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Visual and Auditory Interference Control of Attention in Developmental Dyslexia

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Abstract

An accumulating body of evidence highlights the contribution of general cognitive processes, such as attention, to language-related skills. **Objective:** The purpose of the present study was to explore how interference control (a subcomponent of selective attention) is affected in developmental dyslexia (DD) by means of control over simple stimulus-response mappings. Furthermore, we aimed to examine interference control in adults with DD across sensory modalities. **Methods:** The performance of 14 dyslexic adults and 14 matched controls was compared on visual/auditory Simon tasks, in which conflict was presented in terms of an incongruent mapping between the location of a visual/auditory stimulus and the appropriate motor response. **Results:** In the auditory task, dyslexic participants exhibited larger Simon effect costs; namely, they showed disproportionately larger reaction times (RTs)/errors costs when the auditory stimulus and response were incongruent relative to RT/errors costs of non-impaired readers. In the visual Simon task, both groups presented Simon effect costs to the same extent. **Conclusion:** These results indicate that the ability to control auditory selective attention is carried out less effectively in those with DD compared with visually controlled processing. The implications of this impaired process for the language-related skills of individuals with DD are discussed.

Keywords: Adults, Developmental dyslexia, Inhibition, Interference control, Selective attention, Sensory modality, Simon task

INTRODUCTION

Developmental dyslexia (DD) is defined as a specific reading disability characterized by a deficit in the accurate or fluent decoding of single printed words, unaccounted for by a specific sensory deficit or a more general intellectual impairment (International Dyslexia Association, 2002). Whether the problem in DD is restricted to a circumscribed difficulty in language or whether the difficulty is more general remains highly controversial (for a review, see Démonet, Taylor, & Chaix, 2004). The commonly held view is that DD is fundamentally a language-specific disorder that arises from phonological impairments (Snowling, 2000a). Consistent with this account, most typical symptoms of DD are phonological by nature and are manifested in problems with phonological awareness, lexical retrieval, and verbal working memory (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Other accounts, however, suggest that DD arises from domain general deficits that are not restricted to the language domain, such as learning impairments, sensory deficits, and attentional problems (Nicolson & Fawcett, 2011; Stein & Walsh, 1997; Vidyasagar & Pammer, 2010). Consistent with the hypothesis of domain general deficits in DD, individuals with DD exhibit implicit and procedural learning impairments (Gabay & Holt, 2015; Gabay, Thiessen, & Holt, 2015; Gabay, Vakil, Schiff, & Holt, 2015). With regard to attentional abilities, both adults and children with DD exhibit deficits in attentional processes across a wide array of tasks (for a review, see Valdois, Bosse, & Tainturier, 2004). However, the exact nature of attentional deficits remains debatable, with some who argue in favor of deficits in orienting of attention (Buchholz & Aimola Davies, 2008; Gabay, Gabay, Henik, Schiff, & Behrmann, 2015; Gabay, Gabay, Schiff, Ashkenazi, & Henik, 2013; Sireteanu, Goertz, Bachert, & Wandert, 2005) or alertness (Goldfarb & Shaul, 2013), while others emphasize impairments in executive control (Brosnan et al., 2002; Helland & Asbjørnsen, 2000; Reiter, Tucha, & Lange, 2005).

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THE RELATIONSHIP BETWEEN EXECUTIVE FUNCTIONS AND LANGUAGE-RELATED SKILLS

Executive functions represent a set of mental processes that are required for the purpose of concentrating and paying attention where automatic response is insufficient. It is commonly agreed that executive functions consist of inhibitory control, working memory, and flexibility (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000). Inhibitory control is the subcomponent of executive attention that enables us to selectively attend to stimuli, focus on what we choose, and suppress attention to other stimuli (Diamond, 2013). The most typical example that illustrates the necessity of blocking irrelevant information during selection is demonstrated when listening to someone talking amid a conversational background (cocktail party phenomenon). For this purpose, listeners must not only select which source of auditory information to attend to, but also ignore other sources of irrelevant information.

This remarkable ability of focusing one's attention on relevant sensory processing while filtering out irrelevant information seems to be particularly important for language acquisition. In order to acquire language, listeners need to segment speech units from a continuous stream of sounds (segmentation) and learn to treat highly variable speech units as equivalent (categorization). Speech segmentation requires listeners to identify cues in a continuous speech stream that signal word boundaries (statistical learning) and attend to those that are more effective while ignoring less effective cues (cue integration) (Weiss, Gerfen, & Mitchel, 2010). Similarly, speech categorization involves attending to specific acoustic dimensions while disregarding others (Goldstone, 1994; Nosofsky, 1986). It has been suggested that domain general abilities such as learning (Holt & Lotto, 2010; Holt, Lotto, & Kluender, 1998; Romberg & Saffran, 2010) and selective attention (Francis & Nusbaum, 2002; Holt, Tierney, Guerra, Laffere, & Dick, 2018; Weiss et al., 2010) play a significant role in speech segmentation and categorization. Consistent with this, Weiss et al. (2010) examined the relationship between executive functions and the ability to segment sequences of speech sounds in a statistical learning task with two conflicting sets of cues to word boundaries. It was demonstrated that the ability to successfully segment a stream of sounds (which contained two opposing segmentation cues) was positively correlated with the ability to inhibit irrelevant information.

Consistent with the assumption of a relation between general cognitive processes (such as attention) and language outcomes, Gomes, Wolfson, and Halperin (2007) showed that the ability to sustain auditory but not visual attention (as measured by the Continuous Performance Test) was found to be related to language functioning. Further research that used electrophysiological measures demonstrated that temporal selective attention during speech discrimination was highly correlated with metalinguistic skills (Astheimer, Janus, Moreno, & Bialystok, 2014). Two additional studies directly showed that auditory selective attention plays a significant role in speech processing. Lehmann and Schönwiesner (2014) demonstrated that endogenous selective attention to speech signals modulates human brainstem response, while Yoncheva, Maurer, Zevin, and McCandliss (2014) showed that selective attention to phonology modulated cortical processing of auditory words. Finally, Reetzke, Maddox, and Chandrasekaran (2016) demonstrated that better executive flexibility as measured by the Wisconsin Card Sorting Test resulted in more successful rule-based learning of sound categories.

Along similar lines, several researches have documented impairments in auditory selective attention in language-related developmental disorders such as specific language impairment (SLI) and DD. For instance, children with SLI exhibit selective impairment in auditory but not in visual selective attention (Spaulding, Plante, & Vance, 2008). Furthermore, individuals with DD were found to be impaired in dichotic listening tasks (Ben-Artzi, Fostick, & Babkoff, 2005). Others have found that selective auditory attention to speech sounds in dyslexic adults produced patterns of deactivation in occipital brain areas that differ significantly from those observed in non-impaired readers (Dufor, Serniclaes, Sprenger-Charolles, & Démonet, 2007). Taken together, these results indicate a possible role between auditory selective attention and language-related skills.

INTERFERENCE CONTROL

Inhibition is an important function of selective attention (Neill, Valdes, & Terry, 1995). Inhibition in itself is not a unitary concept and can be divided into inhibition in action (the ability to inhibit a prepotent automatic response, usually termed response inhibition) and inhibition of attention (i.e., the efficiency with which one is able to ignore irrelevant information while processing target stimuli, termed interference control) (Diamond, 2013). Response inhibition is usually tapped by tasks in which one merely needs to inhibit a response. In tasks that tap response inhibition, such as the stop signal tasks and go/no-go tasks, participants respond as fast as possible to most stimuli, while inhibiting a response to some stimuli, which are signaled by the presence of a specific stimulus (e.g., a specific letter or tone). Hence, participants must completely stop an initiated response in order to perform well. In contrast, tasks that measure interference control require participants to inhibit one response in order to make another and inhibition is required on the perceptual level. Interference control can be measured by Stroop and Simon tasks in which conflict is evident within two dimensions of a stimulus. In the Stroop task, participants are presented with series of color words and are asked to name the color of the word (e.g., BLUE in red ink) and ignore the meaning of the word. The usual pattern of results is that participants are faster in congruent trials compared with incongruent trials. It has been suggested that the Stroop task measures the ability to control interference because it requires participants to inhibit the dominant response tendency to read the words and, instead, name the color of the words

(Homack & Riccio, 2004). Similarly, in a typical Simon task, participants view a colored box presented to the left or right of the fixation and have to make a left or right button press based on stimulus color and ignore location. In the critical incongruent trials (when the location of the stimulus and the location of the response do not match), responses are typically slower than in congruent trials (when stimulus and response locations match) because of the need to inhibit the prepotent tendency to respond based on stimulus location. Thus, the degree of interference in incongruent trials (termed the Simon effect) is taken as a measure of inhibitory control. Simon effects have been observed in both the visual and auditory modalities (Lu & Proctor, 1995). Within the auditory modality, participants hear tones presented to the left or the right ear and must press a left or right button based on stimulus pitch (to indicate whether they heard either low- or high-pitched tones) and ignore location. Here, as within the visual modality, responses on incongruent trials (when the stimulated ear and the pure tone that signaled the appropriate response do not match), responses are slower than in congruent trials (when the stimulated ear and the response location match) because of the need to inhibit the prepotent tendency to respond based on stimulus location. The magnitude of the Simon effect is between 20 and 30 ms and is larger in the auditory modality compared with the visual modality (Lu & Proctor, 1995). The mechanism that is believed to account for the Simon effect is the activation of a response code corresponding to the general spatial location of the stimulus that needs to be controlled in order for the participant to select the correct response (Hommel, 1994).

INTERFERENCE CONTROL IN DD

Inhibition processes (response inhibition and interference control) have been studied in DD. Some of the studies have shown, for example, that children with DD are impaired in response inhibition as measured by the stop signal task (de Jong et al., 2009; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005), while other studies failed to reveal such a deficit (Schmid, Labuhn, & Hasselhorn, 2011; Willcutt et al., 2001). Others studies failed to observe response inhibition deficit in DD as measured by the Go/No-go tasks (Reiter et al., 2005). With regard to interference control, although the Simon task has never been examined in those with DD, several studies have employed the Stroop task in these individuals. Stroop performance revealed inconsistent findings, with several studies demonstrating larger interference effects in individuals with DD (Everatt, Warner, Miles, & Thomson, 1997; Faccioli, Peru, Rubini, & Tassinari, 2008; Helland & Asbjørnsen, 2000; Protopapas, Archonti, & Skaloumbakas, 2007), while others reporting decreased Stroop interference in adults with DD compared with non-impaired readers (Beidas, Khateb, & Breznitz, 2013). This inconsistency may partially derive from the fact that the Stroop task is not ideally suited for investigating interference control processes in populations with learning disabilities (Mullane, Corkum, Klein, & McLaughlin, 2009). Specifically, studying interference control in those with DD using the Stroop task might be problematic for several reasons. First, DD is characterized by limited reading experience (Snowling, 2000b). It is possible that Stroop performance of participants with DD in previous studies was confounded by their limited experience with reading materials. In addition to reading ability, the Stroop task involves nonexecutive processes such as lexical access to the word dimension as well as rapid naming, both known to be significantly impaired in DD (Denckla & Rudel, 1976; Milne, Nicholson, & Corballis, 2003). For instance, it is possible that poor naming ability of dyslexics may cause more interference, since more time is allocated for the processing of the unrelated dimension (word meaning).

Based on these findings, it would be more useful to examine interference control in DD using a task that involves the control of more general or primitive sets of stimulus-response (S-R) mappings such as the Simon task. However, this task has never been investigated in DD. Another limitation of previous studies that examined interference control in DD is the concentration upon the visual modality. Examining interference control in the auditory modality among individuals with DD has been rare. This is somewhat surprising based on the accumulated body of evidence indicating the involvement of auditory selective attention in language acquisition, as reviewed above. Furthermore, DD is largely associated with auditory deficits (Farmer & Klein, 1995); it is possible that these deficits may partially derive from poor auditory attentional processes. Also, examining interference control in different modalities using the same experimental tasks has been rarely reported in the study of DD. This point is important since different tasks may tap different cognitive processes. Several studies that used the same tests in both modalities for studying other cognitive processes in DD research revealed modality-specific impairments (Gabay, Schiff, & Vakil, 2012; Raveh & Schiff, 2008). Those studies highlight the importance of examining visual as well as auditory modalities for understanding the nature of deficits associated with this disorder. The purpose of the current study, therefore, was twofold: first, it aimed to examine pure inhibitory processes in DD by means of control over simple S-R mappings using the Simon task. Second, it aimed to determine whether inhibitory impairments in DD are modality-dependent, by examining the Simon effect in both the visual and auditory modalities in a group of adults with DD.

Method

Participants

Twenty-eight university and college students were selected for two experimental groups: a group with DD (4 females and 10 males) and a control group (4 females and 10 males). DD participants were recruited by advertisements and through learning disabilities centers in universities and colleges. The mean age was 26.07 years ($SD = 2.43$) and

Table 1. Cognitive and literacy scores for the DD and control groups

	Group			
	Control	DD		
Subtest	Mean (*SD*)	Mean (*SD*)	*p*	*Cohen's d*
Raven	56.5 (2.59)	57.14 (1.95)	*ns*	.27
DF	12.07 (2.01)	9.69 (2.25)	**	1.11
DB	8.78 (1.96)	5.69 (1.65)	**	1.7
Digit span (combined)	20.85 (3.39)	12.57 (4.6)	**	2.04
Letter naming	17.71 (2.84)	22.78 (4.74)	**	1.29
Digit naming	16.28 (2.05)	19.71 (3.95)	**	1.08
RT word reading	85.78 (14. 32)	64.53 (14.4)	**	1.6
Acc word reading	106.92 (3.12)	93.21 (6.84)	**	2.57
RT nonword reading	54.57 (10.85)	25.07 (6.3)	**	3.32
Acc nonword reading	39.64 (2.92)	18.64 (5.66)	**	4.66

Note. The values of RT word and nonword reading subtests represent the number of correct responses participants made in 45 s. The values of Acc word and nonword reading subtests represent the number of correct responses participants made. $^{*}p < .05$, $^{**}p < .01$.

24.28 years ($SD = 3.47$), in the DD and control groups. All participants were native Hebrew speakers with no reported signs of sensory or neurological deficits/attention-deficit hyperactive disorder (ADHD) (according to the American Psychiatric Association, 2000) and came from families with middle to high socioeconomic status. A documented diagnosis of a comorbid learning disability such as ADHD or SLI was an exclusion criterion. All participants with DD had a well-documented history of DD, which was assessed by an educational psychologist. They reported experiencing substantial difficulties in acquiring reading and writing skills during school entry. They were diagnosed as having dyslexia during childhood as well as during adolescence/adulthood. They were identified as dyslexics by learning disabilities centers in their institutions and received testing accommodations. All students were paid 30 NIS (~$7.5) or received a course credit for participation in the experiment.

Psychometric evaluation

All participants underwent a series of cognitive tests in order to evaluate their general intelligence (as measured by the Raven Progressive Matrices), reading abilities (Schiff & Kahta, 2009a, 2009b), verbal working memory (as measured by the forward and backward digit span from the Wechsler Adult Intelligence Scale (Wechsler, 1997), and rapid naming (as measured by a test from the "Alef Ad Taf"; Shany, Lachman, Shalem, Bahat, & Zeiger, 2006). Based on the characteristics associated with DD (Vellutino et al., 2004), it was expected that individuals with DD would differ significantly from the control group on their reading measures, processing speed, short-term auditory memory, as well as on verbal working memory, but would not differ according to their intelligence.

Naming tasks

The digit naming speed subtest consisted of five digits, each repeated randomly 10 times. The 50 printed digits were presented to the participant, who was then asked to read them aloud as fast as possible. The number of digits per minute was calculated. The letter naming subtest consisted of five (non-word ending) Hebrew letters, each repeated randomly 10 times. The 50 printed letters were presented to the participant, who was asked to read them aloud, as fast as possible. The number of letters per minute was calculated (Shany et al., 2006).

Reading skills

The participants also completed single-word reading tests (Schiff & Kahta, 2009b) and nonword reading tests (Schiff & Kahta, 2009a) in order to measure reading accuracy and speed abilities. Single-word reading tests were composed of 112 single words (for the accuracy measure subtest) or 104 single words (for the speed measure test). Nonword reading tests were composed of 45 nonwords (for the accuracy measure subtest) or 114 nonwords (for the speed measure subtest). In single-word and nonword reading *accuracy* subtests, the printed stimuli were presented to the participant, who was then asked to read them aloud, as accurately as possible. The number of correctly read words was calculated. In single-word and nonword *speed* subtests, the printed stimuli were presented to the participant, who was asked to read them aloud, as fast and as accurately as possible. The number of correctly read words per 45 s was calculated.

The two groups did not differ in cognitive ability. However, as expected, the performance of the DD group was worse than that of the control group in tests of single-word and nonword reading as well as in rapid automatized naming tests and verbal working memory. The reading achievement of participants with DD on the reading tests was significantly below expectations given age, cognitive ability (all scored above the 50th percentile on the Standardized Progressive Matrices) and educational opportunities, scoring below the 50th percentile in word and nonword reading tests on either accuracy or speed measures (see Table 1).

Materials and procedure

Stimulus presentation and the recording of response time and accuracy were controlled by a computer program (E-PRIME). Participants performed both the auditory and the visual Simon tasks. The order of the tasks was counterbalanced between participants.

Visual Simon task

Stimuli were a red or blue patch displayed on the left or right central horizontal meridian of the screen. Consequently, there were two different incongruent stimuli (when the patch appeared on the side opposite to the required key press) and two different congruent stimuli (when the patch appeared on the side corresponding to the required key press). Each one of the four stimuli conditions appeared 20 times in each experimental block (i.e., a total of 80 stimuli per experimental block). A practice block consisting of 16 trials preceded experimental blocks. For half of the participants, the "D" key represented red, and the "L" key represented blue, and for the other half of the participants the "D" key represented blue, and the "L" key represented red. The participants pressed the "D" key with their left index finger and the "L" key with their right index finger. Participants were asked to respond according to the stimuli color while ignoring its spatial location as quickly as possible without making mistakes (see Figure 1). They sat approximately 60 cm from the computer screen. Participants practiced on 16 Simon trials. Each trial started with the appearance of a blank white screen for 500 ms, followed by a 500-ms fixation point—a black plus sign at the center of the white screen. After the fixation point disappeared, the stimulus appeared at either the right or the left of the central vertical meridian of the screen and remained in view until the participant responded or 3500 ms elapsed. For incorrect trials, a 1000-ms feedback message with the word "error" appeared before the next trial began. RT was measured in milliseconds by the computer from stimulus onset until the participant's response. After performing the practice trials, participants performed two experimental blocks of the Simon task with trials identical to those of the practice block.

Auditory Simon task

The task was identical to the visual task with the following exceptions. Instead of the visual stimuli, two auditory stimuli 333 Hz and 416 Hz for 1 ms were presented. Participants were required to respond according to the stimuli frequency (low or high). The auditory stimulus was presented either to the right or to the left ear and participants were requested to ignore its spatial location and response according to its frequency (See Figure 2). For half of the participants, the "D" key represented low-frequency sound, and the "L" key represented high-frequency sound, and for the other half of the participants the "D" key represented high-frequency sound, and the "L" key represented low-frequency sound.

Fig. 1. (Colour online) Visual Simon task. Participants are required to respond to either blue or red stimuli while ignoring its spatial location using the appropriate key responses. In congruent trials, there is a correspondence between key presses and stimulus location, whereas in incongruent trials stimulus location and response key presses mismatch.

Fig. 2. Auditory Simon task. Participants are required to respond to either high- or low-pitch auditory stimuli while ignoring its spatial location using the appropriate key responses. In congruent trials, the stimulated ear and the pure tone that signaled the appropriate response correspond. In incongruent trials, stimulus location and responses do not match.

RESULTS

Preliminary analysis revealed that the type of the Simon task that participants performed (red *vs*. blue stimuli correspond either to the left or the right key button or high- *vs*. low-frequency sounds correspond either to the left or the right key button) did not interact with the group variable either for the accuracy or RT measures (minimum $p = .25$). The results, therefore, were analyzed across task type.[1]

Visual Simon Task

Accuracy

A mixed-design model of variance (ANOVA) with congruency as a within-subject factor and group as a between-subject

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[1] Given the small sample size there might be a risk that distributional properties of the measures (normality and spread) influenced the statistical results. A Levine test for Equality of Variances indicated that the distributions obey to the assumption of homogeneity. In order to address the possibility that the data differ from normality, a non-parametric analysis was also conducted. In this analysis (Mann Whitney U test), we compared the Simon effect incongruent trials minus congruent trials between the two groups. This analysis confirmed the results of the ANOVA, yielding significant group differences for the auditory ($U = 55$, $p = .048$) but not for the visual Simon task ($U = 89$, $p = .67$).

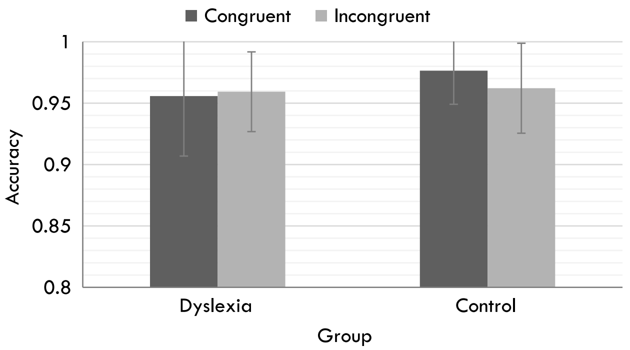

Fig. 3. Accurate responses as a function of group and congruency in the visual Simon task. Error bars represent standard errors.

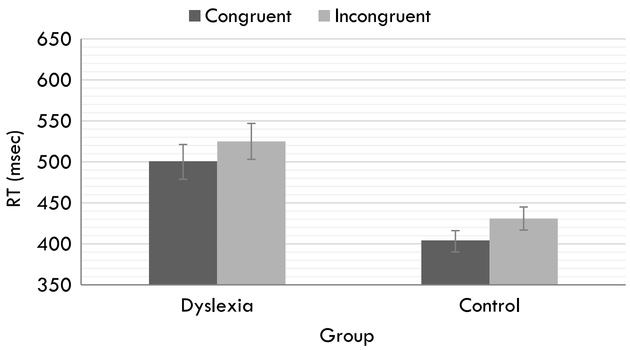

Fig. 4. RTs as a function of group and congruency in the visual Simon task. Error bars represent standard errors.

factor was conducted with mean accuracy as the dependent variable. Neither main effects nor interactions were significant (minimum $p = .296$) (See Figure 3).

Reaction time

Erroneous responses (4%) and RTs that were greater or smaller than 2.5 standard deviations from the mean for each participant (3%) were removed from the analysis. A mixed-design model of variance (ANOVA) with congruency as a within-subject factor and group as between-subject factor was conducted with mean RT as the dependent variable. Figure 4 presents RTs as a function of group and congruency. The group main effect was significant, $F(1,26) = 15.51$, $p = .001$; $\eta^2_p = .37$, indicating the DD group was overall slower ($M = 512.89$ msec, $SE = 17.10$) than the control group ($M = 417.59$ msec, $SE = 17.10$). The congruency main effect was also significant, $F(1,26) = 19.62$, $p = .001$; $\eta^2_p = .43$, suggesting that participants responded faster to congruent trials ($M = 452.50$ msec, $SE = 11.83$) in comparison to incongruent trials ($M = 477.97$ msec, $SE = 13.001$). The interaction of congruency by group was not significant, $F(1,26) = .043$, $p = .83$, $\eta^2_p = .001$.

Auditory Simon Task

Accuracy

A mixed-design model of variance (ANOVA) with congruency as a within-subject factor and group as a between-subject factor was conducted with mean accuracy as the dependent variable. Figure 5 presents RTs as a function of group and congruency. The group main effect was marginally significant, $F(1,26) = 3.69$, $p = .06$; $\eta^2_p = .12$, indicating the DD group was overall less accurate ($M = .94$, $SE = .01$) than the control group ($M = .97$, $SE = .01$). The congruency main effect was significant, $F(1,26) = 22.96$, $p = .001$; $\eta^2_p = .46$, suggesting that participants were more accurate while responding to congruent trials ($M = .99$, $SE = .004$) in comparison to incongruent trials ($M = .92$, $SE = .015$). The interaction of congruency by group was marginally significant, $F(1,26) = 3.96$, $p = .05$; $\eta^2_p = .13$. Further analysis revealed that the Simon effect in the DD group, $F(1,26) = 22.99$, $p = .001$, was significantly larger in comparison to the control group, $F(1,26) = 3.92$, $p = .05$. ($M = .08$, M = .03 for the DD and control groups, respectively).

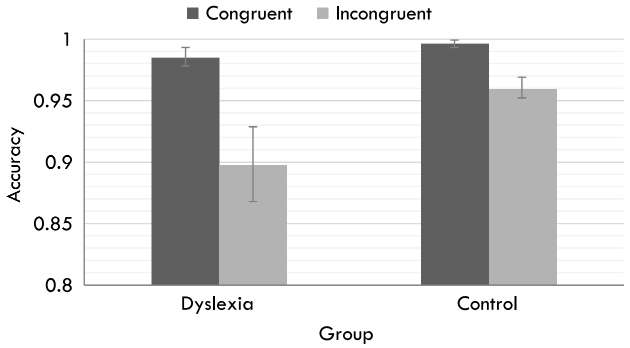

Fig. 5. Accurate responses as a function of group and congruency in the auditory Simon task. Error bars represent standard errors.

Reaction time

Erroneous responses (4%) *and* RTs that were greater or smaller than 2.5 standard deviations from the mean for each participant (3%) were removed from the analysis. A mixed-design model of variance (ANOVA) with congruency as a within-subject factor and group as a between-subject factor was conducted with mean RT as the dependent variable. Figure 6 presents RTs as a function of group and congruency. The group main effect was significant, $F(1,26) = 6.95$, $p = .02$; $\eta^2_p = .21$, indicating the DD group was overall slower ($M = 534.41$ msec, $SE = 31.38$) than the control group ($M = 417.04$ msec, $SE = 31.38$). The congruency main effect was also significant, $F(1,26) = 110.64$, $p = .00$; $\eta^2_p = .81$, suggesting that participants responded faster to congruent trials ($M = 448.10$ msec, $SE = 23.08$), in comparison to incongruent trials ($M = 503.08$ msec, $SE = 21.58$). The interaction of congruency by group was significant, $F(1,26) = 7.32$,

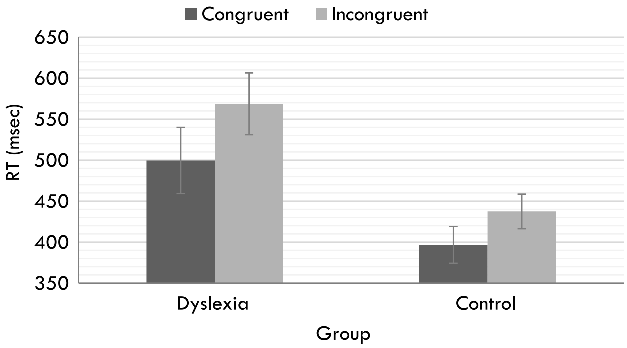

Fig. 6. RTs as a function of group and congruency in the auditory Simon task. Error bars represent standard errors.

$p = .01$; $\eta^2_p = .22$. Further analysis revealed that the Simon effect in the DD group, $F(1,24) = 87.44$, $p = .01$, was significantly larger in comparison to the control group, $F(1,24) = 30.52$, $p = .01$ ($M = 69.12$ msec, $M = 40.84$ msec for the DD and control groups, respectively).

Since the DD group was, in general, significantly slower than the control group, it is possible that the greater interference observed in the DD group during the auditory Simon task arises from slower processing speed. To investigate this possibility, we conducted an ANCOVA analysis with group as a between-subject factor, congruency as a within-subject factor, and general processing speed (averaged RT across conditions) as a covariate on mean RT as the dependent variable. The interaction of congruency by group remained significant, $F(1,25) = 9.96$, $p = .004$, $\eta^2_p = .28$. Additionally, a Vincentizing analyzing method (Ratcliff, 1979) was used in order to exclude the possibility that general RTs can account for group differences (for instance that the Simon effect gets larger as RT is slower and that this is the reason for the observed group differences in the Simon effect). For this purpose, we divided the RT data of each participant in each condition into four bins: 0 to 25th percentile, 25th to 50th percentile, 50th to 75th percentile, and 75th to 100th percentile. We added the bin value as a factor in our analysis and it was observed that bin did not modulate the interaction between group and condition. Thus, general slowness was not the driving force behind the observed group differences.

Correlations between phonological decoding and the Simon effect

Attention is hypothesized to contribute to phonological decoding skills by influencing segmentation and categorization. Therefore, one could expect to observe a smaller Simon effect (better inhibition processes) alongside better phonological decoding skills. In order to test this hypothesis, we conducted correlation analyses between the magnitude of the Simon effect (auditory task) and phonological decoding (nonword reading test). Significant negative correlations were found between the speed (the number of correct responses participants made in 45 s) and accuracy of reading nonwords (RT/accuracy nonword reading measures) and the magnitude of the Simon effect (which was calculated by subtracting RT of congruent trials from RT of incongruent trials) ($r = -.393$, $r = -.352$ for speed and accuracy measures, respectively). Together these findings suggest that the more participants were better in their phonological decoding skills, the less they exhibited auditory interference control.

Power of the study

Given the small sample size, there was need to estimate whether our study has adequate power to detect attentional problems. The power of the study was estimated using G*Power software (Faul, Erdfelder, Lang, & Buchner, 2007). The power of the study was estimated using the effect size of the interaction between the Simon effect and a group variable reported in a previous study (Castel, Balota, Hutchison, Logan, & Yap, 2007). Our calculation showed that the levels of power for detecting differences in the Simon effect was >95%. This indicates that we had a large enough sample size to detect group differences in the Simon effect.

DISCUSSION

The commonly held view suggests DD may stem from phonological deficits (Snowling, 2000a). However, recently researchers have started to consider other nonlinguistic factors in DD etiology such as attention (Facoetti et al., 2003; Valdois et al., 2004). Importantly, auditory selective attention has been suggested to play a significant role in language acquisition as reviewed above. However, most studies that examined the ability of dyslexics to control selective attention were confined to the visual modality and tended to use the Stroop task, which may not be ideally suited for studying interference control in learning disabled populations. To the best of our knowledge, other known tasks of cognitive control such as the Simon task have never been examined in those with DD.

The results from the auditory Simon task indicated faster RT when the S-R mapping was congruent in both the DD and control groups. Reversing this S-R mapping resulted in general slowness and increased errors (Simon effect), which were more evident for the DD group in comparison to the control group. This greater Simon effect for the DD group was also evident even after examining the influence of general RT on the effect using the Vincentizing method (Ratcliff, 1979). Similarly, the results from the visual Simon task demonstrated faster RT when the responding hand was congruent with the spatial location of the target, while a significant increase in RT was observed when these S-R relationships were reversed (Simon effect). Furthermore, better phonological decoding skills were associated with a smaller Simon effect, which indicates more proficient inhibitory processes. Interestingly, contrary to the auditory task, the Simon effect in the visual task was of the same magnitude for both the DD and control groups. The finding of increased interference in the auditory Simon task indicates that adults with DD find it more difficult to inhibit auditory distracting information. Furthermore, because the main difference between the auditory and visual Simon tasks is the sensory modality in which relevant and irrelevant information is presented, it seems possible to conclude that dyslexics are more vulnerable to auditory distracting information compared with visual distracting information. Indeed, it has been demonstrated that DD is associated with greater vulnerability to auditory distraction. Specifically, previous studies have demonstrated that both children and adults with DD perform poorly for speech tokens presented in noise compared with tokens presented in quiet (Brady, Shankweiler, & Mann, 1983; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). Other studies have also reported impaired performance of those with DD on dichotic listening tasks (Ben-Artzi et al., 2005). The present study is consistent with these findings and extends them to situations of interference control, suggesting a possible link between attentional and phonological decoding skills in DD.

Notably, group differences were not observed in the visual Simon task. Although previous studies reported impaired visual interference control tasks using the Stroop task in those with DD (Everatt et al., 1997; Faccioli et al., 2008; Helland & Asbjørnsen, 2000), these findings do not seem to generalize to other interference tasks such as the visual Simon task. Note, however, that findings were not always consistent with research demonstrating better Stroop performance in those with DD (Beidas et al., 2013). Part of this may be because of the fact that the Stroop task is not ideal for studying interference control in learning disabilities populations (Mullane et al., 2009). For example, it is possible that slower naming/reading may lead to more time for processing the unrelated dimension causing greater interference. In fact, a recent study confirmed this prediction. Wang and Gathercole (2015) suggested that the verbal response involved in the Stroop task is the one responsible for greater interference observed in DD participants compared with typical readers. In line with this assumption, they demonstrated that greater interference control of DD individuals in a visual Stroop task was evident only when a verbal response was required. This finding indicates that impaired performance of DD individuals on a visual Stroop task is not a product of a general deficit in inhibiting irrelevant information. Thus, the unimpaired performance of the DD group on the visual Simon task is in accordance with Wang and Gathercole's conclusions. Nevertheless, the impaired performance on the auditory Simon task does suggest specific modality inhibition deficits in those with DD. Notably, inhibition is not a unitary concept and it consists of inhibition of attention (interference control) and inhibition in action (response inhibition). In the current study, we observed that the ability to exhibit inhibition at the perceptual level is impaired in DD, specifically in the auditory modality. Other studies reported response inhibition deficits in DD (de Jong et al., 2009; Willcutt et al., 2005), but results were not always consistent (Schmid et al., 2011; Willcutt et al., 2001). Partially, this arises from the use of different tasks, procedures, or child *versus* adult populations. It seems that future studies are needed to better understand inhibition processes in DD. For example, it might be important to compare between response inhibition and interference control processes in the same sample in order to determine when inhibition deficits are mostly pronounced in DD: when these conflicts arise at a perceptual level or when they arise at the response selection stage.

Current conceptualizations of DD differ in the relative emphasis placed on linguistic *versus* cognitive processes in the etiology of DD. The commonly held view is that DD is fundamentally a language-specific disorder that arises from phonological impairments. Other accounts, however, suggest that DD arises from domain general deficits that are not restricted to the language domain, such as learning impairments, sensory deficits, and executive function impairments. The multifactorial hypothesis of DD, for example, suggests that both cognitive and linguistic deficits coexist in people with DD (Pennington, 2006). Another account also posits that impaired skill acquisition deficiencies and impaired executive functions could be manifested in those with DD (Fawcett & Nicolson, 2019). The observation of impaired auditory interference control of attention in DD is consistent with these domain general accounts but also implies that this impaired ability may be modality-dependent. Furthermore, the present investigation highlights the importance of examining processes that are beyond the linguistic/phonological domain and their potential contribution to language-related skills in DD.

The present study is the first we know of that has examined the Simon effect in those with DD and it provides some insights regarding auditory interference control and conflict resolution in DD. It seems that dyslexics are poor at maintaining auditory attention on the relevant stimulus in the presence of conflicting distracting information. The observation that adults with DD are less efficient at inhibiting irrelevant auditory information suggests a number of possible paths to the poor language outcomes that characterize DD. Selective attention has been found to be a general domain process that contributes to language learning. Specifically, research suggests that the ability to successfully segment (Weiss et al., 2010) or categorize (Reetzke et al., 2016) sounds relies upon executive attention processes. Impaired attention could influence the ability to extract word forms from fluent speech which could in turn lead to a reduced vocabulary and more difficulty in processing lexical items. Providing that lexical development interacts with phonological development (Stoel-Gammon, 2011), inefficiency in speech segmentation may result in smaller or less robust vocabularies, which could influence the resolution of phonological representations and thus reading. Alternatively, it is possible that impaired auditory attention could impact learning to read by influencing the ability to form precise phonological representations. During speech perception, listeners make decisions about the phonological category of sounds using many acoustic cues for each phonological distinction (Toscano & McMurray, 2010). The ability to selectively attend to relevant acoustic cues while disregarding others is believed to play a significant role in this process (Francis & Nusbaum, 2002; Goldstone, 1994; Nosofsky, 1986) and thus could potentially account for the deficient phonological representations that characterize individuals with DD. Both speech segmentation and incidental nonspeech category learning were found to be impaired in individuals with DD (Gabay & Holt, 2015; Gabay, Thiessen, et al., 2015).

The present study has several limitations. A first limitation is the small sample size employed. It should be noted, however, that the observation of significant group differences in such sample size speaks to the robustness of the results. Furthermore, our power analysis calculations suggest that the present sample size is sensitive enough to detect group differences in the Simon effect. Nevertheless, it will be important to replicate the current findings in a larger and more varied sample of participants in the future. The current study included high-functioning adults with DD and this could restrict the variability of the scores (as a result of the homogenous sample of DD). In addition, it should be noted that accuracy rates were relatively high (as expected in this type of tasks) and hence might suffer from a celling effect, therefore being less informative than the RT measures (which is the common dependent variable in this task). Notably, although our study implies a relationship between auditory interference control and language-related skills (phonological decoding) it will be important, in the future, to examine this speculated relationship using additional linguistic measures such as vocabulary and complex phonological processing (e.g., spoonerism). Finally, it will be important in future research to directly examine the relations between auditory interference control and learning processes in those with DD and to further examine whether training on auditory inhibitory control could positively influence dyslexics' phonological and reading skills.

In conclusion, the present study examined auditory and visual interference control in adults with DD using the Simon task. The DD group exhibited disproportionally larger impairments in RT on incongruent trials (larger Simon effect) in the auditory task compared with non-impaired readers, while no such difference between the groups was observed in the visual Simon task. These results suggest that auditory interference control is handled less effectively in those with DD and as such could potentially be linked to their poor phonological and reading skills.

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CONFLICTS OF INTEREST

The authors have nothing to disclose.

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