Using Pupillometry to Measure Cognitive Effort During a Task of Inhibition in People with Aphasia

Bethany Hartman & Jenny-Lynn Reid

Supervisors: Esther Kim Reader: Salima Suleman

Inhibition and pupillometry in PWA

Abstract

Background: Aphasia is a communication disorder resulting from stroke, characterized by difficulty speaking, listening, reading and writing. Recent evidence suggests that persons with aphasia (PWA) can exhibit impairments in cognition, such as inhibition. Inhibition is the ability to suppress irrelevant information, which is important in decision-making and self-regulation. Measuring cognitive performance in PWA is difficult due to the linguistic demands of many cognitive tests. The spatial Stroop task is a nonverbal test of inhibition that is appropriate for use with PWA. Measures of pupil size (i.e. pupillometry) can be used in conjunction with cognitive tasks to index cognitive effort.

Purpose: The purpose of this study is to examine the performance and cognitive effort of PWA on the spatial Stroop task using pupillometry.

Methods: In this study, PWA (n = 16) and age- and education-matched controls (n = 16) completed the spatial Stroop task. Performance was compared between groups on three measures: 1) accuracy; 2) reaction time; and 3) change in pupil size.

Results: There was no significant difference between measures of accuracy for PWA and controls. PWA had significantly larger reaction times and greater pupil dilation across all three trial types.

Conclusions: Results suggest that PWA perform similarly in accuracy for tasks of inhibition but require more time and effort to do so.

INTRODUCTION

Aphasia

Aphasia is a communication disorder typically caused by stroke, characterized by difficulty speaking, listening, reading and writing (Beeson & Rapcsak, 2006). Linguistic deficits in people with aphasia (PWA) are variable and an individual's performance can be inconsistent from month to month, or even day to day (Hula & McNeil, 2008). Such variability in performance is thought to be associated with impaired cognitive mechanisms, which affect access to language representations that may be more intact than performance suggests (Hula & McNeil, 2008).

Cognition is the "process... by which sensory input is transformed, reduced, elaborated, stored, recovered and used" (Helm-Estabrooks, 2014, p. 137). Cognitive functions include the mechanisms humans use to attend to important stimuli (attention); ignore irrelevant stimuli (inhibition); process, store, and retrieve information (memory); and initiate and perform goal-directed behavior (executive functions). Researchers have found that PWA perform worse than people without aphasia on measures of attention, working memory, language, executive functioning, as well as visuospatial skills (Hamilton & Martin, 2005; Helm-Estabrooks, 2014; Hula & McNeil, 2008; Martin & Allen, 2008; Heuer & Hallowell, 2015; Chapman & Hallowell, 2015). Each person with aphasia is different and can display one, all, or a combination of cognitive deficits (Helm-Estabrooks, 2014). Cognitive impairments may negatively impact an individual's ability to communicate, navigate everyday situations (Helm-Estabrooks, 2014) and make decisions (Del Missier, Mäntylä & Bruin, 2012). It is important to note that PWA are intelligent individuals even though they demonstrate cognitive deficits. Therefore, a thorough understanding of an individual's aphasia profile should include cognitive assessment.

Aphasia and Inhibition

Inhibition. Inhibition is the ability to suppress irrelevant information and filter unnecessary stimuli (Kertesz, 2007). Difficulty with inhibition may make the suppression of reflexive behaviours more challenging. Inhibition has been proposed as a mechanism to explain perseveration in PWA (Christman, Boutsen, & Buckingham, 2004). Perseveration is the tendency to repeat a behaviour regardless of change in stimulus or context and is prevalent in PWA (Christman, Boutsen, & Buckingham, 2004). In many situations, people need to suppress reflexive responses via inhibition to produce an appropriate response. However, when there is brain damage, the information processing system can become inflexible and perseveration may occur (Christman, Boutsen, & Buckingham, 2004). This inflexibility can interfere with a person's ability to respond appropriately to tasks that can involve fast, automatic reactions to a stimulus, such as speaking, pointing, and writing. As such, we want to learn more about inhibition in PWA. Our particular area of interest for this study lies within the potential deficits PWA may have in inhibition and the impact these deficits could have on their daily functioning.

Inhibition theoretically overlaps with the function of selective attention processes. Attention is the ability to maintain focus of a thought or action (Helm-Estabrooks, 2014). In order to attend to relevant information, inhibition is needed to suppress any irrelevant information. Heuer and Hallowell (2015) noted PWA have a harder time allocating attention, and filtering out competing stimuli (selective processing) than people who do not have a neurological disorder. It is still unclear why PWA have inefficiencies in their attentional allocation and which cognitive mechanisms may be involved. Wiener, Connor and Obler (2004) suggest that selective processing may be determined by an inhibitory mechanism. Therefore it is important to investigate the role of inhibition in cognitive processing, focusing on how it may impact functioning in this population.

Testing Inhibition*.* The Stroop task (Stroop, 1935/1992) is a commonly used test of inhibition. Two types of information are presented during this task: colour ink and colour name. In order to respond correctly, the participant must verbally identify the colour of the ink while disregarding the colour name. For instance, if the word blue is written in yellow ink, the correct verbal response is yellow. Measures of response accuracy and response time provide information about an individual's ability to inhibit irrelevant information (i.e., the written word).

The Stroop task relies heavily on the use of language to correctly read the target word and verbally respond. For PWA, the presence of language impairments potentially confound and complicate interpretations of performance measures on the Stroop task.

Wiener, Connor and Obler (2004) illustrated the possible language confound by administering the Stroop task to people with Wernicke's aphasia. They found that reaction times for incongruent trials were significantly greater for those with aphasia compared to controls (Wiener, Connor & Obler, 2004). These results could be interpreted in two ways: 1) PWA are not as capable at inhibiting unnecessary information; or 2) the language aspect of the stimuli and response negatively impacted PWA's performance. In order to substantiate either of these conclusions, a task of inhibition that is independent of language processing should be used with PWA.

The spatial Stroop task, or Simon Spatial Incompatibility task (Simon & Rudell, 1967; Clark & Brownell, 1975) is an alternative to the Stroop task that has minimal linguistic demands. Like the standard Stroop task, two types of information are presented: arrow direction and arrow location. In order to respond correctly, the participant must disregard the arrow location and press the appropriate computer key to identify the direction of the arrow (Hamilton & Martin, 2005). For instance, if the arrow is on the left side of the screen and is pointing to the right, the correct response is a right key press. Trials where direction and location match are considered congruent. Trials where direction and location do not match are considered incongruent. Measures of response accuracy and response time provide information about an individual's ability to inhibit irrelevant information (arrow location).

Hamilton and Martin (2005) used both the standard Stroop and the spatial Stroop in a case study with an individual (ML) with an inferior frontal lesion who presented with deficits in semantic short term memory. Results from the standard Stroop showed significant differences between neutral (trials where ink and colour name match) and incongruent trials for ML, compared to control participants. In comparison, results from the spatial Stroop showed no significant difference between neutral (trials where the arrow was presented in the center of the screen) and incongruent trials. These results suggest that inhibitory deficits may be compounded by the language component of the Stroop Task. This highlights the importance of using valid tasks to measure cognitive function, particularly with populations with language impairments such as aphasia.

Pupillometry

In addition to measuring inhibition using a non-linguistic task, another tool that can be used to measure cognitive functioning is pupillometry. Pupillometry is "the measurement of pupil dilation and constriction during a cognitive task" (Chapman & Hallowell, 2015, pg. 1508). Pupil dilation is a well-established construct of cognitive effort (Beatty, 1982; Kahneman, 1973). Several studies have indicated that changes in pupil size are sensitive to the amount of mental effort required for a given task; and that these changes occur automatically without disruption to any behavioral responses (Chapman & Hallowell, 2015; Laeng, Orbo, Holmlund, & Miozzo, 2011; Beatty, 1982). Pupillometry provides us with an effective method of determining cognitive effort via autonomic processes (Laeng, Orbo, Holmlund, & Miozzo, 2011).

Beatty (1982) reviewed multiple studies that used pupillometry and concluded that differences in cognitive effort between individuals, between tasks, and within a single task with differing conditions of complexity can be measured using pupillometry. The ability to compare cognitive effort both within and between individuals is particularly important when interested in constructs that are not easily measured, such as inhibition.

Pupillometry as a test of inhibition. Laeng, Orbo, Holmlund, and Miozzo (2011) used pupillometry in conjunction with the standard Stroop task to explore cognitive effort during an inhibition task. Results of their study indicated pupil dilation changed significantly across the three conditions (congruent, incongruent, neutral). Congruent trials were associated with the smallest change in pupil size. The incongruent trials produced the largest increase of pupil dilation. Neutral trials (non-colour words) produced intermediate changes in pupil dilation.

These results suggest more cognitive effort is needed for incongruent conditions, which aligns with the current understanding of inhibitory processing.

Pupillometry in PWA. Pupillometry is an ideal tool for investigating cognitive processes such as attention allocation and inhibition in PWA. Allocating attention is more challenging for people who have neurological disorders, and using a tool to better understand the potential impact on language is important (Heuer & Hallowell, 2015). Pupillometry is ideal for this task because it does not require any verbal response, is sensitive to changes in attention demands, and provides an objective measure of cognitive effort (Heuer & Hallowell, 2015).

To our knowledge, only one investigation of cognitive effort in PWA using pupillometry has been published. Chapman and Hallowell (2015) used pupil dilation to effectively measure cognitive effort during a task of linguistic processing in people with and without aphasia. When participants heard difficult nouns, their pupil dilation was larger than when presented with easy nouns. The researchers did not find any significant differences between people with and without aphasia on measures of pupil dilation. Chapman and Hallowell (2015) effectively demonstrated that pupillometry is an appropriate tool for investigating cognitive effort in PWA. Future investigations with PWA can couple pupillometry with a variety of cognitive measures, including measures of inhibition.

Research Questions

The spatial Stroop functions as a non-verbal task of inhibition, which is important for certain populations, including PWA, who may have difficulty with language processing, language expression, or both. Researchers have demonstrated that pupillometry is an effective way to determine how much effort is required for a person interacting with tasks of varying complexities (Chapman & Hallowell, 2015; Beatty, 1982). Previous researchers provide insight into the need for studies to focus on removing barriers that may inhibit performance, and potentially provide an inaccurate representation of abilities. The purpose of this study is to examine the performance and cognitive effort of PWA on the spatial Stroop task using accuracy, reaction time and pupillometry.

Our specific research questions are as follows:

1. Do participants perform differently on congruent, neutral, and incongruent trials of the spatial Stroop task?
    a. On accuracy
    b. On reaction time
    c. On pupil size
2. Do PWA and controls differ in their performance on the spatial Stroop?
    a. On accuracy
    b. On reaction time
    c. On pupil size

Hypotheses. Based on the results of Hamilton and Martin (2005), we predict less accurate performance on incongruent trials for all participants due to the inhibition needed for these trials. Similarly, we expect longer response times (RT) for incongruent trials because participants must actively inhibit location information. Greater changes in pupil size are predicted for incongruent trials for all participants, based on results from Laeng et al, (2011) who used pupillometry during the standard Stroop task. As well as a pupillometric study by

Chapman and Hallowell (2015) that investigated cognitive effort during a linguistic task in PWA, and multiple pupillometric experiments by Beatty (1982).

We expect that PWA will perform with less accuracy and longer reaction times compared to control participants. PWA and control participants are also expected to differ in average pupil size change.

METHODS

Design

A quasi-experimental design was used to compare performance of PWA (*n* = 16) and demographically matched controls (*n* = 16) on the spatial Stroop test of inhibition (Hamilton & Martin, 2005). Three dependent variables (accuracy, reaction time, and change in pupil size) were analyzed using a mixed ANOVA with one between groups factor (2 levels: PWA and controls) and one within groups factor (3 levels: congruent, neutral, and incongruent).

Participants

PWA had mild to moderate aphasia as measured by scores on the Western Aphasia Battery-Revised (Kertesz, 2007), were at least six months post onset, and spoke English as their primary language. Control participants were matched in age and education to PWA. All participants were screened for basic vision, hearing and depression. Thirty-two participants took part in our study (PWA = 16, controls = 16). See *Table 1,* for mean age and education of each group, as well as mean months post stroke.

Table 1
Demographic Information

	People with Aphasia			Controls		
	n	Mean	Std. Dev	*n*	Mean	Std. Dev
Age	16	60.688	8.761	16	60.313	8.860
Education (total years)	16	14.125	2.941	16	15.188	2.105
Months Post Stroke	16	98.73	87.01			

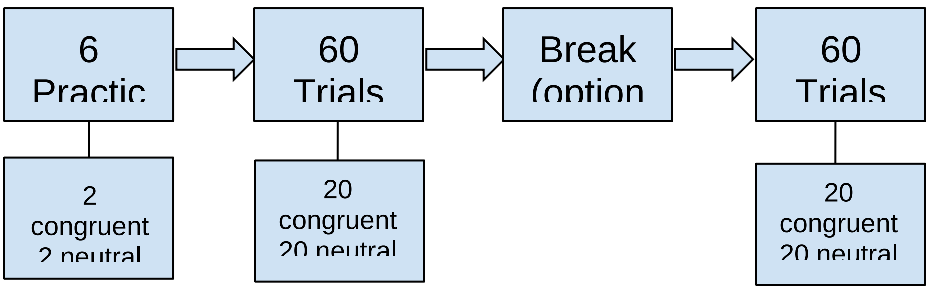
Task and measures

Each participant completed a computerized spatial Stroop task. Participants viewed an arrow on a computer screen and pressed a button corresponding to the direction of the arrow (left or right). The arrow was positioned on the left, right, or centre of the screen. Each trial displayed one of three types of arrangements: congruent (i.e., right arrow, right side of the screen); incongruent (i.e., left arrow, right side of the screen); or neutral (i.e., left or right arrow in centre of the screen). Participants completed two sets of 60 trials containing equal numbers of congruent, incongruent, and neutral trials (See *Figure 1*).

While participants completed the spatial Stroop task, an eye-tracker measured pupil size. Pupil dilation was monitored by the Eyelink 1000+ eye-tracking system using a 35mm lens and a desk mount configuration. Participants' heads were stabilized using a chin rest. Change in pupil size within each trial was measured and averaged within congruent, neutral, and incongruent trials, providing an estimate of cognitive effort exerted in each of these conditions.

Three dependent measures were collected during this task: 1) reaction time (i.e., time between stimulus onset and button response); 2) response accuracy (i.e., correctly identifying arrow direction); and 3) changes in pupil dilation using an eye-tracking paradigm (i.e., change = maximum - minimum pupil size). For reaction time analysis, trials 1 and 61 were deleted to account for task initiation.

Figure 1 - Sequence of task



Analyses

A 2x3 mixed ANOVA was used to compare between PWA and controls on the three different trial types of the spatial Stroop (1 between groups factor - PWA and controls; 1 within groups factor - congruent, neutral, incongruent). Mixed ANOVA analyses were conducted for each of the three dependent variables: 1) accuracy; 2) reaction time; 3) average change in pupil size. For cases where the sphericity assumption was violated, values are reported using the Greenhouse-Geisser correction (accuracy and pupillometry). Significance was determined at a level of $p < 0.05$. *Post-hoc* t-tests were used to further explore significant main effects and interactions.

RESULTS

Accuracy Results

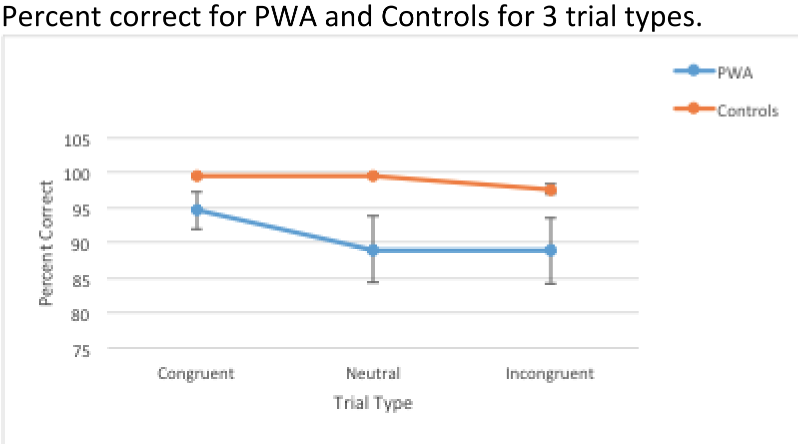
The dependent variable of accuracy was measured by determining the number of correct responses for the three trial types (40 of each), and calculating percent trials correct value. In this section we will examine the main effects to: 1) establish whether or not there is a significant different between trial types; and 2) determine whether or not PWA and controls differ on a measure of accuracy during the spatial Stroop task.

The main effect for trial type was significant, F (1.356, 29) =7.243, p = 0.006, but there was no main effect for group F (1, 30) = 3.964, p = 0.056. A significant interaction was identified, F (1.356, 29) = 4.04, p = 0.039. Please refer to Table 2 for a summary of means and standard deviations on the measure of accuracy for PWA and controls during different trial types on the spatial Stroop task.

Table 2
Average percent correct across trials for people with aphasia and controls.

	People with Aphasia			Controls			Combined		
	n	Mean	Standard Deviation	*n*	Mean	Standard Deviation	*N*	Mean	Standard Deviation
Congruent	*16*	94.6255	10.844	*16*	99.3755	0.957	*32*	97.000	1.361
Neutral	*16*	89.063	18.866	*16*	99.500	0.894	*32*	93.219	2.368
Incongruent	*16*	88.875	18.694	*16*	97.563	3.076	*32*	94.281	2.361
Combined	*16*	90.854	2.826	*16*	98.813	2.826			

Figure 2
Percent correct for PWA and Controls for 3 trial types.



Notes: Error bars represent +/- 1 Standard Error of Measure.

Post-hoc analysis. We explored the significant main effect for trial type using *post hoc* t-tests to compare overall accuracy on congruent, neutral and incongruent trials. Because of the exploratory nature of this study, we maintained alpha at $p < 0.05$.

For all participants (n = 32), independent samples *t*-tests showed that there was a significant difference between congruent and neutral trials, $t(31) = 2.070$, $p = 0.047$ and between congruent and incongruent trials, $t(31) = -3.214$, $p = 0.003$. There was no significant difference between neutral and incongruent trials, $t(31) = 1.794$, $p = 0.083$.

We used a stratified post-hoc analyses to explore differences between trial types for each group. For PWA, we found there were significant differences between congruent and neutral trials, $t(15) = 2.284$, $p= 0.03$; and congruent and incongruent trials, $t(15) = 12.665$, $p = 0.018$. There was no significant difference between neutral and incongruent $t(15) = 0.204$, $p = 0.841$ for PWA. For controls, we found significant differences between congruent and incongruent trials, $t(15) = -2.440$, $p = 0.028$; and neutral and incongruent trials, $t(15) = 2.729$, $p = 0.016$. Congruent and neutral trials were not significantly different, $t(15) = -0.368$, $p = 0.718$.

For all participants, incongruent trials were the least accurate. PWA and controls did not differ in accuracy across trial types. *Post-hoc* analyses revealed that PWA performed similarly on neutral and incongruent trials, whereas controls performed similarly on congruent and neutral trials.

Reaction time results

The dependent variable RT was measured by timing how long it took a participant to respond. Analysis was done with correct-trials only. This section will address whether there is a difference in RT between congruent, neutral and incongruent trials for all participants. It will also address whether there is a difference in accuracy and RT for PWA and controls.

The main effect for both trial type (F (2, 30) = 29.487, p = 0.000) and group (F (2, 30) = 10.999, p = 0.002) were significant. There was no significant interaction (F (2, 30) = 2.982, p = 0.058). Please refer to Table 3 for a summary of means and standard deviations on the measure of RT for PWA and controls during different trial types on the spatial Stroop task.

Table 3

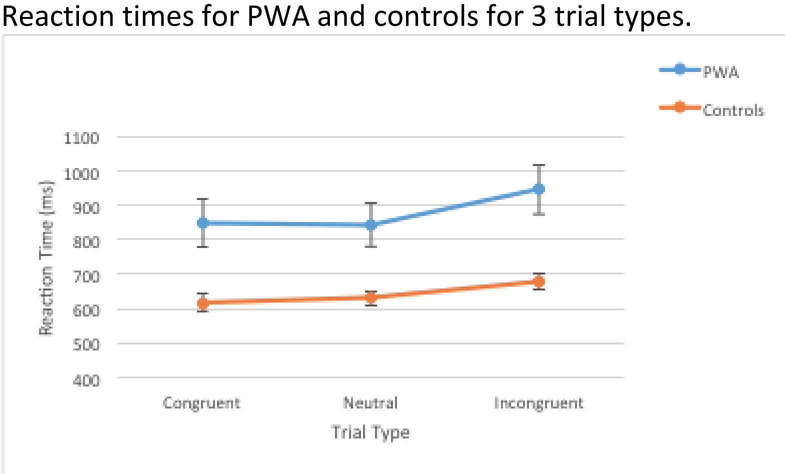
Average reaction times across trial types for PWA and control participants.

	People with Aphasia			**Controls**			**Combined**		
	n	Mean	Standard Deviation	*n*	Mean	Standard Deviation	*N*	Mean	Standard Deviation
Congruent	*16*	848.496	282.865	*16*	618.147	102.401	*32*	733.321	37.604
Neutral	*16*	841.883	249.678	*16*	630.469	89.979	*32*	736.176	33.175
Incongruent	*16*	945.377	286.750	*16*	678.271	95.362	*32*	811.824	37.774
Combined	*16*	878.585	50.379	*16*	642.295	50.379			

Notes: results presented include correct trials only.

Figure 3

Reaction times for PWA and controls for 3 trial types.



Notes: Correct trials only. Error bars represent Standard Error of Measure.

***Post-hoc analysis*.**

We explored the significant main effect for trial type using *post hoc* t-tests to compare overall RT on congruent, neutral and incongruent trials. Because of the exploratory nature of this study significance was determined at $p < 0.05$.

For all participants (n=32), independent samples *t*-tests showed that there was a significant difference between congruent and incongruent trials, $t(31) = 6.338$, p = 0.000, as well as neutral and incongruent trials, $t(31) = -6.686$, p = 0.000. No significant difference was identified between congruent and neutral trials, $t(31) = -0.235$, p = 0.816. Because we only have two levels of our between groups factor, no further statistical analyses were required to determine which group was the slowest.

Interference. The interference effect (i.e., the difference in mean RT between incongruent and neutral trials on only correct trials; Hamilton & Martin, 2005), was calculated for both groups and compared using an independent samples t-test (See table 4). There was a significant difference between PWA and controls for the size of the interference effect $t(24.844) = 2.699$, p = 0.012. PWA had greater interference than control participants.

Facilitation. The facilitation effect (i.e., the difference in mean RT between neutral and congruent trials on only correct trials; Hamilton & Martin, 2005) was calculated to compare PWA with controls (see table 4). There was no significant difference between PWA and controls for the size of the facilitation effect $t(26.994) = -0.774$, p = 0.446.

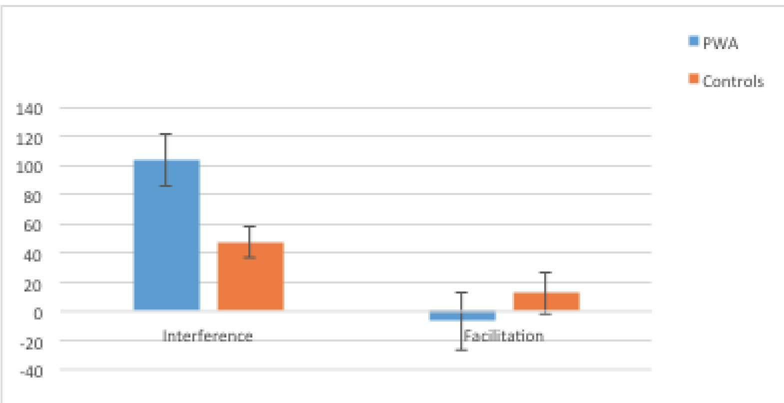
There was a significant difference in the interference effect between PWA and controls, but no significant difference in facilitation.

Table 4
Interference and facilitation effects for PWA and controls.

	People with Aphasia			Controls		
	n	Mean	Standard Deviation	*n*	Mean	Standard Deviation
Interference	*16*	103.494	70.412	*16*	47.802	43.064
Facilitation	*16*	-6.612	79.907	*16*	12.322	56.479

Note. Reaction time values measured in milliseconds. Interference: incongruent mean RT - neutral mean RT. Facilitation: neutral mean RT - congruent mean RT.

Figure 4
Interference and facilitation effects for PWA and controls.



Notes: Error bars represent +/- 1 Standard Error of Measure.

Pupillometry Results

The dependent variable of change in pupil dilation was measured by calculating the difference between the minimum and maximum pupil dilation for each of the 120 trials completed by each participant. This section will address if there is a difference in average change in pupil size between congruent, neutral and incongruent trials. It will also address whether there is a difference in average change in pupil size between PWA and controls. Please refer to Table 5 for a summary of means and standard deviations of change in pupil size measure for PWA and controls during different trial types on the spatial Stroop task.

The main effect for group was significant, $F\ (1, 29) = 6.909$, $p = 0.013$. However, the main effect for trial type was not significant, $F\ (1.237, 29) = 2.747$, $p = 0.099$, and no significant interaction was identified, $F\ (1.356, 29) = 0.832$, $p = 0.391$.

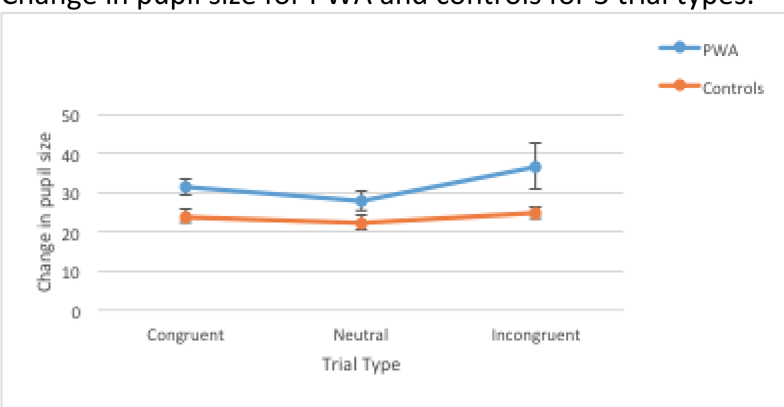
Table 5

Change in pupil size for people with aphasia and controls.

	People with Aphasia			Controls			Combined		
	n	Mean	Standard Deviation	*n*	Mean	Standard Deviation	*N*	Mean	Standard Deviation
Congruent	*16*	31.343	8.465	*16*	23.967	6.180	*32*	27.655	1.310
Neutral	*16*	27.755	9.546	*16*	22.319	6.671	*32*	25.037	1.456
Incongruent	*16*	36.562	23.657	*16*	24.959	6.131	*32*	30.760	3.055
Combined	*16*	31.886	2.189	*16*	23.748	2.189			

Figure 5

Change in pupil size for PWA and controls for 3 trial types.



Notes: Error bars represent +/- 1 Standard Error of Measure.

For all participants, there was no significant difference in change in pupil dilation between trial types (congruent, neutral, incongruent). Overall, PWA showed greater pupil dilation across trial types compared to controls, which suggests PWA exerted more cognitive effort than control participants to complete the task.

DISCUSSION

In this study we investigated the performance and cognitive effort of PWA on the spatial Stroop task using pupillometry. Participants were asked to determine the direction of an arrow when presented with a stimulus in the middle, left or right side of a computer screen. Controls and PWA did not differ in accuracy performance. However, PWA were observed having larger RTs and greater change in pupil size. To our knowledge, this is the first study to investigate cognitive effort using eye tracking during a non-linguistic task of inhibition in PWA.

Accuracy

It was originally predicted that PWA would perform with less accuracy. However, we found that PWA and control participants did not perform differently on the measure of accuracy. The data was examined to determine whether outliers were present and potentially affecting the group mean difference, but no participants performed more than 3 standard deviations above or below the mean. Two PWA performed worse than chance, but were not statistical outliers so were retained in our analyses. Due to a small sample size, we cannot determine if these participants are clinical outliers. These results demonstrate that PWA and controls were similar in their performance, which did not support our original hypothesis where we predicted PWA to be less accurate because of researched deficits with executive functions (Hamilton & Martin, 2005; Helm-Estabrooks, 2014; Hula & McNeil, 2008; Martin & Allen, 2008; Heuer & Hallowell, 2015; Chapman & Hallowell, 2015). Our results indicate that PWA are capable of responding accurately during a task of inhibition and of inhibiting irrelevant information.

Incongruent trials were the least accurate for all participants, which supported our original hypothesis. Hamilton and Martin (2005) found similar results in their study which investigated the standard and nonverbal Stroop task for an individual with semantic short term memory deficits. Incongruent trials require the most inhibitory function because the participant is presented with conflicting location and arrow direction information. To respond accurately, the participant must ignore location information and respond only to arrow direction.

We anticipated all participants to respond most accurately for congruent trials because location and arrow direction were aligned, based on previous Stroop task results (Beatty, 1982; Hamilton & Martin, 2005). However, in the current study, PWA responded similarly for neutral and incongruent trials, whereas controls responded similarly for congruent and neutral trials. This difference in response pattern indicates that the difficulty of neutral and incongruent trials was similar for PWA, but not for control participants. This could be that the controls were near ceiling in their accuracy, resulting in little variability in their performance. Overall, PWA and controls demonstrated different patterns of accuracy across trial types, but these pattern did not differ significantly.

Reaction time

All participants were expected to have the slowest reaction times for incongruent trials. In order to respond correctly on incongruent trials, the participant must actively inhibit screen location information (Hamilton & Martin, 2005). The results were consistent with our hypotheses, demonstrating that all participants had the longest reaction times for incongruent trials. These results are similar to those of Weiner, Connor, and Obler (2004) who looked at attention allocation in auditory comprehension via a numeric version of the Stroop task in people with Wernicke's aphasia. They found both control participants and people with Wernicke's aphasia took longer to respond to trials involving incompatible information.

While both PWA and controls were slowest for incongruent trials, the two groups differed in their fastest trial type. PWA were fastest for neutral trials, whereas controls were fastest for congruent trials. Congruent trials have been found to be the fastest trial type in previous research for a numeric Stroop task (Weiner, Connor & Obler, 2004). Hamilton and Martin (2005) however, found similar results as the present study: neutral trials were the fastest for a participant with left inferior frontal damage on the spatial Stroop task. An explanation for this discrepancy is that PWA had difficulty orienting to the congruent trials (i.e., finding the arrow), compared to neutral trials when the arrow appeared in the center of the screen. Therefore, the time it took for them to locate and respond to the congruent trials produced longer reaction times.

When comparing between groups, PWA were predicted to have longer reaction times compared to controls due to cognitive deficits in attention allocation and executive functioning associated with PWA (Hamilton & Martin, 2005; Helm-Estabrooks, 2014; Hula & McNeil, 2008; Martin & Allen, 2008; Heuer & Hallowell, 2015; Chapman & Hallowell, 2015), which impacts the amount of time needed to make a decision. We found that PWA took significantly longer to respond on all trial types compared to controls. This result, paired with our accuracy results, suggest that PWA require more time to respond correctly on a task of inhibition.

Interference and facilitation. We also found a significant between-groups difference in the interference effect but no significant between-groups difference in the facilitation effect, which was consistent with previous research findings (Weiner, Connor & Obler, 2004). PWA exhibit difficulty with incongruent trials when compared directly to neutral trials, suggesting PWA display an impairment in inhibition for a non-verbal Stroop task. This result could be explained by a speed-accuracy trade-off because PWA are taking longer on incongruent trials in an attempt to answer correctly; PWA require more time than controls, who do not have deficits in inhibitory function. The significant difference in interference for PWA and controls compared to their lack of difference in facilitation suggests that PWA show only a deficit in inhibitory function (Weiner, Connor, & Obler, 2004).

Pupillometry

We predicted greater changes in pupil size for incongruent trials for all participants. However, our results indicated no differences in pupil dilation between trial types (i.e., no specific trial type required more cognitive effort than another). This is a surprising result because we expected more effort would be necessary for incongruent trials when the participant had to engage inhibitory processes in order to respond accurately. A similar study recruited university students to investigate cognitive effort using pupillometry for the standard Stroop task, and found a significant change in pupil size for incongruent trials (Laeng et al, 2011). Our differing results could be caused by the differences in task requirements between the standard and spatial Stroop tasks.

The results of this study confirmed our hypothesis that PWA would exhibit larger changes in pupil size than controls. Because there was no significant interaction between trial type and group, we conclude that PWA and controls are likely using different amounts of effort to complete the whole task, not just during particular trials. Our results demonstrate that PWA use more cognitive effort across trials, evidenced by their larger changes in pupil dilation. A previous study of linguistic processing using pupillometry did not find any significant differences between people with and without aphasia on measures of pupil dilation (Chapman & Hallowell, 2015). Chapman and Hallowell (2015) suggested that the task used in their study may not have been challenging enough for the participants (i.e., the passive listening test did not require much cognitive effort). This suggests group differences may emerge only under more difficult tasks like the spatial Stroop task in the current study. Our results indicate that PWA expend more cognitive effort to respond than controls.

Integration of performance measures

PWA performed similarly to control participants on measures of accuracy during the spatial Stroop. However, PWA took longer on all trials (reaction time), experienced great interference for incongruent trials, and had greater overall pupil dilation, indicating they were exerting more cognitive effort to complete the task. We believe the results from the current study provide evidence that even on a simple cognitive task, PWA experience disruption to their inhibitory abilities. Future investigation should triangulate multiple indicators (e.g., accuracy, RT, and pupil dilation) of performance to allow for more robust interpretations of performance in PWA on cognitive tasks. It is important that some of these indicators are non-linguistic in order to reveal an individual's competence, despite any linguistic deficits associated with this population (Beeson & Rapcsak, 2006). Previous research has indicated that inhibition plays a role in decision-making (Del Missier, Mäntylä & Bruin, 2012). Our study reveals that

PWA are capable of inhibitory function, therefore should be able to make decisions that require inhibition, if given enough time to do so.

CONCLUSION

In this study we paired a non-linguistic task of inhibition with an autonomic measure of cognitive effort to explore and understand one cognitive process in PWA: inhibition. Bypassing the use of language provides a more accurate representation of cognition in this population. Results from this paper provide preliminary evidence to suggest PWA have the ability to perform similarly to control participants when completing non-linguistic tasks that require inhibition, though PWA may require more time and expend more cognitive effort to reach the same conclusions.

These findings have implications for PWA in health care systems; health care providers who work with PWA should allow extra time for decision-making tasks and understand that PWA are able to complete tasks of inhibition just as well as those without aphasia, but it may take more effort for them to do so.

Limitations and future directions

The sample size for a study of this nature is small (*N = 32)*. Small sample sizes make it more challenging to reproduce the statistical findings in future studies. Another limitation is there was only one cognitive task used to determine cognitive effort and measure performance (i.e., accuracy and reaction time). Finally, the spatial Stroop task has not been used extensively in the literature, and validity of the task has not yet been established.

Future studies with larger sample sizes could replicate the methodology of the current study to establish reliability of the findings. Larger sample sizes could allow for stratified analyses and the discovery of patterns within and between the different subtypes of aphasia. It is also important for future studies to include other tasks that can explore broader cognitive functions such as working memory. Another recommendation is to implement the same eye-tracking methods used in this study with a variety of linguistic tasks, bridging the pupillometry findings from this study with Chapman & Hallowell's (2015) study of indexing word difficulty in individuals with and without aphasia.

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