Title: Exploring online eye movement indices of attention allocation in aphasia

INTRODUCTION

Eye-tracking methods have been used to study cognitive and linguistic processes, such as auditory comprehension (Hallowell, 1999; Hallowell et al.,2002; Hallowell, 2012), semantic priming (Odekar et al., 2009), attention allocation (Heuer & Hallowell, 2009, 2012) working memory (Ivanova & Hallowell, in press), grammatical processing (Choy & Thompson, 2010; Dickey, Choy, & Thompson, 2007; Thompson, Dickey, & Choy, 2004; Thompson, Dickey, Choy, Lee, & Griffin, 2007), and lexical activation (Yee, Blumstein, & Sedivy, 2004), in people with and without aphasia. Eye-tracking methods have excellent potential for use with individuals with a broad range of neurological disorders, especially in terms of improving validity of cognitive and linguistic assessment. Such methods do not require understanding of complex instructions. Participants are not required to respond verbally, in writing, or with gestures. Responses do not require device manipulation. These features reduce critical response confounds. Additionally, eye-tracking methods yield online measures. Heuer and Hallowell (2012) demonstrated the validity and effectiveness of a novel eye-tracking method for studying attention allocation. An important next step is to examine how such a method may be used to enhance knowledge of the temporal aspects of attention processes in people with and without aphasia.

An obstacle to be overcome in enhancing the validity of eye-tracking methods is the lack of research validating specific means of indexing responses during cognitive and linguistic tasks, making it difficult to compare and interpret results across studies (Inhoff & Radach,1998). Developing reliable evidence-based and theory-supported dependent measures for analyzing and reporting eye-tracking results is crucial (Hallowell & Lansing, 2004). While eye tracking provides online measures, it is important to explore in what time interval to probe for data in order to capture targeted effects. For instance, when analyzing data at a very early stage post stimulus onset, the participant might not have been able to process visual and/or verbal stimuli presented and the data recorded may only incompletely capture cognitive processes. On the other hand, when probing data during a longer time window, after stimuli have been presented, the participant might have completed the cognitive process much sooner and eye-tracking data would include substantial noise. Thus, crucial experimental effects might be lost.

There are many examples in the literature of inappropriate means of analyzing online eye-tracking data, the most egregious of which is the use of raw eye-position samples to make conclusions about cognitive processing. Eye-position samples are typically collected at 60 or 120 Hz. A minimum of 100 ms of eye position stability is required for viewers to actually take in visual information; given that no actual visual information uptake is possible when the eyes are moving from one area of fixation to another, use of raw data for online analyses leads to substantial noise in the data and no valid means of interpretation of results.

One dependent measure that yields robust results in comprehension, memory, and attention experiments entailing carefully controlled multiple-image displays is the proportion of the total fixation time during a specific segment of visual stimulus presentation that a viewer spends fixating on a “target” image (e.g., Hallowell, 1999, 2012; Heuer & Hallowell, 2009, 2012; Ivanova & Hallowell, in press). The measure, the proportion of fixation duration on the target (PFDT), entails the use of actual fixation data rather than raw eye position samples and allows the experimenter to define time windows to be used for analysis so that temporal aspects of online responses may be studied.

PURPOSE

The goal of this study was to determine the most sensitive time intervals for data sampling during an attention allocation task, using a dual-task paradigm previously validated on people with and without aphasia (Heuer & Hallowell, 2012). Attention demands were manipulated by varying task and stimulus complexity. Changes in attention demands were indexed through performance on a visual search task using PFDT as the dependent measure. Probes were taken at 500-ms intervals (0-500 ms, 0-1000 ms, etc., up to 4000 ms post stimulus onset).

METHOD

Twenty-three adults with aphasia participated. Presence of a left CVA was verified through medical records. Aphasia was assessed with the Western Aphasia Battery (WAB-R, Kertesz, 2007). Type and severity of aphasia were documented. Thirty age- and education-matched individuals who passed a mental status screening (Mini Mental Status Examination; MMSE; Folstein, Folstein, & McHugh, 1975) served as controls. All participants passed vision and hearing screenings.

Visual search. Multiple-choice image displays containing one target and three foil images were shown. Stimuli shared the same image characteristics (size, shape, and complexity). The target differed from the foils with respect to one image characteristic. Thirty “simple” trials included images with identical orientation. In thirty “complex” trials, stimuli were rotated. Participants were instructed to “look at the different image.” Eye-tracking studies with individuals without neurogenic impairment have shown that 3000 ms is sufficient to process similar multiple-choice image displays (Heuer & Hallowell, 2007; Heuer & Hallowell, 2009). An interval of 6000 ms was chosen to provide individuals with aphasia additional processing time.

Dual-task. Participants engaged in the visual search task for 3000 ms and were simultaneously presented a verbal stimulus. They were asked to: “look at the different image and listen carefully to the words.” Eye movements were monitored and recorded at 60 Hz using an LC Technologies Eyegaze remote pupil center/corneal reflection system.

Analysis. Custom software was used for eye-tracking data analysis. A fixation was defined as a stable eye position of at least 100 ms with a range of motion limited to four degrees vertically and six degrees horizontally (Manor & Gordon, 2003).

RESULTS

Two-way repeated-measures ANOVAS were conducted to assess changes in attention demands with increases in stimulus complexity (simple and complex), task differences (single and dual task), and group differences (individuals with aphasia and control participants) at every time interval. Means and standard deviations and ANOVA results are summarized for stimulus complexity in the single-task condition (Table 1 and 2), complexity effects in the dual-task condition (Table 3 and 4), and differences due to changes in task demands (Table 5 and 6). Effect sizes across time intervals are presented in Table 7.

DISCUSSION

Heuer and Hallowell (2012) established that PFDT is a valid measure to index attention allocation as it indexed increases in attention allocation from single-to dual task processing and simple-to complex conditions, as well as differences in people with and without aphasia at 4000 ms. The analysis of the time segments examined in the current study confirmed those results. Generally, effects for stimulus complexity were greater than those for group differences. With an increase in time, effect sizes for significant main effects tended to increase until 4000 ms. Effect sizes plateaued at 4000 ms and decreased at 6000 ms (except for the single- to dual-task comparison). For the single-to dual-task comparison, significant main effects started to manifest later and effect sizes peaked later as well.

SUMMARY

At 4000 ms post stimulus onset, effect sizes for main effects were largest, indicating greatest discrepancies in processing between groups, and greatest sensitivity to stimulus complexity differences. The results are important because they contribute to the development of more stringent eye-tracking protocols and improved validity of eye-tracking indices. They also enhance our understanding of the time course of attention allocation in the context studied and provide guidance for future studies.

Table 1

Means and Standard Deviations for Dependent Measures in the Simple and Complex Stimulus Conditions in the Single-task Condition During the Visual Search Task

Source	*M*	*SD*	*N*
		500 ms	
Simple			
Aphasia	0.25	0.05	27
Control	0.24	0.07	33
Total	0.24	0.06	60
Complex			
Aphasia	0.24	0.05	27
Control	0.23	0.07	33
Total	0.24	0.06	60
		1000 ms	
Simple			
Aphasia	0.28	0.05	27
Control	0.27	0.05	33
Total	0.28	0.05	60
Complex			
Aphasia	0.25	0.04	27
Control	0.26	0.04	33
Total	0.25	0.04	60
		1500 ms	
Simple			
Aphasia	0.29	0.05	27
Control	0.33	0.06	33

Table 1 (continued).

Complex			
Aphasia	0.26	0.03	27
Control	0.28	0.04	33
Total	0.27	0.04	60
		2000 ms	
Simple			
Aphasia	0.33	0.05	27
Control	0.43	0.09	33
Total	0.39	0.09	60
Complex			
Aphasia	0.28	0.03	27
Control	0.35	0.06	33
Total	0.32	0.06	60
		2500 ms	
Simple			
Aphasia	0.42	0.06	27
Control	0.53	0.10	33
Total	0.48	0.10	60
Complex			
Aphasia	0.33	0.05	27
Control	0.44	0.08	33
Total	0.40	0.09	60

Table 1 (continued).

		3000 ms	
Simple			
Aphasia	0.50	0.07	27
Control	0.61	0.10	33
Total	0.56	0.10	60
Complex			
Aphasia	0.40	0.07	27
Control	0.52	0.09	33
Total	0.46	0.10	60
		3500 ms	
Simple			
Aphasia	0.56	0.07	27
Control	0.67	0.09	33
Total	0.62	0.10	60
Complex			
Aphasia	0.45	0.08	27
Control	0.58	0.09	33
Total	0.52	0.10	60
		4000 ms	
Simple			
Aphasia	0.61	0.07	27
Control	0.71	0.09	33
Total	0.67	0.10	60

Table 1 (continued).

Complex			
Aphasia	0.50	0.08	27
Control	0.63	0.09	33
Total	0.57	0.11	60
		6000 ms	
Simple			
Aphasia	0.72	0.07	26
Control	0.77	0.06	22
Total	0.74	0.07	48
Complex			
Aphasia	0.62	0.09	26
Control	0.70	0.070	22
Total	0.66	0.09	48

Table 2
Repeated Measures ANOVA Comparing Performance in the Simple and Complex Stimulus Conditions in the Single-task Condition During the Visual Search Task

Source	*df*	*F*	*η*	*p*
		500 ms		
		Between subjects		
Group	1	.30	.005	.59
Error	58	(.005)		
		Within subjects		
Complexity	1	.70	.01	.41
Complexity x Group	1	.05	.001	.82
Error	58	(.002)		
		1000 ms		
		Between subjects		
Group	1	.08	.001	.78
Error	58	(.003)		
		Within subjects		
Complexity	1	12.32**	.18	.001
Complexity x Group	1	1.14	.02	.29
Error	58	(.001)		
		1500 ms		
		Between subjects		
Group	1	6.05*	.09	.02
Error	58	(.003)		
		Within subjects		
Complexity	1	42.82**	.43	<.001

Table 2 (continued).

Complexity x Group	1	2.07	.03	.16
Error	58	(.001)		
		2000ms		
		Between subjects		
Group	1	28.09**	.33	<.001
Error	58	(.007)		
		Within subjects		
Complexity	1	123.25**	.68	<.001
Complexity x Group	1	4.35*	.07	.04
Error	58	(.001)		
		2500 ms		
		Between subjects		
Group	1	30.44**	.34	<.001
Error	58	(.011)		
		Within subjects		
Complexity	1	234.36**	.80	<.001
Complexity x Group	1	1.34	.02	.25
Error	58	(.001)		
		3000 ms		
		Between subjects		
Group	1	30.90**	.35	<.001
Error	58	(.013)		

Table 2(continued).

Within subjects				
Complexity	1	272.22**	.82	<.001
Complexity x Group	1	.14	.002	.70
Error	58	(.001)		
3500 ms				
Between subjects				
Group	1	30.23**	.34	<.001
Error	58	(.013)		
Within subjects				
Complexity	1	316.85**	.85	<.001
Complexity x Group	1	2.50	.04	.12
Error	58	(.001)		
4000 ms				
Between subjects				
Group	1	30.24**	.36	<.001
Error	58	(.013)		
Within subjects				
Complexity	1	259.19**	.82	<.001
Complexity x Group	1	4.64*	.07	.04
Error	58	(.001)		
6000 ms				
Between subjects				
Group	1	9.17**	.17	.004
Error	46	(.013)		

Table 2(continued).

		Within subjects		
Complexity	1	128.33**	.74	<.001
Complexity x Group	1	3.99*	.08	.05
Error	46	(.001)		

Note. Values in parentheses represent mean square errors.
*p < .05. ** p <.01

Table 3

Means and Standard Deviations in the Simple, Medium, and Complex Stimulus Conditions in the Dual-task Condition During the Visual Search Task

Source	M	SD	N
	500 ms		
Simple			
Aphasia	0.22	0.09	24
Control	0.21	0.06	32
Total	0.21	0.07	56
Medium			
Aphasia	0.22	0.08	24
Control	0.21	0.09	32
Total	0.22	0.09	56
Complex			
Aphasia	0.20	0.06	24
Control	0.20	0.08	32
Total	0.20	0.07	56

Table 3(continued).

	1000 ms		
Simple			
Aphasia	0.26	0.07	24
Control	0.27	0.07	32
Total	0.26	0.07	56
Medium			
Aphasia	0.27	0.05	24
Control	0.27	0.06	32
Total	0.27	0.06	56
Complex			
Aphasia	0.25	0.04	24
Control	0.25	0.06	32
Total	0.25	0.05	56
	1500 ms		
Simple			
Aphasia	0.28	0.08	24
Control	0.31	0.08	32
Total	0.30	0.08	56
Medium			
Aphasia	0.28	0.03	24
Control	0.32	0.08	32
Total	0.30	0.07	56
Complex			

Table 3 (continued).

Aphasia	0.25	0.07	24
Control	0.28	0.10	32
Total	0.27	0.09	56
	2000 ms		
Simple			
Aphasia	0.34	0.07	24
Control	0.41	0.10	32
Total	0.38	0.10	56
Medium			
Aphasia	0.32	0.04	24
Control	0.39	0.09	32
Total	0.36	0.08	56
Complex			
Aphasia	0.29	0.04	24
Control	0.34	0.07	32
Total	0.32	0.06	56
	2500 ms		
Simple			
Aphasia	0.40	0.09	24
Control	0.50	0.12	32
Total	0.46	0.12	56
Medium			
Aphasia	0.38	0.06	24

Table 3 (continued).

Control	0.48	0.12	32
Total	0.43	0.11	56
Complex			
Aphasia	0.33	0.04	24
Control	0.41	0.09	32
Total	0.37	0.08	56
	3000 ms		
Simple			
Aphasia	0.46	0.10	24
Control	0.57	0.12	31
Total	0.52	0.13	55
Medium			
Aphasia	0.43	0.07	24
Control	0.54	0.13	31
Total	0.49	0.12	55
Complex			
Aphasia	0.37	0.05	24
Control	0.46	0.10	31
Total	0.42	0.10	55
	3500 ms		
Simple			
Aphasia	0.50	0.10	24
Control	0.62	0.13	32

Table 3 (continued).

Total	0.57	0.13	56
Medium			
Aphasia	0.49	0.09	24
Control	0.60	0.13	32
Total	0.55	0.13	56
Complex			
Aphasia	0.40	0.06	24
Control	0.52	0.11	32
Total	0.47	0.11	56
	4000 ms		
Simple			
Aphasia	0.54	0.11	24
Control	0.67	0.12	34
Total	0.62	0.13	58
Medium			
Aphasia	0.53	0.10	24
Control	0.65	0.13	34
Total	0.60	0.13	58
Complex			
Aphasia	0.43	0.07	24
Control	0.57	0.11	34
Total	0.51	0.12	58

Table 3 (continued).

	6000 ms		
Simple			
Aphasia	0.63	0.13	24
Control	0.72	0.13	34
Total	0.68	0.14	58
Medium			
Aphasia	0.62	0.13	24
Control	0.70	0.13	34
Total	0.66	0.13	58
Complex			
Aphasia	0.52	0.10	24
Control	0.63	0.11	34
Total	0.58	0.12	58

Table 4

Repeated Measures ANOVA Comparing Performance in the Simple, Medium and Complex Stimulus Conditions in the Dual-task Condition During the Visual Search Task

Source	*df*	*F*	*η*	*p*
500 ms				
Between subjects				
Group	1	.43	.008	.51
Error	54	(.008)		
Within subjects				
Complexity	2	1.01	.02	.37
Complexity x Group	2	.09	.002	.92
Error	108	(.005)		
1000 ms				
Between subjects				
Group	1	.003	.00	.96
Error	54	(.005)		
Within subjects				
Complexity	2	2.77	.05	.07
Complexity x Group	2	.08	.001	.93
Error	108	(.003)		
1500 ms				
Between subjects				
Group	1	5.10*	.10	.03
Error	54	(.008)		

Table 4 (continued).

		Within subjects		
Complexity	2	2.92	.06	.06
Complexity x Group	2	.12	.002	.89
Error	108	(.010)		
		2000ms		
		Between subjects		
Group	1	13.87**	.20	<.001
Error	54	(.013)		
		Within subjects		
Complexity	2	22.17**	.29	<.001
Complexity x Group	2	.83	.02	.43
Error	108	(.003)		
		2500 ms		
		Between subjects		
Group	1	16.96**	.24	<.001
Error	54	(.022)		
		Within subjects		
Complexity	2	48.44**	.47	<.001
Complexity x Group	2	.82	.02	.45
Error	108	(.002)		

Table 4 (continued).

		3000 ms		
		Between subjects		
Group	1	16.35**	.24	<.001
Error	54	(.03)		
		Within subjects		
Complexity	2	70.56**	.57	<.001
Complexity x Group	2	.86	.02	.43
Error	108	(.002)		
		3500 ms		
		Between subjects		
Group	1	17.72**	.25	<.001
Error	54	(.031)		
		Within subjects		
Complexity	2	77.42**	.59	<.001
Complexity x Group	2	.28	.005	.76
Error	108	(.004)		
		4000 ms		
		Between subjects		
Group	1	23.22**	.29	<.001
Error	56	(.031)		
		Within subjects		
Complexity	2	77.54**	.58	<.001
Complexity x Group	2	.88	.02	.42
Error	112	(.002)		

Table 4 (continued).

		6000 ms		
		Between subjects		
Group	1	8.38*	.13	.005
Error	56	(.041)		
		Within subjects		
Complexity	2	67.76**	.53	<.001
Complexity x Group	2	1.02	.02	.37
Error	112	(.002)		

Note. Values in parentheses represent mean square errors.
*p < .05. ** p <.01

Table 5
Means and Standard Deviations for PFDT Comparing Single-and Dual-task Conditions During the Visual Search Task

Source	*M*	*SD*	N
	500 ms		
Single task			
Aphasia	0.25	0.04	24
Control	0.24	0.06	31
Total	0.24	0.05	55
Dual task			
Aphasia	0.21	0.04	24
Control	0.20	0.06	31
Total	0.21	0.05	55

Table 5 (continued).

	1000 ms		
Single task			
Aphasia	0.26	0.04	24
Control	0.26	0.04	31
Total	0.26	0.04	55
Dual task			
Aphasia	0.26	0.03	24
Control	0.26	0.05	31
Total	0.26	0.04	55
	1500 ms		
Single task			
Aphasia	0.28	0.04	23
Control	0.30	0.05	26
Total	0.29	0.04	49
Dual task			
Aphasia	0.27	0.04	23
Control	0.31	0.06	26
Total	0.29	0.06	49
	2000 ms		
Single task			
Aphasia	0.32	0.04	24
Control	0.40	0.07	31
Total	0.36	0.07	55
Dual task			
Aphasia	0.32	0.04	24
Control	0.38	0.08	31

Table 5 (continued).

Total	0.35	0.07	55
	2500 ms		
Single task			
Aphasia	0.39	0.05	24
Control	0.49	0.09	31
Total	0.44	0.09	55
Dual task			
Aphasia	0.37	0.06	24
Control	0.46	0.10	31
Total	0.42	0.10	55
	3000 ms		
Single task			
Aphasia	0.46	0.06	24
Control	0.56	0.09	30
Total	0.51	0.10	54
Dual task			
Aphasia	0.42	0.07	24
Control	0.52	0.11	30
Total	0.48	0.11	54
	3500 ms		
Single task			
Aphasia	0.52	0.07	24
Control	0.62	0.09	31
Total	0.58	0.10	55
Dual task			
Aphasia	0.46	.08	24

Table 5 (continued).

Control	0.58	0.12	31
Total	0.53	0.12	55
	4000 ms		
Single task			
Aphasia	0.56	0.08	25
Control	0.67	0.09	31
Total	0.62	0.10	56
Dual task			
Aphasia	0.50	0.09	25
Control	0.63	0.11	31
Total	0.58	0.12	56
	6000 ms		
Single task			
Aphasia	0.68	0.07	24
Control	0.75	0.11	14
Total	0.71	0.09	38
Dual task			
Aphasia	0.59	0.12	24
Control	0.71	0.12	14
Total	0.64	0.13	38

Table 6
Repeated Measures ANOVA Comparing Performance in Single and Dual-task Conditions During the Visual Search Task

Source	*df*	*F*	*η*	*p*
		500 ms		
		Between subjects		
Group	1	.41	.008	.53
Error	53	(.004)		
		Within subjects		
Task	1	19.99**	.27	<.001
Task x Group	1	.06	.001	.81
Error	53	(.002)		
		1000 ms		
		Between subjects		
Group	1	.03	.001	.87
Error	53	(.002)		
		Within subjects		
Task	1	1.29	.02	.26
Task x Group	1	.07	.001	.79
Error	53	(.001)		
		1500 ms		
		Between subjects		
Group	1	7.19*	.13	.01
Error	47	(.003)		

Table 6 (continued).

		Within subjects		
Task	1	.01	.002	.75
Task x Group	1	.38	.008	.54
Error	47	(.002)		
		2000ms		
		Between subjects		
Group	1	22.58**	.30	<.001
Error	53	(.006)		
		Within subjects		
Task	1	.54	.01	.47
Task x Group	1	.37	.007	.55
Error	53	(.002)		
		2500 ms		
		Between subjects		
Group	1	24.79**	.32	<.001
Error	53	(.010)		
		Within subjects		
Task	1	3.60	.06	.06
Task x Group	1	.12	.002	.73
Error	53	(.003)		

Table 6 (continued).

		3000 ms		
		Between subjects		
Group	1	23.55**	.31	<.001
Error	52	(.012)		
		Within subjects		
Task	1	8.54*	.14	.005
Task x Group	1	.02	.00	.90
Error	52	(.004)		
		3500 ms		
		Between subjects		
Group	1	25.63**	.33	<.001
Error	53	(.013)		
		Within subjects		
Task	1	13.58**	.21	.001
Task x Group	1	.03	.001	.87
Error	53	(.005)		
		4000 ms		
		Between subjects		
Group	1	32.78**	.38	<.001
Error	53	(.013)		

Table 6 (continued).

Within subjects				
Task	1	16.22**	.23	<.001
Task x Group	1	.68	.01	.41
Error	53	(.004)		
6000 ms				
Between subjects				
Group	1	10.80*	.23	.002
Error	36	(.016)		
Within subjects				
Task	1	14.57**	.29	.001
Task x Group	1	1.65	.04	.21
Error	36	(.005)		

Note. Values in parentheses represent mean square errors. *p < .05. ** p <.01

Table 7

Effect Sizes η² for Significant Main Effects of Repeated Measures ANOVAs for Each Time Segment

		Time Segments in ms								
		500	1000	1500	2000	2500	3000	3500	4000	6000
Single Task	Complexity	.01	.18**	.43**	.68**	.80**	.82**	.85**	.82**	.74**
	Group	.005	.001	.09*	.33**	.34**	.35**	.34**	.34**	.17**
Dual Task	Complexity	.02	.05	.06	.29**	.47**	.57**	.59**	.58**	.53**
	Group	.008	.00	.10	.20**	.24**	.24**	.25**	.30**	.13*
Single vs Dual Task	Task	.27**	.02	.002	.01	.06	.14*	.21**	.23**	.29**
	Group	.008	.002	.13*	.30**	.32**	.31**	.33**	.38**	.23**

Note. *p < .05. ** p <.01

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