Introduction

It is well documented that there are many potential confounds in assessing linguistic abilities individuals with stroke and brain injury. Such individuals often have impairments of attention, vision, and motor function, concurrent with impairments of language (Hallowell, 1999; Heuer & Hallowell, 2007; Heuer & Hallowell, 2009; Hallowell, Wertz, & Kruse, 2002). A set of measures that may aid in reducing these confounds entails task-evoked responses of the pupil (TERPs). TERPs are "a time-locked averaged record of pupillary dilation and constriction occurring during the performance of a mental task" (Ahern & Beatty, 1981, p. 122), which occur after the onset of processing (within 100-200 msec) and subside quickly following the termination of processing (Beatty, 1982). Kahneman (1973) highlighted the validity of pupillometric measures of "mental effort" (p. 18). The notion that greater cognitive or linguistic task difficulty leads to greater intensity of effort that can be captured through pupillometric indices has been affirmed through the results of studies on memory load (Kahneman & Beatty, 1966), mental arithmetic (Hess & Polt, 1964), letter discrimination (Beatty & Wagoner, 1978) , sentence repetition (Piquado, Isaacowitz, & Wingfield, 2010), sentence comprehension (Just & Carpenter, 1993), and cross-linguistic interpretation (Hyönä, Tommola, & Alaja, 1995). When experimenters carefully control participant characteristics, stimulus features, and environmental conditions, TERPs potentially provide valuable information regarding individual differences in cognitive and linguistic abilities.

Purpose

The primary aims of this study were to (a) develop and test a new method for indexing pupillometric responses to differences in word difficulty for individuals without neurological disorders (controls) and individuals with aphasia due to stroke, and (b) determine whether the degree of effort that people with aphasia (PWA) exhibit for easy versus difficult words, as indexed through pupillometric measures, is associated with the severity of comprehension deficits and/or overall aphasia.

Method

Seventy-eight adults participated (40 controls and 38 PWA). Inclusion criteria included American English as a native language, no history of learning/developmental disorders, no history of traumatic brain injury, and no knowledge of the purpose of this study. Participants were administered a case history interview and hearing, vision, ocular motor, and pupillary screenings. PWA were given the Aphasia Quotient (AQ) components of the Western Aphasia Battery-Revised (WAB-R; Kertesz, 2007).

Stimulus words were selected based on estimated difficulty such that each fit clearly into one of two categories: easy or difficult. Difficulty was estimated using four types of measures recommended in the literature: age of acquisition, word frequency, word familiarity, and naming latency.

Baseline condition. Participants were exposed to all visual stimuli without accompanying auditory stimuli. Instructions were "Look at the pictures in any way that comes naturally." Mean pupil diameter, maximum pupil diameter, and latency of maximum pupil diameter were measured for each participant in each trial. These points were used to determine the amount of pupil dilation, rather than absolute pupil diameter, observed during the experimental condition.

Experimental condition. Visual and auditory stimulus items were presented simultaneously. Instructions were "Listen to the words and look at the pictures." Images were displayed for three seconds before the computer advanced to the next item.

Following baseline and experimental conditions, participants completed a sorting task by placing each stimulus item in an easy or difficult pile, based on his or her own conception of difficulty. This task was intended to validate the stimulus selection method.

Hypotheses tested:

1. When viewing a single image presented simultaneously with an auditory stimulus, participants with and without aphasia will exhibit differences in pupillary response.

2. When viewing a single image presented simultaneously with an auditory stimulus, the pupillary responses of PWA will be correlated with the severity of their aphasia as indexed by the WAB AQ and Auditory Comprehension (AC) score.

3. When viewing a single image presented simultaneously with an auditory stimulus, pupillary responses will be correlated with each of the five measures of word "difficulty" (as indexed by age of acquisition, word frequency, word familiarity, naming latency, and perceived difficulty).

Each hypothesis was tested using three dependent measures (mean pupil diameter, simple maximum pupil diameter, and latency of simple maximum pupil diameter), which have been shown to reflect both intensity and time-course of cognitive processing.

<u>Results</u>

In comparisons of pupillometric responses of controls and PWA, a significant main effect was found for mean pupil diameter and item difficulty; mean pupil diameter was smaller for easy words than for difficult words (see Table 1 and Figure 1).

There was a negative correlation between PWA scores on the WAB-R AC and the latency of maximum pupil diameter for easy words (see Table 2 and Figure 2). .

There was a positive correlation between the age of acquisition and mean pupil diameter for control participants and PWA. For PWA, there was also a positive correlation between naming latency and mean pupil diameter (see Tables 3 and 4 and Figures 3 and 4).

<u>Discussion</u>

Results confirm that the intensity of cognitive effort as indexed through pupillometry was less for easy words than for difficult words. This is consistent with previous findings linking the magnitude of pupillary dilation to the intensity of cognitive processing (Just & Carpenter, 1993). Pupillary dilation increases as the intensity of cognitive processing increases

The higher a PWA scored on the WAB AC, indicating less severe comprehension deficits, the less time it took to reach maximum pupil dilation for easy words. This relationship indicates that pupillometry can capture how PWA with less severe auditory comprehension deficits process easy words more quickly than difficult words, whereas PWA with more severe auditory comprehension deficits do not. Kahneman and Beatty (1966) showed that maximum pupil dilation indicates the point at which an individual's processing is at a high intensity level, often immediately prior to the completion of a task (Hess & Polt, 1964).

The correlation between age of acquisition and mean pupil diameter for control participants and PWA and the correlation between naming latency and mean pupil diameter for PWA suggest that the later a word is learned, the greater the effort required to process that word. Age of acquisition has been implicated in determining naming latency, so the significance of these two correlations is not surprising. That PWA had significant correlations between mean pupil diameter and two measures of word difficulty may be an example of the increased sensitivity to difficult linguistic stimuli in PWA. These correlations also provide insight into the measures that have the best potential for determining word difficulty in future research.

Future Directions

Results show that pupillometry can capture effects of word difficulty in individuals with and without aphasia. That difficulty effects were captured using single nouns, all of which many participants believed to be "easy", shows that pupillometry may be sensitive enough to capture even subtle differences in the effort required to process words. Pupillometric results not only reflected differences related to word difficulty, but also differences in the time frame required for the processing of stimuli for PWA with varying levels of comprehension deficits. Together, these findings provide evidence for the potential application of pupillometry within comprehension assessment for individuals with neurological disorders. Further developments in task design and analysis may increase the sensitivity of pupillometric measures in the future. The method may also be extended to longer and more complex verbal stimuli.

References

Ahern, S. K., & Beatty, J. (1981). Physiological evidence that demand for processing capacity varies with intelligence. In M. Friedman, J. Dos, & N. O'Connor (Eds.), *Intelligence and learning*. New York, NY: Plenum Press.

Beatty, J. (1982). Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychological Bulletin*, 91, 276-292.

Beatty, J., & Wagoner, B. L. (1978). Pupillometric signs of brain activation vary with level of cognitive processing. *Science*, 199, 1216-1218.

Hallowell, B. (1999). A new way of looking at auditory linguistic comprehension. In W. Becker, & T. Mergner (Eds.), *Current oculomotor research: Physiological and psychological aspects* (pp. 292-299). New York, NY: Plenum Publishing Company.

Hallowell, B., Wertz, R. T., & Kruse, H. (2002). Using eye movement responses to index auditory comprehension: An adaptation of the Revised Token Test. *Aphasiology*, 16, 587-594.

Hess, E. H., & Polt, J. M. (1964). Pupil size in relation to mental activity during simple problem solving. *Science*, 143, 1190-1192.

Heuer, S., & Hallowell, B. (2007). An evaluation of test images for multiple-choice comprehension assessment in aphasia. *Aphasiology*, 21, 883-900.

Heuer, S., & Hallowell, B. (2009). Visual attention in a multiple-choice task: Influences of image characteristics with and without presentation of a verbal stimulus. *Aphasiology*, 23, 351-363.

Hyönä, J., Tommola, J., & Alaja, A. (1995). Pupil dilation as a measure of processing load in simultaneous interpretation and other language tasks. *The Quarterly Journal of Experimental Psychology*, 48A, 598-612.

Just, M. A., & Carpenter, P. A. (1993). The intensity dimension of thought: Pupillometric indices of sentence processing. *Canadian Journal of Experimental Psychology*, 42, 310-339.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science*, 154, 1583-1585.

Kertesz, A. (2007). Western Aphasia Battery–Revised. San Antonio, TX; PsychCorp.

Piquado, T., Isaacowitz, D., & Wingfield, A. (2010). Pupillometry as a measure of cognitive effort in younger and older adults. *Psychophysiology,* 47, 560-569.

Tables and Figures

Table 1

Repeated Measures ANOVA for Control Participants and PWA

Measure type	Measure	Source	*df*	*MS*	*F*	*p*	η^2
Diameter measures	Max	Group	1, 66	0.66	3.19	0.08	0.05
		Difficulty	1, 66	0.11	1.13	0.29	0.02
		Difficulty*Group	1, 66	0.03	0.36	0.55	0.01
	Mean	Group	1, 66	0.006	0.65	0.42	0.01
		Difficulty	1, 66	0.16	60.85	0.000	0.47
		Difficulty*Group	1, 66	0.004	1.51	0.22	0.01
Latency measures	Latency	Group	1, 66	0.006	0.04	0.85	0.00
		Difficulty	1, 66	0.00	0.003	0.95	0.00
		Difficulty*Group	1, 66	0.002	0.02	0.88	0.00

Note. Max = simple maximum; Latency = latency of simple maximum

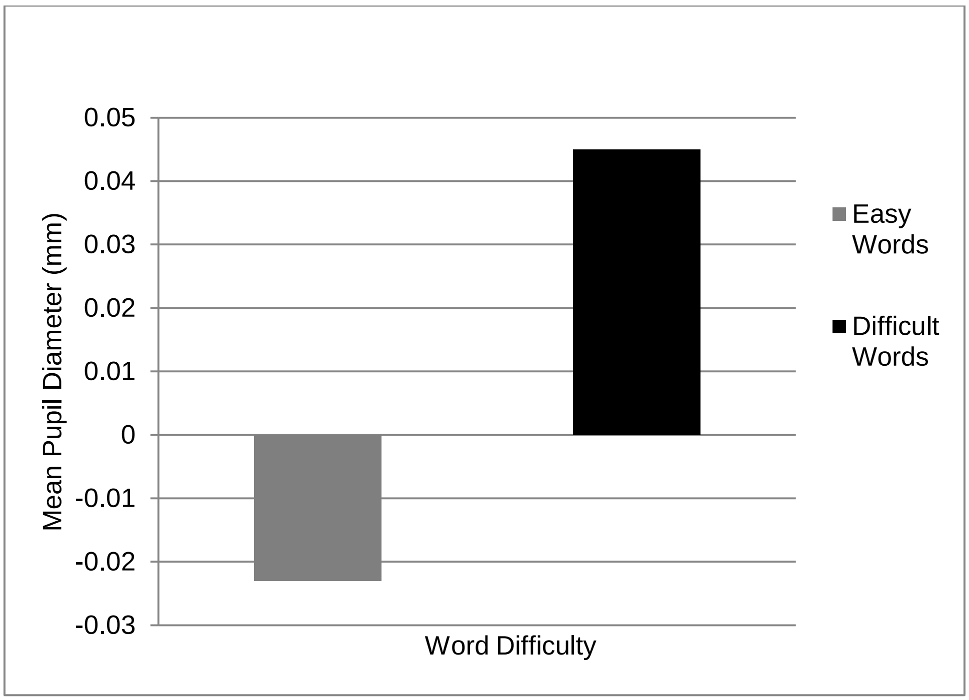

Figure 1. Mean pupil diameter as a function of word difficulty for 48 control participants and 38 PWA.

Table 2

Correlations of the Severity of Aphasia and Severity of Comprehension Deficits with Pupillary Responses for PWA

Measure Type	Pupillary responses	Severity scores	
		WAB AQ	WAB AC
Diameter measures	Max – Easy	*r*(38) = -0.19, *p* = 0.26	*r*(38) = -0.23, *p* = 0.17
	Max – Difficult	*r*(36) = 0.25, *p* = 0.14	*r*(36) = 0.12, *p* = 0.47
	Mean – Easy	*r*(38) = -0.24, *p* = 0.15	*r*(38) = -0.21, *p* = 0.20
	Mean – Difficult	*r*(36) = -0.21, *p* = 0.21	*r*(36) = -0.20, *p* = 0.24
Latency Measures	Latency – Easy	*r*(38) = -0.26, *p* = 0.12	*r*(38) = -0.40*, *p* = 0.01
	Latency - Difficult	*r*(36) = 0.10, *p* = 0.55	*r*(36) = -0.01, *p* = 0.98

* Correlation is significant at the 0.05 level (2-tailed).

Note. WAB AQ = Aphasia Quotient from the Western Aphasia Battery – Revised; WAB AC = Auditory Verbal Comprehension sections of the Western Aphasia Battery – Revised; Max – easy = simple maximum measure for easy words; Max – difficult = simple maximum measure for difficult words; Mean – Easy= mean pupil diameter for easy words; Mean- Difficult = mean pupil diameter for difficult words; Latency – Easy = latency of simple maximum diameter for easy words; Latency – Difficult= latency of simple maximum diameter for difficult words.

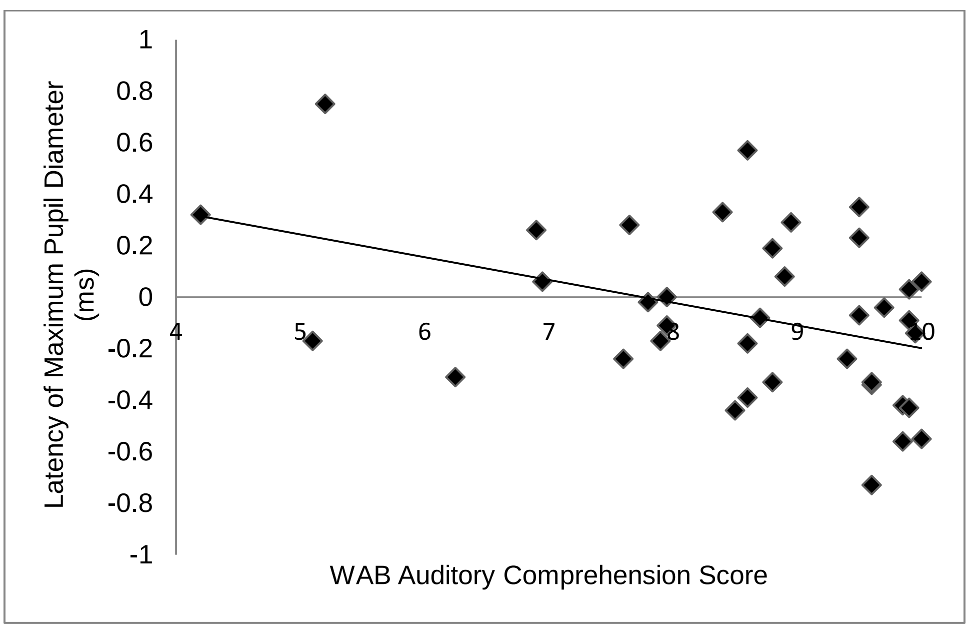

Figure 2. Latency of maximum pupil diameter as a function of WAB Auditory Comprehension score for 38 PWA.

Table 3

Correlations between Measures of Word Difficulty and Pupillary Responses for Control Participants

Measures of word difficulty	Pupillary responses: Diameter measures		Latency Measures
	Max	Mean	Latency
Familiarity	$r(30) = -0.17$ $p = 0.38$	$r(30) = -0.26$ $p = 0.17$	$r(30) = -0.003$ $p = 0.99$
Frequency	$r(30) = -0.04$ $p = 0.83$	$r(30) = -0.13$ $p = 0.51$	$r(30) = -0.10$ $p = 0.59$
Age of Acquisition	$r(30) = 0.26$ $p = 0.17$	$r(30) = 0.44^{*}$ $p = 0.02$	$r(30) = -0.05$ $p = 0.80$
Naming Latency	$r(30) = 0.11$ $p = 0.55$	$r(30) = 0.35$ $p = 0.06$	$r(30) = 0.16$ $p = 0.39$
Perceived difficulty	$r(30) = 0.27$ $p = 0.15$	$r(30) = 0.14$ $p = 0.47$	$r(30) = 0.000$ $p = 0.10$

* Correlation is significant at the 0.05 level (2-tailed).
Note. Max = simple maximum; Latency = latency of simple maximum

Table 4

Correlations between Measures of Word Difficulty and Pupillary Responses for PWA

Measures of word difficulty	Pupillary responses: Diameter measures		Latency Measures
	Max	Mean	Latency
Familiarity	$r(30) = 0.15$ $p = 0.44$	$r(30) = -0.25$ $p = 0.18$	$r(30) = 0.08$ $p = 0.68$
Frequency	$r(30) = -0.03$ $p = 0.88$	$r(30) = -0.10$ $p = 0.60$	$r(30) = 0.08$ $p = 0.67$
Age of Acquisition	$r(30) = 0.04$ $p = 0.84$	$r(30) = 0.44^{*}$ $p = 0.03$	$r(30) = 0.06$ $p = 0.77$
Naming Latency	$r(30) = -0.10$ $p = 0.60$	$r(30) = 0.41$* $p = 0.03$	$r(30) = 0.03$ $p = 0.87$
Perceived difficulty	$r(30) = -0.30$ $p = 0.41$	$r(30) = 0.11$ $p = 0.56$	$r(30) = -0.06$ $p = 0.76$

* Correlation is significant at the 0.05 level (2-tailed).
Note. Max = simple maximum; Latency = latency of simple maximum

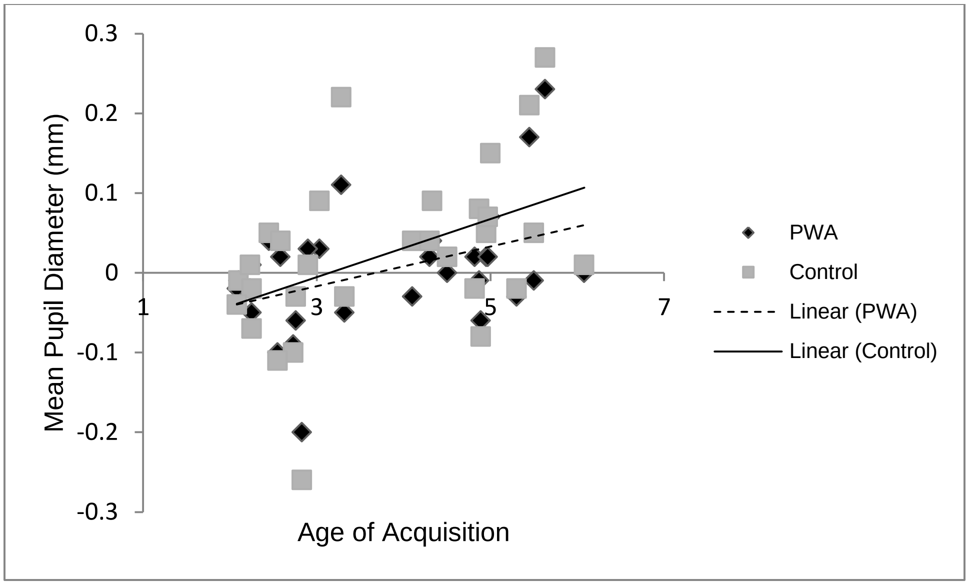

Figure 3. Mean pupil diameter as a function of age of acquisition for 40 control participants and 38 PWA.

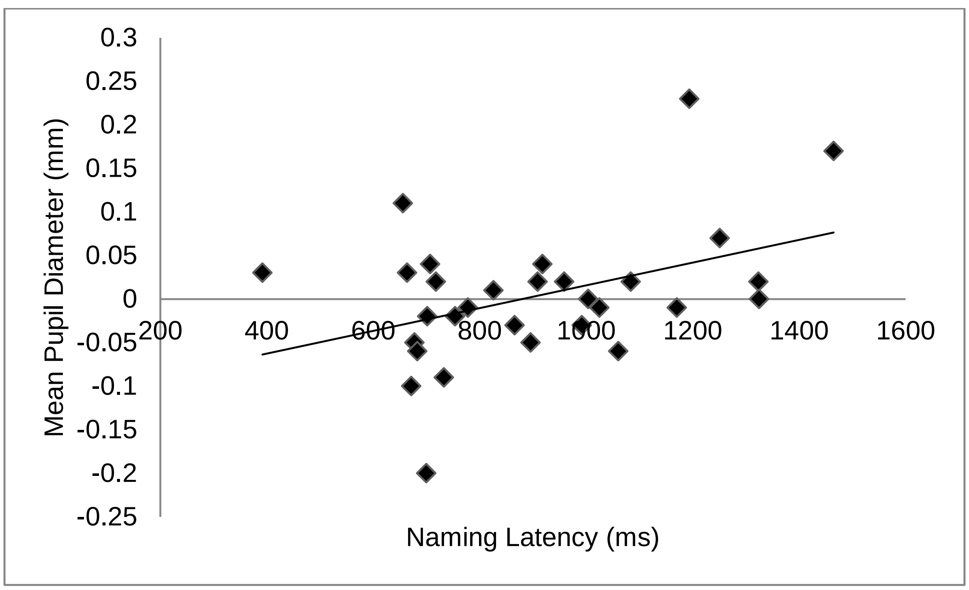

Figure 4. Mean pupil diameter as a function of naming latency for 38 PWA.