RUNNING TITLE: RESPONSE INHIBITION IN DEVELOPMENTAL STUTTERING

Exogenously Triggered Response Inhibition in Developmental Stuttering.

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Abstract

Purpose: The purpose of the present study was to examine relations between children's exogenously triggered response inhibition and stuttering.

Method: Participants were 18 children who stutter (CWS; mean age = 9;01 years) and 18 children who not stutter (CWNS; mean age = 9;01 years). Participants were matched on age (± 3 months) and gender. Response inhibition was assessed by a stop signal task (Verbruggen, Logan, & Stevens, 2008).

Results: Results suggest that CWS, compared to CWNS, perform comparable to CWNS in a task where response control is externally triggered.

Conclusions: Our findings seem to indicate that previous questionnaire-based findings (Eggers, De Nil, & Van den Bergh, 2010) of a decreased efficiency of response inhibition cannot be generalized to all types of response inhibition.

Key words: stuttering; response control; temperament; executive control

Introduction

Response inhibition is the ability to suppress a preplanned (Eagle, Bari, & Robbins, 2008), a habitual or a prepotent response (Congdon et al., 2010) or behaviors that are inappropriate or no longer required (Chambers, Garavan, & Bellgrove, 2009). It refers to the suppression of both motor actions as well as higher order responses, such as thoughts and emotions (Verbruggen & Logan, 2009); it is critical to deliberately or unconsciously (Eimer & Schlaghecken, 2003) stopping automatic behaviors in response to goals or environmental contingencies; and, it is also a key component of executive control (Cools, 2008). Although response inhibition is sometimes used as a term for one specific process, namely stopping a motor response, it generally reflects a set of related response control processes such as attending to and interpreting stimuli, decision making based on these stimuli and related internal or external cues, response selection, and successfully executing the appropriate motor response (Eagle et al., 2008; Nigg, 2000).

Several behavioral paradigms have been developed to investigate response inhibition across different age ranges. Currently a variety of measures are being employed of which it is often assumed they all evaluate a common or at least closely related inhibitory mechanism (Baron, 2004; Chambers et al., 2009). Frequently used well-defined paradigms of response inhibition are stop signal tasks (e.g., Logan, 1994), gonogo tasks (e.g., Bokura, Yamaguchi, & Kobayashi, 2001), sustained attention to response tasks (e.g., Robertson, Manly, Andrade, Baddeley, & Yiend, 1997), continuous performance tasks (e.g., Klee & Garfinkel, 1983), and anti-saccadic tasks (e.g., Anderson, Husain, & Sumner, 2008). The common feature of these tasks is that they require participants to respond to one set of stimuli (Go trials) and inhibit their response to another set of stimuli (Stop trials). Response inhibition is also thought to be involved in other but related forms of 'effortful' inhibition, such as response interference control and response switching (e.g., Dimoska-Di Marco, McDonald, Kelly, Tate, Johnstone, 2011), which are generally assessed by using paradigms like the Stroop color word tasks (e.g., Milham et al., 2002) or flanker tasks (e.g., Eriksen, 1995). During these tasks participants need to maintain their goal-oriented behavior when confronted with distractors or strongly activated but misleading representations (Friedman & Miyake, 2004). Many of these paradigms have been used in studying response inhibition deficits in different clinical populations such as attention deficit and hyperactivity disorder (Schachar et al., 2007), autism (Schmitz et al., 2007), Parkinson's disease (Hershey et al., 2010), and Tourette's syndrome (Li et al., 2006). Traditionally these tasks have been used in children 6 or 7 years of age or older (Williams, Ponesse, Schachar, Logan, & Tannock, 1999) but Carver, Livesey, and Charles (2001) showed that modifications to popular tasks, such as the stop signal paradigm (e.g., the use of simple shapes as stimuli, longer stimulus presentation times, fewer trials), make them also appropriate for use in preschool and kindergarten children, and thus making them ideal tools to study aging and developmental effects across a wide age range.

Previous studies in children who stutter (CWS) have yielded results pointing in the direction of reduced response inhibition. Using the Children's Behavior Questionnaire (CBQ; Rothbart, Ahadi, Hershey, & Fisher, 2001), a parent-report temperament questionnaire, Eggers, De Nil, and Van den Bergh (2009, 2010) found a lowered score for 3-to-8-year-old CWS on the 'Inhibitory Control' scale, a finding in line with an earlier questionnaire-based study by Embrechts, Ebben, Franke, and van de Poel (2000). Since response inhibition can be directly linked to the broader concept of self-control (Aron, et al., 2007), the lowered scores for CWS on the CBQ-superfactor of Effortful Control (Eggers et al., 2010) and on the Behavioral Style Questionnaire (McDevitt & Carey, 1978) scales of emotional and attentional self-regulation (Karrass et al., 2006) corroborate these findings. Also, studies employing computerized paradigms, such as gonogo- and stopsignal-tasks, have revealed lowered response inhibition in both CWS (Eggers, De Nil, & Van den Bergh, 2013) and adults who stutter (Markett et al., 2016). However, not all findings have been unequivocal. Anderson and Wagovich (2010) used the CBQ and did not find any differences in inhibitory control between CWS and CWNS, although it needs to be added their participant group was considerably smaller compared to those of Eggers et al. (2010) and Embrechts et al. (2000). Finally, a recent study using both behavioral measurements and event-related potentials in a gonogo-paradigm did not find inhibition differences (Piispala et al., 2017; Piispala, Kallio, Bloigu, Jansson-Verkasalo, 2016). Taken together, response inhibition may be an important dimension to study in stuttering but since prior studies have reported inconsistent findings, more specific studies are warranted.

The right prefrontal cortex and the fronto-basal ganglia circuit play a crucial role in response inhibition (e.g., Aron et al., 2007; Boehler, Appelbaum, Krebs, Hopf, & Woldorff, 2010; Chambers et al., 2009; Congdon et al., 2010; Jahanshahi, Obeso, Rothwell, & Obeso, 2015). Interestingly, several authors have hypothesized about a possible role of the basal ganglia or the cortical and/or subcortical structures of the fronto-basal ganglia circuit in the pathophysiology of developmental stuttering (e.g., Alm, 2004; Caruso, 1991; Smits-Bandstra & De Nil, 2007; Toyomura & Omori, 2004). Alm (2004) suggests that a dysfunction of this circuit may have various causes, such as focal lesions or aberrant neurotransmitter release, but implies that the core dysfunction lies in the "*impaired ability of the basal ganglia to produce timing cues*" (pp. 359). Also more recently, several authors have linked stuttering to a generalized deficit in the internal timing network, comprised of the basal ganglia and the supplementary motor area (Etchell, Johnson, & Sowman, 2014; Etchell, Ryan, Martin, Johnson, & Sowman, 2017). In a same line of reasoning, Smits-Bandstra and De Nil (2007) proposed that dysfunctions in this circuit might result in deficits in motor sequence skill learning and reduced automaticity development.

Many authors have adhered to the idea that a single mechanism underlies the ability to inhibit responses by generalizing the results obtained from different paradigms previously mentioned and several data point in the direction of at least partly overlapping circuits, especially with respect to the involvement of the pre-supplementary motor area (pre-SMA) and inferior frontal cortex (IFC) (e.g., Aron et al., 2007; Boehler et al., 2010; Chambers et al., 2009; Jahanshahi et al., 2015). Others have argued that these tasks assess slightly different but related response inhibition processes or even that it is not clear that all of these tasks isolate response inhibition processes rather than related control processes such as response selection, conflict resolution, sustained attention, and working memory (Nigg, 2000). At the least, there seems a reasonable amount of support for the existence of different, partly overlapping forms of response inhibition. Three categorizations are commonly made (Jahanshahi et al., 2015), namely the difference between a) volitional/intentional (i.e. self-generated, in the absence of external stimuli) versus automatic inhibition, b) reactive (triggered by external stimuli) versus proactive inhibition (preparedness to respond with restraint when faced with temptations), and c) global (stopping all actions) versus selective inhibition (stopping only certain actions). Friedman and Miyake (2004) distinguish three components of response inhibition: a) inhibition of prepotent responses, b) resistance to interference from distracting stimuli, and c) protection from proactive interference. Inhibition is also influenced by maturation since at a young age primarily reactive inhibition is present whereas older children and adults show more proactive mechanisms of inhibition (Chatham, Frank, & Munakata, 2009).

Response inhibition

In the current study, we will focus on externally/exogenously triggered response inhibition, in other words the process that cancels the action is the result of an external signal (e.g., an auditory signal indicating the response has to be inhibited). This type of inhibition differs from endogenously triggered or internally generated inhibition since different brain regions seem to be involved (Filevich, Kühn, & Haggard, 2012; Schel et al., 2014). Endogenously triggered inhibition refers to tasks with no external stop signals. Examples are the marble task (Kühn, Haggard, & Brass, 2009) in which the person has to intentionally/voluntarily stop externally triggered responses or sustained attention tasks (e.g., Robertson et al., 1997) in which the person needs to self-sustain conscious processing of repetitive stimuli that would otherwise lead to habituation or distraction to other stimuli. Support for the distinction between these two forms of response control can be found in the fact that several functions involving the prefrontal cortex (e.g., vigilance, directing of attention, generating motor patterns) have been found to implicate different areas depending upon whether they were externally or internally generated (Fernandez-Duque & Posner, 2001; Van den Bergh, 2005); moreover, both clinical (Robertson et al., 1997) and normal (Van den Bergh et al., 2005, 2006) populations have shown different proficiencies in externally versus internally generated response control. For example, findings in patients with Parkinson's disease point towards an impaired ability to self-initiate movements versus a better-preserved ability for externally cued movements (Georgiou et al., 1994; Hanakawa, Fukuyama, Katsumi, Honda, Shibasaki, 1999). Alm (2004) takes these findings to suggest that also in stuttering a possible causal mechanism might lie in the dysfunction of internal (and not externally triggered) motor activation control mechanisms, which seems to be corroborated by studies showing that exogenous auditory feedback can ameliorate stuttering symptomatology (Saltuklaroglu et al., 2003; Saltuklaroglu, Kalinowski, Guntupalli, 2004).

Response inhibition

Although there are some studies in stuttering that have evaluated the influence of external feedback, to our knowledge, only one study (Harrewijn et al., 2017) has specifically investigated differences in externally (exogenous) generated response inhibition in CWS. Therefore, the purpose of this study was to test experimentally previous findings of parent-reported (CBQ) differences in response inhibition between CWS and children who not stutter (CWNS). Based on our previous findings (Eggers et al., 2010, 2013) and the earlier described literature (e.g., Alm, 2004; Harrewijn, 2017; Saltuklaroglu et al., 2003, 2004), we hypothesized that CWS, as a group, would perform differently. For this reason, the stop signal task (Verbruggen, Logan, & Stevens, 2008) was selected, a paradigm of which it is assumed to assess exogenous response inhibition. The stop signal task consisted of a primary reaction time (RT) task where the participant had to press the left or right response button depending on the presented stimulus; on a limited number of trials an auditory stop signal, was presented after the primary stimulus, indicating the response had to be inhibited.

Method

Participants

Participants in the study were 30 boys and 6 girls between the ages of 7;04 and 10;11 years. Eighteen of the children (15 boys and 3 girls) were diagnosed with developmental stuttering. The other 18 children were nonstuttering, typically developing children, matched by age (± 3 months) and gender to the CWS. The mean age was 9;01 years (*SD* = 0;11 years) for the CWS and 9;01 years (*SD* = 1;00 years) for the CWNS. All children were monolingual Dutch speaking. Participants had no known or parent-reported neurological, psychological, developmental or hearing problems. All participants had normal or corrected to normal vision and normal speech and language development (except for stuttering in the CWS), based on the criteria described below. Handedness was determined based on the hand they used for writing. Two of the CWS and two of the CWNS were left-handed, all others were right-handed. Participants and parents were all paid volunteers recruited through their fluency specialists (for the CWS) or through their school systems (for the CWNS). The Research Ethics committee of Leuven University Hospitals approved the study; informed consent forms were signed by all parents.

All participants were administered a verbal and nonverbal subtest of the Wechsler Intelligence Scale for Children-Third Edition Dutch (WISC-III; Wechsler, 2005). In the Vocabulary subtest participants had to explain the meaning of single words. The Block Design subtest, a visual reconstruction task, required participants to rebuild as quickly as possible a geometrical pattern, by using red and white cubes. Both subtests correlate highly with the WISC-III overall score (Groth-Marnat, 2009). To avoid a possible influence of socio-economic status (Hackman & Farah, 2009), parental socio-economic status was assessed based on the highest educational level (1=primary education, 2=high school, 3=college degree, 4=university degree) of both parents, resulting in a composite score. On the WISC-III, the CWS had a mean Vocabulary score of 28.28 (range 9 – 39) and a Block Design score of 42.56 (range 10 – 63) while the CWNS scored respectively 29.56 (range 15 – 41) and 44.50 (range 19 – 62). In terms of socioeconomic status, the average for CWS was 5.61 (range 4 – 8), and 6.22 (range 3 – 8) for the CWNS. No significant between-group differences were found for either Vocabulary (t =.55, p = .59), Block Design (t = .47, p = .64) or parents' socio-economic status (U = 121, p = .20).

Participants were also administered two subtests of the Language Test for Children (van Bon & Hoekstra, 1982). In the Vocabulary Production subtest participants had to complete a phrase with a target-word linked to the presented picture. The Sentence Production subtest required participants to correct syntactically incorrect sentences. Participants had to score above percentile 16 (mean – 1SD) on both subtests in order to show normal language function. All participants passed a screening for articulation and hearing disorders, using the Antwerp Screening Instrument for Articulation (ASIA-5, Stes & Elen, 1992), a picture based test used to evaluate if children are able to produce age-specific phonemes in different word positions, and Accuscreen (Wood, 2003), a handheld hearing-screening device, employing transient-evoked otoacoustic emissions. Mean percentiles on Vocabulary Production were 61 for the CWS (range 20 – 93) and 66 for the CWNS (range 20 – 96). For Sentence Production, CWS had a mean percentile of 56 (range 20 – 97) compared to 61 for the CWNS (range 20 – 99). No significant differences were found for Vocabulary Production (t = .75, p = .46) or Sentence Production (t = .68, p = .50).

Spontaneous speech samples were collected during two free play situations. For each participant, a minimum of 300 words was used to calculate severity scores on the Stuttering Severity Instrument-3 (SSI-3; Riley, 1994). CWS produced a minimum of three within-word disfluencies (sound/syllable repetitions, including monosyllabic word repetitions, prolongations or blocks) per 100 words of spontaneous speech (Conture, 2001) and scored at least mild on the SSI-3. Average word-based percentages of within-word disfluencies were 10.25 (SD = 5.22) for CWS and .91 (SD = .72) for CWNS. Nine CWS were classified as mild, 8 as moderate, and 1 as severe.

All participants were part of an ongoing series of studies on the relationship between temperament and attentional processes in developmental stuttering (see Eggers, De Nil, & Van den Bergh, 2012, 2013).

Materials

Baseline Speed Task

The baseline speed task of the Amsterdam Neuropsychological Tasks (De Sonneville, 2009), a simple RT task, was administered to all participants prior to the other tasks. In addition to serving as a preparation for the stop signal task, it provided simple RT measures that could be used as a baseline, preventing an influence of possible between-group differences in simple RT on the later measurements. The task consisted of two experimental blocks of 32 trials each, one for the right index finger and one for the left index finger (standard for this task), preceded by a 10-trial practice session. All trials started with a white fixation cross on a black background, followed by the stimulus, a white centralized square, disappearing with the response. Participants were instructed to press the response button as quickly as possible after the appearance of the target; valid responses fell between 150 ms and 4000 ms after stimulus onset. Inter-trial intervals varied randomly between 500 ms and 2500 ms. The response button was either the right or left mouse button (below the touchpad of the laptop), depending on the experimental block. All children started the task with their nondominant hand.

Measure of exogenously triggered response inhibition: Stop Signal Task

The stop signal task (Verbruggen, Logan, Stevens, 2008) consisted of a primary choice RT task where on a random selection of trials an auditory stop signal appeared, indicating participants to withhold their response. The primary task was a shape judgment task requiring participants to discriminate between a square and a circle. When the square was presented, they had to press to right mouse button below the track pad of the laptop with their right index finger and when a circle appeared the left mouse button needed to be pressed with their left index finger (see Figure 1). This was independent of hand preference. To make sure they understood this primary task they were shown several printouts on paper of stimuli and they had to demonstrate that they understood the task by pressing the correct mouse button. Each trial began with a white centralized fixation cross on a black background. The fixation period had a fixed duration of 250 ms and was followed by the presentation of the primary-task stimulus, which remained on the screen until the end of the trial. Participants had to respond as quick and accurately as possible. Maximum RT was set at 2500 ms. On 25% of the trials, the primary-task stimulus was followed by a stop signal (a 750 Hz tone, 75 ms in duration), presented through earphones, during which participants had to refrain from responding (stop trials). Interstimulus interval was 500 ms.

FIGURE 1 ABOUT HERE

The speed of the inhibition process, the stop signal RT (SSRT), cannot be observed because the response to the stop signal is a covert response. Logan (1994) used a race model to estimate SSRT. In this model, two independent processes race against each other: the go process (triggered by the primary-task stimulus and resulting in a button press) and the stop process (triggered by the stop signal and resulting in response inhibition). Depending on which process finishes first, the response will be executed or inhibited. To estimate the SSRT, a specific tracking procedure was used in which the delay between the primary-task stimulus and the stop signal, the stop signal delay (SSD), was varied. When the SSD increased, the chances of responding on a stop signal trial also increased; in other words, the longer the interval between primary-task stimulus and stop signal, the more difficult it became to withhold the response. Initial SSD was set at 250 ms and was adjusted continuously as follows: if the child inhibited successfully, the SSD was increased with 50 ms (thus making it more difficult to inhibit the response on the next stop signal trial); if the child failed to inhibit, the SSD was decreased with 50 ms (thus making it easier to inhibit one's response on the next stop signal trial). The goal of this so-called 'staircase tracking procedure' was to allow children to inhibit their responses on about 50% of the stop signal trials (see Figure 2). SSRT was calculated by subtracting the mean SSD from the mean primary-task RT.

FIGURE 2 ABOUT HERE

The task consisted of a practice session of 32 trials, followed by three experimental blocks of 64 trials each. Between each experimental block a pause of 5 minutes was inserted. During these intervals children received, as a reward, some pieces of a puzzle of a cartoon figure. At the end of the task they could complete the puzzle with all the pieces they had obtained. Total task duration was approximately 20 minutes, including 2 breaks of each 5 minutes.

The primary performance measure for the stop signal task was SSRT. In addition, mean SSD, mean RT for go trials, mean RT for stop trials, percentage of correct go trials, and percentage of missed go trials were calculated.

Procedure

Participants were tested in a quiet setting during two home visits (test session A & B) by the first author, a qualified speech-language therapist with expertise in fluency disorders. For the computer paradigms, stimuli were presented on a 15-inch screen of an Asus laptop computer. Both the baseline speed task and the stop signal task run on precompiled, windows executable software. A black pliable cardboard screen was positioned around the computer to avoid distracting visual stimuli; headphones reduced distracting environmental sounds. Test session A involved the following tests: a) the Baseline Speed subtask of the Amsterdam Neuropsychological Tasks (De Sonneville, 2009), b) a computerized attention task, not reported in this manuscript, but part of an ongoing series of studies (see Eggers, De Nil, & Van den Bergh, 2012, 2013), c) the Vocabulary and Block Design subtest of WISC-III (Wechsler, 2005), d) the collection of a speech sample. During test session B the following tests were administered: a) the Stop signal task (Verbruggen, Logan, Stevens, 2008), b) the Vocabulary and Sentence Production subtests of the Language Test for Children (van Bon & Hoekstra, 1982), and c) the collection of a speech sample, and d) the ASIA-5 (Stes & Elen, 1992), and e) Accuscreen (Wood, 2003). These two test sessions (A and B) took approximately 1hr each and were structured in such a way that the most attention-dependent tasks were administered at the beginning of each session. To avoid an influence of testing order, half of the CWS and their matched controls, were presented with test session A during the first visit while the rest of the participants started with test session B.

Results

The average baseline speed RT was 366 ms (*SD* = 57) for CWS and 368 ms (*SD* = 49) for CWNS; both groups did not differ significantly: t (34) = -.11, p = .92.

In the Stop signal task, the percentage of successful stops was similar for CWS (*M* = 47.59; *SD* = 2.57) and CWNS (*M* = 47.34; *SD* = 3.71), t (34) = .23, p = .81. Table 1 gives an overview of the performance measures of the Stop signal task for both participant groups. One-way Analyses of Variance (ANOVAs) were conducted to investigate the effect of participant group on each of these variables (SSRT, SSD, RT go trials, RT stop trials, % correct go trials, and % missed go trials). No differences were found for SSRT, F (1, 34) =

.07, p = .79, and percentage of correct go trials, F (1, 34) = 2.70, p = .11. Between-group differences were found for RT go trials, F (1, 34) = 7.00, p = .01, RT stop trials, F (1, 34) = 6.69, p = .01, and SSD, F (1, 34) = 8.67, p = .005, showing that the RTs and SSDs were lower* in the stuttering group than in the nonstuttering group. Also a significant lower* percentage of missed go trials was found for the CWS, F (1, 34) = 6.22, p = .01 (Figure 4).

TABLE 1 ABOUT HERE

FIGURE 3 ABOUT HERE

FIGURE 4 ABOUT HERE

Discussion

Previous questionnaire-based studies revealed differences between CWS and CWNS on response inhibition or on processes influenced by inhibitory control, such as emotional regulation (Eggers et al., 2010, Embrechts et al., 2001; Karrass et al., 2006) pointing towards a lowered response inhibition in CWS. The current study employed a stop signal task (Verbruggen et al., 2008) to specifically examine exogenously triggered response inhibition. CWS performed comparable to CWNS on SSRT, i.e., the speed of response of the inhibition. RTs for both go and stop trials, SSD, as well as percentage of missed go trials were lower in CWS, although only SSD remained significant after Bonferroni correction for multiple comparisons.

No differences were found on the most important measure of inhibition of the stop signal task, namely SSRT, the speed of response inhibition. This is a parameter that cannot be directly measured but has to be estimated because if the inhibition process is successful, the response to the primary-task stimulus is suppressed (Verbruggen et al., 2008). Our results

*It needs to be noted that if a Bonferroni correction for multiple comparisons is applied, the significance threshold would be p < .008 and only SSD is significantly lower for CWS.

showed that CWS were as fast in generating this response suppression as CWNS. In other words, if an external sound signals that a motor response needs to be interrupted, CWS are as fast as CWNS to react to this signal. This result seems to challenge two recent contradicting findings of both decreased SSRT in CWS (Harrewijn et al., 2017) and increased SSRT adults who stutter (Markett et al., 2016). Harrewijn et al. (2017) studied a group of 9 to 14-year-olds. Initially they did not find a difference on SSRT but once they added IQ as a covariate, the CWS had significantly faster SSRTs. In our study, both participant groups did not significantly differ on the IQ-subscales. We have rerun our statistical analyses with IQ as a covariate but as expected this did not change our results. A contributing factor to these opposing results might be the fact that the stop signal paradigms used showed differences. For example, both the primary choice RT task as well as the stop signal was different. While we used an auditory signal as a stop signal (similar to the procedure by Verbruggen et al., 2008) they used a visual one: participants had to respond as fast as possible to the direction of a green left or right pointing arrow and in 25% of the trials, the arrow turned red, signaling participants they had to inhibit their reaction. Another explanation might be found in the age difference of the participants in both studies. We studied 7 to 10-year-old children, so our participant group was younger. Williams et al. (1999) also provided evidence of significant improvements of response inhibition throughout childhood until reaching a plateau at adolescent age. Chatham et al. (2009) also found that older children were showing more proactive inhibition whereas younger children demonstrated more reactive inhibition. The findings by Markett et al. of increased SSRT in adults who stutter on the other hand, cannot be easily attributed to the age components since one would have expected similar results, and not opposing results from those by Harrewijn et al. Possible contributing factors might be that both the procedure used to vary SSD as well as the calculation for estimating SSRT differed from the two other studies. Moreover, Markett et al. did not control for possible underlying group-differences in IQ, which might have affected the performance differences.

The results from this stop signal task also differ from previous findings on response inhibition using a gonogo task (Eggers et al., 2013). During this task participants had to press the response button as soon as possible when a green man, the ‘go-stimulus’, appeared but they had to refrain from responding when a red man, the ‘nogo-stimulus’, appeared. CWS were less able to inhibit their responses (not pressing the response box while a red man appeared). Although both tasks evaluate response inhibition, they are characterized by some fundamental differences. In both tasks, the inhibition takes place at different stages of the response execution process. In the gonogo task the inhibition occurs when response execution is at preparational or early-activational level while in the stop signal task execution of the response is already initiated (Johnstone et al., 2007). Another difference is that the decision-making component in the gonogo task was directly linked to the suppression of the response (in case of a red man, the response should be suppressed) whereas the decision-making component in the stop signal task was not linked to response inhibition but to the primary task. In the gonogo task, children had to select a response strategy (respond or not respond) before response execution, depending on the presence of a go or nogo stimulus. Each trial of the stop signal task always started out as a ‘go’-trial, and in case an auditory signal appeared, this always meant that the response had to be inhibited, so the child did not have to make an interpretative decision at the level of response suppression. In other words, although both paradigms provide external cues for inhibiting responses (exogenous response inhibition), the auditory signal in the stop signal task is always indicative of inhibiting whereas the visual stimulus in the gonogo task can both be indicative of inhibiting (red man) as well as responding (green man).

Our findings might be considered as mapping onto earlier questionnaire-based findings by Anderson & Wagovich (2010) revealing no differences in inhibitory control between CWS and CWNS. However, an alternative interpretation might be that questionnaire-based findings like those by Eggers et al. (2009 & 2010) and Embrechts et al. (2001) of lowered inhibitory control in CWS cannot be automatically generalized to all types of response inhibition. Especially since earlier findings by the same group (Eggers et al., 2013) did show lowered response inhibition in CWS when another neurocognitive task, i.e. a gonogo-task, was used. Questionnaires such as the CBQ (Rothbart et al., 2001) use a specific conceptualization of response inhibition, like 'the capacity to plan and to suppress inappropriate approach responses under instructions or in novel or uncertain situations' (p. 1406) and assess this by a set of questions about daily situations such as 'My child can easily stop an activity when s/he is told no' or 'My child has difficulties waiting in line for something'. In other words, while questionnaires are ideal for detecting general distinctions in the broad concept of response inhibition, they are not specific enough to provide more insight in the different and overlapping types of behavioral inhibition. Nigg (2000) already stated that inhibition is not a single, unitary process and suggested different forms of response inhibition. Also, Jahanshahi et al. (2015) discussed these different and sometimes overlapping and interacting (e.g., Castro-Meneses, Johnson, & Sowman, 2015; Schel et al., 2014) types of behavioral inhibition such as intentional versus automatic inhibition, and reactive versus proactive inhibition. While this stop signal task evaluates reactive inhibition (i.e., triggered by external stimuli) by measuring the inhibition of prepotent responses, the CBQ also contains questions on proactive inhibition.

While no differences were found on SSRT, differences did emerge on RTs of go and stop trials, SSD, and percentage of missed go trials. However, these differences need to be interpreted with caution since after the use of Bonferroni correction, only SSD remained significant. On the other hand, some (e.g., Perneger, 1998) have advised not to use Bonferroni adjustment to avoid dismissing significant differences (Type II errors). Overall, CWS were significantly faster because of shorter RTs both in go and stop trials. These shorter RTs were also found in previous computer-based RT paradigms (Eggers et al., 2013; Subramanian & Yairi, 2006) although remarkable at first sight because most studies (for an overview see Bloodstein & Ratner, 2008) showed longer RTs in people who stutter. The shorter RTs automatically resulted in shorter SSDs because due to the staircase-tracking (Verbruggen et al., 2008) procedure of the task, participants were able to inhibit their responses in about 50% of the trials; if participants respond faster to the primary stimulus, then also the time between the presentation of the primary stimulus and the stop signal needs to be shorter since otherwise participants will not be able to inhibit their responses in 50% of the trials.

It is also noteworthy that, despite the shorter RTs in CWS, the percentage of correct go trials showed no between-group differences. In light of a speed-accuracy trade-off, i.e. the shorter the RTs the higher the likelihood of making errors (e.g., Magill, 2011), it would not have been unreasonable to expect CWS to make more errors. Combined with the lower percentage of missed go trials, this leads us to conclude that CWS were as efficient in exogenously triggered response inhibition, even more, in these circumstances (during a task with external auditory signals) they appear to react faster (shorter RTs) and seem more able to maintain their concentration and attentional focus (less missed go trials). The latter findings seem to be in line with Anderson, Pellowski, Conture, and Kelly's (2003) findings of lower scores for CWS on the distractibility scale (defined as "*the effectiveness of extraneous stimuli in drawing attention away from ongoing behaviors*"; pp.1225) of the Behavioral Style Questionnaire.

Response inhibition

Overall, based on the current findings, there is no evidence to conclude that exogenously triggered response inhibition was different between the groups in this task. Taken together, current and sometimes seemingly conflicting earlier findings on response inhibition in people who stutter (Eggers et al., 2010, 2013; Embrechts et al., 2001; Harrewijn et al., 2017; Markott et al., 2016) necessitate further behavioral and imaging research into the possible role of response inhibition in stuttering and into the conditions under which response inhibition does and does not differentiate between CWS and CWNS. Especially since the underlying neural mechanism for the suppression of initiated but no longer appropriate responses (Aron et al., 2007), both manual as well as verbal (van den Wildenberg & Christoffels, 2010), shows similarities with causal mechanisms being discussed in the stuttering literature. The prefrontal cortex has been viewed as playing an important role in the ability to inhibit stimulus-evoked responses (Miller & Cohen, 2001) and neuroimaging studies have unveiled an integrated network of cortical and subcortical regions crucial for cancelling responses (Chambers, Garavan, & Bellgrove, 2009; Chikazoe, 2009). This fronto-basal ganglia network interconnects the inferior frontal cortex (IFC) and pre-supplementary motor area (pre-SMA) through the basal ganglia structures and the thalamus to the cortex (Aron, Behrens, Smith, Frank, & Poldrack, 2007; Aron & Poldrack, 2006; Mink, 1996, 2003). There is evidence (e.g., Ballanger et al., 2009; Jahfari et al., 2011; Mink, 1996, 2003; Nambu, 2004) for the existence of 3 different loops, namely a direct pathway (via the striatum and internal globus pallidus), an indirect pathway (via the striatum, external globus pallidus, subthalamic nucleus, and internal globus pallidus) and a hyperdirect pathway, which does not pass through the striatum (directly via the subthalamic nucleus, and internal globus pallidus). The hyperdirect pathway is responsible for suppressing all motor programs before response execution. This initial ‘reset’ signal is followed by releasing the selected motor response via the direct pathway. Finally, responses are terminated again via the slower indirect pathway.

Response inhibition

On stop trials in a stop signal paradigm, it is believed that the faster hyperdirect pathway is reactivated to inhibit responses (Boehler et al., 2010; Chambers et al., 2009; Jahfari et al., 2011).

Imaging studies in people who stutter have provided evidence for atypical activations in cortical and/or subcortical structures of this circuit, such as overactivity in the midbrain at the level of the basal ganglia nuclei (e.g., Beal et al., 2015; Beal, Gracco, Brettschneider, Kroll, & De Nil, 2013; Brown, Ingham, Ingham, Laird, Fox, 2005; Chang et al., 2017; Chang, Chow, Wieland, & McAuley, 2016; Foundas, Cindass, Mock, & Corey, 2013; Ludlow & Loucks, 2003; Neef et al., 2016; Sowman et al., 2017; Watkins, Smith, Davis, & Howell, 2008; Wu et al., 1995) and seem to provide validation for the hypotheses linking the fronto-basal ganglia network to the etiology of developmental stuttering (Alm, 2004; Smits-Bandstra & De Nil, 2007). A recent study by Liu et al. (2014) also showed heightened activations of the frontostriatal regions in PWS during a self-regulatory task. They speculated that this might reflect a compensatory mechanism for an underlying neural inefficiency in the frontal regions when processing conflict. Studies in stroke patients revealed that perseveration errors, both continuous (abnormal prolongation of a specific activity) and recurrent perseverations (repetition of a previous response to a subsequent stimulus), were strongly associated with lesions involving the nucleus caudatus (Nys, van Zandvoort, van der Worp, Kapelle, & de Haan, 2006). A more recent study on neurogenic stuttering by Theys, De Nil, Thijs, van Wieringen, and Sunaert (2012) revealed that one or several lesions throughout the fronto-basal ganglia circuit could result in neurogenic stuttering as opposed to a dysfunction limited to one specific brain area. Also in other motor movement-related disorders sometimes being linked to stuttering, such as Parkinson's disease (Burghaus et al., 2006; Frank, Samanta, Moustafa, Sherman, 2007; Hershey et al., 2010; Ray et al., 2009; Seiss & Praamstra, 2004;

Shahed & Jankovic, 2001; Toft & Dietrichs, 2011; Van den Wildenberg et al., 2006; Walker et al., 2009), Tourette's syndrome (Li, Chang, Hsu, Wang, & Ko, 2006; Serrien, Orth, Evans, Lees, & Brown, 2005), and tic disorders (Mulligan, Anderson, Jones, Williams, & Donaldson, 2003), the implication of the basal ganglia has been extensively studied. Moreover, the basal ganglia also play a key role in several other functions where differences have emerged between stuttering and nonstuttering populations, such as set-shifting, attention, and movement initiation (Brown, Schneider, & Lidsky, 1997; Hauber, 1998)

Additional considerations and suggestions for further research

In this study, SSRT was calculated by the mean method (Verbruggen et al., 2008), as part of the standard software procedure of the used program. This means that SSRT was calculated by subtracting the mean SSD from the mean primary-task RT. This method should only be used if the percentage of successful stops converges on 50%, as was the case in this study. Otherwise, SSRT must be calculated by another method, such as the integration method (Verbruggen, Chambers, & Logan, 2013).

Some caveats of the study must also be mentioned. First of all, while both the administration and the measurements of the stop signal task were identical to Verbruggen et al. (2008), a possible influence of other response organization processes, such as auditory signal processing, cannot be fully ruled out. Especially because the existing literature has shown auditory processing differences between stuttering and nonstuttering individuals (e.g., Jansson-Verkasalo et al., 2014; Kaganovich, Wray, Weber-Fox, 2010). Secondly, the findings discussed here represent group means and must therefore also be interpreted as such. Although CWS, as a group, were as efficient in exogenously inhibiting motor responses, individual variations are possible and the findings may therefore not necessarily apply to each individual CWS. Finally, exogenous response inhibition was operationalized by using only one specifically chosen computer paradigm; in order to reach more definite conclusions on exogenously generated but also others kinds of response inhibition in CWS, additional studies employing other paradigms would be needed. This might also yield additional insights in the impact of various stimulus characteristics on task performances. Future studies might also combine different ways of evaluating response inhibition, such as questionnaires, computer paradigms, and laboratory testing. Since the majority of our participants had a stuttering severity score in the range mild-to-moderate and only one participant scored in the severe-to-very severe range, results might be sample specific and our dataset did not allow for evaluating a correlation with stuttering severity.

Acknowledgments

The present study was supported by Thomas More University College. We are grateful to the families, schools and fluency specialists who participated in the study and to students Karen Remans and Sofie Sambre for their assistance.

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Table 1

Mean Stop signal task performance measures for CWS and CWNS

	SSRT		SSD		RT go trials		RT stop trials		% correct go trials		% missed go trials	
Group	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
CWS	594	114	557**	253	905*	217	1152*	298	94	4,55	3,66*	3,75
CWNS	604	123	792**	225	1101*	229	1396*	266	89	11,23	7,50*	5,34

*$p < .05$, **$p = .005$

Figure Captions

Figure 1. Overview of the stop signal task

Figure 2. Illustration of the stop signal task probabilities of responding [*p*(respond|signal)] based on the horserace model. Reprinted from “STOP-IT: Windows executable software for the stop signal paradigm,” by F. Verbruggen, G. D. Logan, and M. A. Stevens, 2008, *Behavior Research Methods*, 40, p. 480. Copyright 2008 by Springer Science and Business Media. Reprinted with permission.

Figure 3. Mean stop signal task RT performance measures for CWS and CWNS (Error bars: 95% CI).

Figure 4. Mean stop signal task error% performance measures for CWS and CWNS (Error bars: 95% CI).

Figure 1

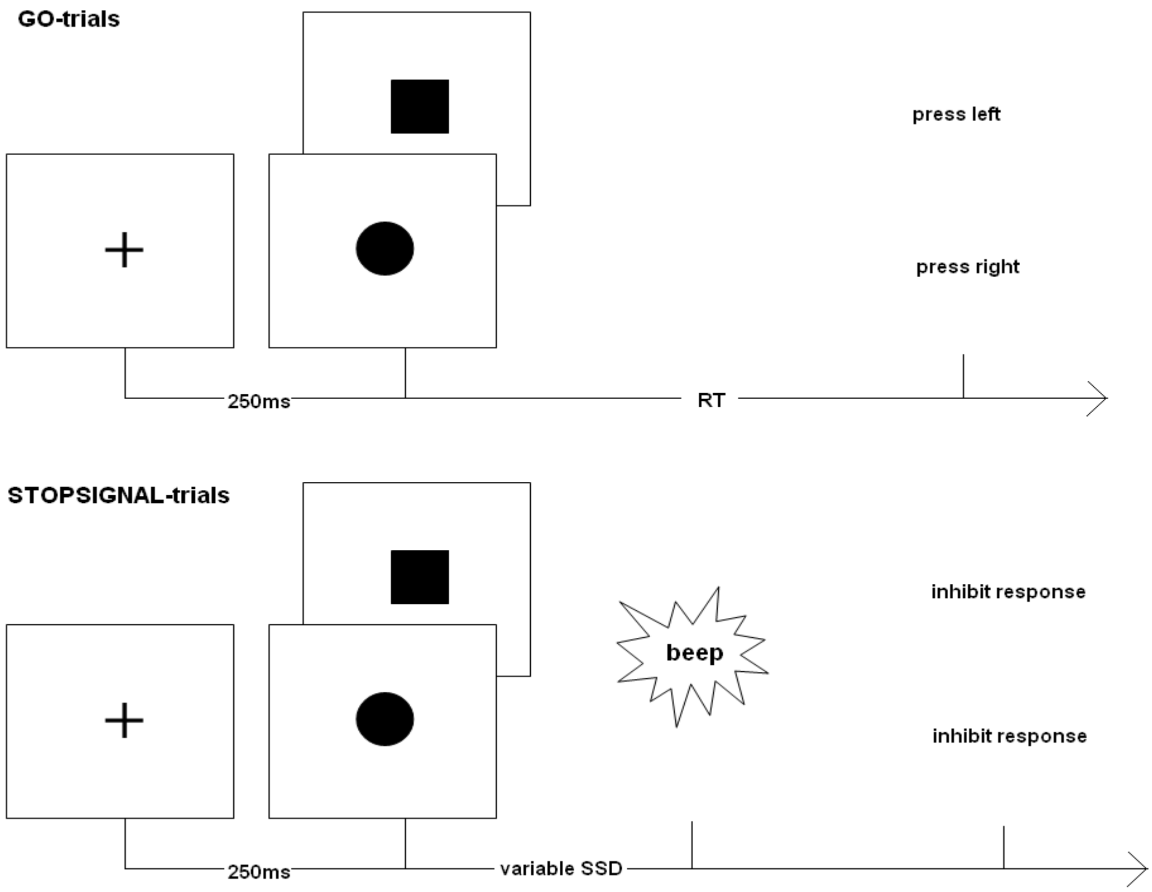

GO-trials
press left
press right
250ms
RT
STOPSIGNAL-trials
beep
inhibit response
inhibit response
250ms
variable SSD

Figure 2

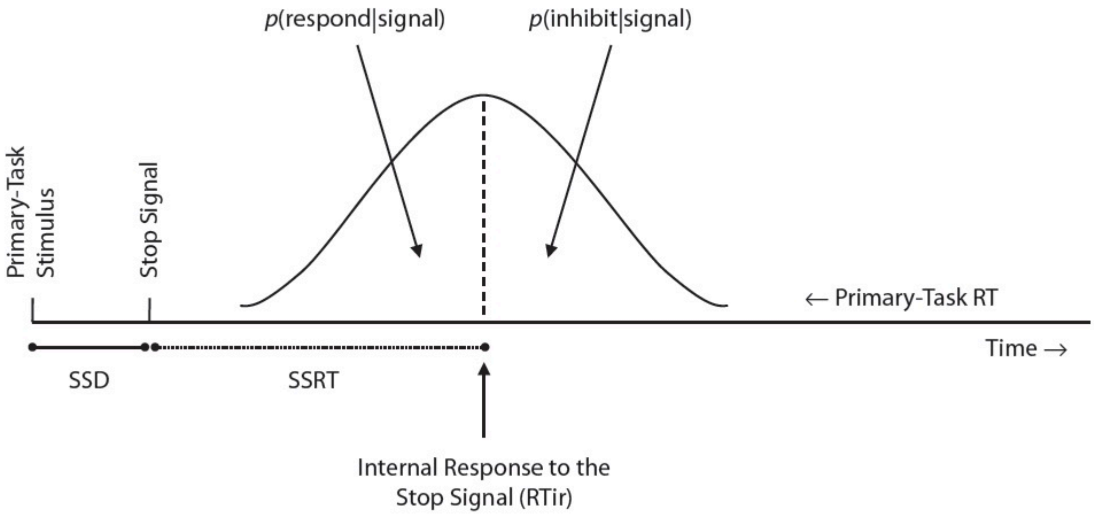
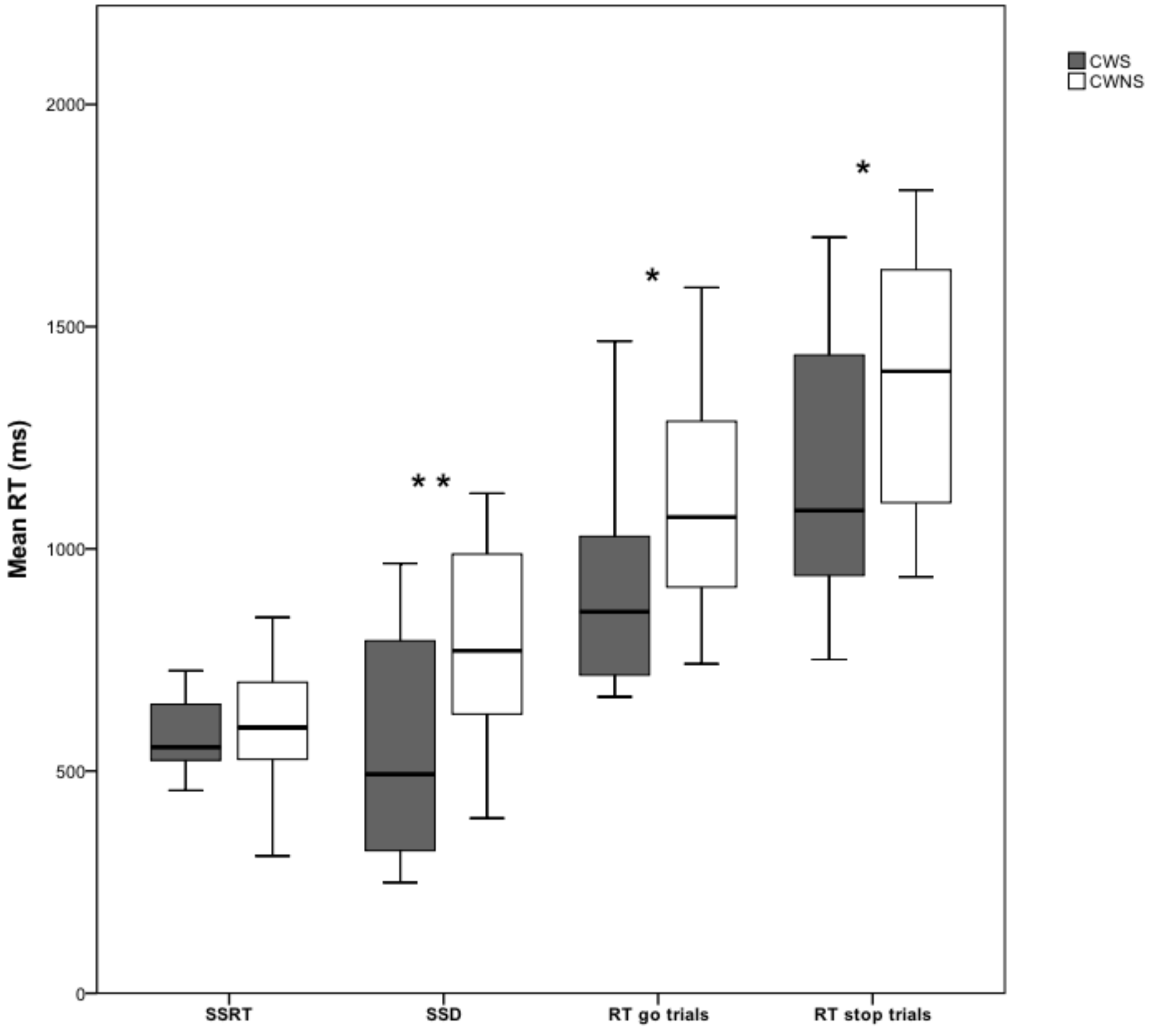
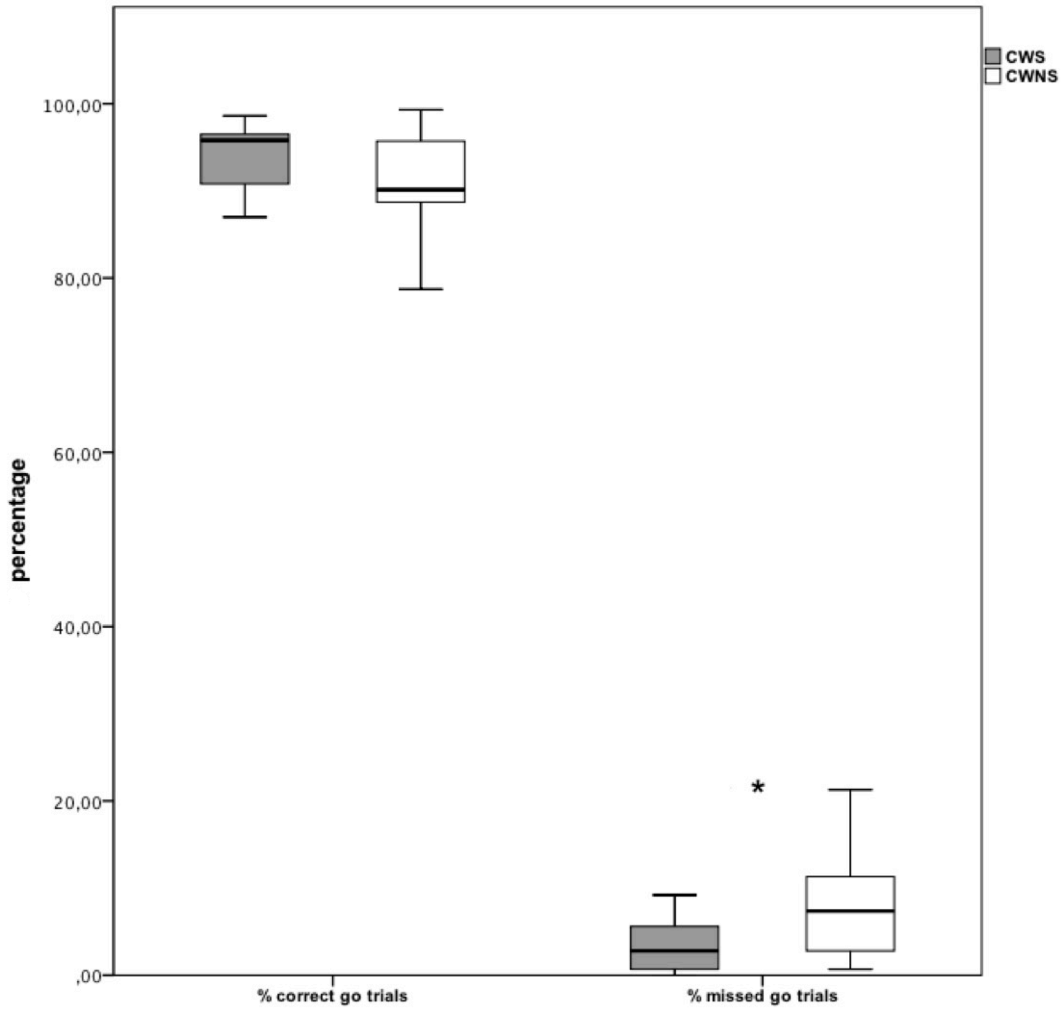

p(respond|signal)
p(inhibit|signal)
Primary-Task Stimulus
Stop Signal
← Primary-Task RT
Time →
SSD
SSRT
Internal Response to the Stop Signal (RTir)

Figure 3



* p < .05, ** p < .005

Figure 4


CWS
CWNS
100,00
80,00
60,00
40,00
20,00
,00
percentage
*
% correct go trials
% missed go trials

* p < .05