F. (1989). Spherical splines for scalp potential and current density mapping. *Electroencephalography and Clinical Neurophysiology, 72*, 184–187.

Pfefferbaum, A., & Ford, J. M. (1988). ERPs to stimuli requiring response production and inhibition: Effects of age, probability and visual noise. *Electroencephalography and Clinical Neurophysiology, 71*, 55–63.

Pimperton, H., & Nation, K. (2010). Suppressing irrelevant information from working memory: Evidence for domain-specific deficits in poor comprehenders. *Journal of Memory and Language, 62*, 380–391.

Polich, J., & Bondurant, T. (1997). P300 sequence effects, probability, and interstimulus interval. *Physiology & Behavior, 61*, 843–849.

Polich, J., Ellerson, P. C., & Cohen, J. (1996). P300, stimulus intensity, modality, and probability. *International Journal of Psychophysiology, 23*, 55–62.

Poulton, E. C. (1950). Perceptual anticipation and reaction time. *Quarterly Journal of Experimental Psychology, 2*, 99–112.

Pressley, M., Woloshyn, V., Lysynchuk, L., Martin, V., Wood, E., & Willoughby, T. (1990). A primer of research on cognitive strategy instruction: The important issues and how to address them. *Educational Psychology Review, 2*, 1–58.

Randall, W. M., & Smith, J. L. (2011). Conflict and inhibition in the cued-Go/NoGo task. *Clinical Neurophysiology, 122*, 2400–2407.

Robin, N., & Holyoak, K. J. (1995). Relational complexity and the function of prefrontal cortex. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 987–997). Cambridge: MIT Press.

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyesbraem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8*, 382–439.

Rosenshine, B., & Meister, C. (1992). The use of scaffolds for teaching higher-level cognitive strategies. *Educational Leadership, 49*, 26–33.

Rubia, K., Russell, T., Overmeyer, S., Brammer, M. J., Bullmore, E. T., Sharma, T., et al. (2001). Mapping motor inhibition: Conjunctive brain activations across different versions of go/no-go and stop tasks. *NeuroImage, 13*, 250–261.

Ryan, M., Martin, R., Denckla, M. B., Mostofsky, S. H., & Mahone, E. M. (2010). Interstimulus jitter facilitates response control in children with ADHD. *Journal of the International Neuropsychological Society, 16*, 388–393.

Salthouse, T. A., Atkinson, T. M., & Berish, D. E. (2003). Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology: General, 132*, 566–594.

Sasaki, K., Gemba, H., Nambu, A., & Matsuzaki, R. (1993). No-go activity in the frontal association cortex of human subjects. *Neuroscience Research, 18*, 249–252.

Sasaki, K., Gemba, H., & Tsujimoto, T. (1989). Suppression of visually initiated hand movement by stimulation of the prefrontal cortex in the monkey. *Brain Research, 495*, 100–107.

Schachar, R., Logan, G., Robaey, P., Chen, S., Ickowicz, A., & Barr, C. (2007). Restraint and cancellation: Multiple inhibition deficits in attention deficit hyperactivity disorder. *Journal of Abnormal Child Psychology, 35*, 229–238.

Segalowitz, N., & Frenkiel-Fishman, S. (2005). Attention control and ability level in a complex cognitive skill: Attention shifting and second-language proficiency. *Memory & Cognition, 33*, 644–653.

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

Simpson, A., & Riggs, K. J. (2006). Conditions under which children experience inhibitory difficulty with a "button-press" go/no-go task. *Journal of Experimental Child Psychology, 94*, 18–26.

Simson, R., Vaughan, H. G., Jr., & Ritter, W. (1977). The scalp topography of potentials in auditory and visual Go/NoGo tasks. *Electroencephalography and Clinical Neurophysiology, 43*, 864–875.

Smith, J. L. (2011). To Go or not to Go, that is the question: Do the N2 and P3 reflect stimulus- or response-related conflict? *International Journal of Psychophysiology, 82*, 143–152.

Smith, J. L., Johnstone, S. J., & Barry, R. J. (2007). Response priming in the Go/NoGo task: The N2 reflects neither inhibition nor conflict. *Clinical Neurophysiology, 118*, 343–355.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6*, 174–215.

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, 31*, 137–149.

Starr, A., Sandroni, P., & Michalewski, H. J. (1995). Readiness to respond in a target detection task: Pre- and post-stimulus event-related potentials in normal subjects. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 96*, 76–92.

Sternberg, R. J., & Gardner, M. K. (1983). Unities in inductive reasoning. *Journal of Experimental Psychology: General, 112*, 80–116.

van der Ven, A. H. G. S., & Ellis, J. L. (2000). A Rasch analysis of Raven's standard progressive matrices. *Personality and Individual Differences, 29*, 45–64.

van Dijk, T. A. (1977). Pragmatic macro-structures in discourse and cognition. In M. de Mey, R. Pinxten, M. Poriau, & R. Vandamme (Eds.), *CC 77 international workshop on the cognitive viewpoint*. Ghent: University of Ghent.

Varma, S., McCandliss, B. D., & Schwartz, D. (2008). Scientific and pragmatic challenges for bridging education and neuroscience. *Educational Researcher, 37*, 140–152.

Vas, A. K., Chapman, S. B., Cook, L. G., Elliott, A. C., & Keebler, M. (2011). Higher-order reasoning training years after traumatic brain injury in adults. *Journal of Head Trauma Rehabilitation, 26*, 224–239.

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Science, 12*, 418–424.

Verbruggen, F., & Logan, G. D. (2009). Models of response inhibition in the stop-signal and stop-change paradigms. *Neuroscience & Biobehavioral Reviews, 33*, 647–661.

Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition, and analogical reasoning in older adults. *Psychology and Aging, 19*, 581–591.

Wagenmakers, E. J., & Brown, S. (2007). On the linear relation between the mean and the standard deviation of a response time distribution. *Psychological Review, 114*, 830–841.

Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence (WASI)*. San Antonio, TX: Pearson/PsychCorp.

Weinstein, C. E., & Mayer, R. E. (1986). The teaching of learning strategies. In M. C. Wittrock (Ed.), *Handbook of research on teaching* (pp. 315–327). NY: Macmillian Publishing Company.

Weinstein, C. E., & Meyer, D. K. (1991). Cognitive learning strategies and college teaching. *New Directions for Teaching and Learning, 1991*, 15–26.

Weinstein, C. E., Ridley, D. S., Dahl, T., & Weber, E. S. (1989). Helping students develop strategies for effective learning. *Educational Leadership, 46*, 17–19.

Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology, 35*, 205–213.

Wodka, E. L., Simmonds, D. J., Mahone, E. M., & Mostofsky, S. H. (2009). Moderate variability in stimulus presentation improves motor response control. *Journal of Clinical Experimental Neuropsychology, 31*, 483–488.

Woodman, G. F. (2010). A brief introduction to the use of event-related potentials in studies of perception and attention. *Attention, Perception, & Psychophysics, 72*, 2031–2046.