Online sentence-level reading and listening times are sensitive measures of lexical access, parsing, syntactic and semantic integration processes (e.g., Rayner et al, 2004; Trueswell et al, 1993). Studies linking online to offline performance in syntactic processing have shown that persons with aphasia (PWA) show normal or near-to-normal parsing processes on sentences that are comprehended correctly (Caplan & Waters, 2003; Caplan et al., 2007, Dickey & Thompson, 2009). However, their reading times are usually slower than those of control participants even on correct items (e.g., Sung et al, 2011; Chenery et al, 1990), suggesting generally slowed reading in this group.

Although slowing of activation/decay processes has been proposed to underlie specific syntactic and semantic processing deficiencies in PWA (Haarmann & Kolk, 1991; Prather et al., 1997), the source of this slowing has received little attention. On items where syntactic, semantic, and memory load is minimized, reading speed should reflect more general, potentially non-linguistic-specific processing variables, such as speed of processing, and/or processes underlying lexical access. These processes might reflect more subtle individual differences that could be compensated for and therefore would not noticeably affect comprehension success. In that case, comprehension success should not be related to reading speed, whereas measures of lexical efficiency should. On the other hand, reading speed could reflect processes that contribute to successful comprehension, or it could reflect even a principle cause of aphasic language disorders. As such, reading speed should be related to comprehension success and aphasia severity.

The current study used a Mixed Model approach to investigate the effects of sentence comprehension performance, lexical efficiency, and aphasia severity on slowed reading times in control participants (CP) and PWA.

Research questions and predictions

(1) To what extent does sentence comprehension predict reading speed in CPs and PWA? Given the pervasive psycholinguistic literature on measurable individual differences on reading times, it was predicted that sentence comprehension is directly related to reading speed. This effect was expected to be larger for PWA because of larger lexical and comprehension deficits in this group.

(2) Does efficiency of lexical processing predict reading speed better than or in addition to sentence comprehension performance? Because lexical processing efficiency is basic to reading, a relationship was expected. Furthermore, it was assumed that reading speed also reflects non-lexical processes that are important in sentence comprehension. Therefore it was not expected that lexical efficiency would subsume sentence comprehension performance. However, it also was considered possible that sentence comprehension would account for lexical effects.

(3) Does aphasia severity predict reading speed in PWA? If speed of activation is a fundamental cause of aphasic impairment, such a relationship would be predicted.

Methods

This study analyzed the data from 29 CP and 25 PWA. See Table 1 and 2 for demographic and selection data for both groups. CPs had no history of brain injury, normal language development (self-report), and/or performed at or above 13.86 on the overall score of the PICA (Duffy & Keith, 1980). PWA met McNeil and Pratt's (2001) definition and criteria for aphasia, evidenced on the *Porch Index of Communicative Ability* (*PICA*) (Porch, 2001) or *Western Aphasia Battery (WAB)*(Kertesz, 2001).

Stimuli consisted of 10 subtests with 10 items each from two versions of the reading version of the computerized Revised Token Test (CRTT-R-fade and CRTT-R-active/passive). Each stimulus was a sentences in which two short (e.g., "the red square") or two long (e.g."the little red square") noun phrases were embedded in sentences varying in verb phrase and prepositional structure (e.g., Put the red square above the blue circle"; "The little red square is touched by the big blue circle"; Table 3 presents examples of all sentence structures). Participants read each sentence in a computer-presented word-by-word, self-paced paradigm.

Log-transformed reading times for the first color adjective in compound sentences served as the dependent variable. These high-frequency adjectives were frequently repeated, therefore lexical and semantic load of these stimuli was low. Because these words were read at the beginning of the sentences, syntactic and memory load was also minimal. However, half of the color adjectives were preceded by a size adjective. For these, some syntactic and semantic integration processes were already evident (Fassbinder et al., 2011). Entering phrase length into the mixed model controlled this effect.

Overall sentence comprehension performance was indexed by the CRTT-R overall score for each subtest, which was the mean of the CRTT-R sentence scores. Efficiency of lexical processing was indexed with digit span forward (DF) length (Wechsler, 1981). Although DF usually is considered to be a test of verbal short-term memory or the phonological loop (e.g., Baddeley, 1990), it relies on basic lexical access and encoding processes. In PWA, performance on this task has been shown to be dependent on lexical processing efficiency (Martin & Ayala, 1994). Because reading the first color word in the sentence does not draw on contributions from STM, it is assumed to be a valid measure of lexical processing efficiency in this context. (3) Overall aphasia severity was indexed by the *PICA* overall or the WAB overall scores, converted to PICA scores.

Log-transformed mean reading times over subtests were modeled with a general linear model. All analyses were computed with R, using the lme4 (Bates, 2011) and the languageR (Baayen, 2012 packages. Mixed Models were calculated by incrementally adding the relevant variables and interaction terms for each research question, with Phrase Length, Group, CRTT-R overall score and DF as Fixed Effects, and Subjects as a Random Effect. All models had outliers for standardized residuals > 2.5 SD removed. Best model fit was determined using the likelihood ratio test.

Results

1. Color word reading times showed a main effect for Phrase Length and overall CRTT-R score, modulated by an interaction of Group and CRTT-R overall score (see Tables 4-8 for results). To

explore this interaction, a mixed model was calculated for each group separately. Results showed an attenuated effect of sentence comprehension ability on reading time for PWA.

2 Model fit was improved by adding DF, which did not interact with group.

3 While PICA score was included in the model, only DF contributed significantly to the result.

Discussion

As predicted, better sentence comprehension performance predicted faster reading times for the sentence-initial color word for both groups, suggesting that reading speed reflects processes that also underlie sentence comprehension. Unexpectedly, this effect was attenuated in PWA, which might have been caused by larger performance variability. However, other factors cannot be ruled out. The added predictive value of digit span suggests that reading times reflect some lexical processes that are not reflected in sentence comprehension. Thus, in both groups, comprehension can be successful regardless of variability in lexical access efficiency. Finally, the fact that PICA scores in PWA did not contribute to predictions of reading speed suggests more subtle processing inefficiencies that the PICA does not capture.

To summarize, based on these results, reading speed reflects lexical and more general processing efficiencies that are essential for successful sentence comprehension, as well as individual differences in lexical processing. Given the limitations of this study, these conclusions are clearly tentative. However, the power of the Mixed Model strengthens these results and this approach to analyzing reading times, and encourages more targeted investigations of slowed reading in PWA.

References

Caplan, D., Waters, G. S., DeDe, G., Michaud, J., & Reddy, A. (2007). A study of syntactic processing in aphasia I: Behavioral (psycholinguistic) aspects. *Brain and Language, 101*, 103-150.

Chenery, H. J., Ingram, J. C. L., & Murdoch, B. E. (1990). Automatic and volitional semantic processing in aphasia. Brain and Language, 38, 215-232.

Dickey, M.W. & Thompson, C.K. (2009). Automatic processing of wh- and NP-movement in agrammatic aphasia: Evidence from eyetracking." Journal of Neurolinguistics, 22, 563-583

Duffy, J.R. & Keith, R. (1980). Performance of non-brain injured adults on the PICA: Descriptive data and comparison to patients with aphasia. Aphasia, Apraxia, and Agnosia. 2, 1-30.

Fassbinder, W., McNeil, M.R., Dickey, M.W., Lim, K.Y., Pratt, S., Kim, A., Kendall, D., Pompon, R.H., & Szuminsky, N. (2011). Developing a standardized measure of short-term memory and syntactic complexity: results from subtests of the CRTT-R. Clinical Aphasiology Conference, Ft. Lauderdale, FL.

Haarmann, H. J., & Kolk, H. H. J. (1991). Syntactic priming in Broca's aphasics: Evidence for slow activation. Aphasiology, 5(3), 247–263.

McNeil, M.R., Kim, A., Lim, K., Pratt, S.R., Kendall, D., Pompon, R., Szuminsky, N., Fassbinder, W., Sung, J. E., Kim, H.S., Hamer, K., Dickey, M. "Automatic activation, interference and facilitation effects in persons with aphasia and normal adult controls on experimental CRTT-R-Stroop tasks. " Paper presented to the Clinical Aphasiology Conference. May, 2010.

McNeil, M. R. & Pratt, S. R. (2001). Defining aphasia: Some theoretical and clinical implications of operating from a formal definition. Aphasiology, 15, 901-911.

Porch, B. E. (2001). The Porch Index of Communicative Ability (3rd Edition). Palo Alto, CA: Consulting Psychologists Press.

Prather, P., Zurif, E., Love, T., and Brownell, H. (1997). Speed of lexical activation in non-fluent Broca's aphasia and fluent Wernicke's aphasia. *Brain and Language*, *59*, 391-411.

Rayner, K., Ashby, J., Pollatsek, A., & Reichle, E. D. (2004). The effects of frequency and predictability on eye fixations in reading: Implications for the E-Z Reader model. Journal of Experimental Psychology: Human Perception and Performance, 30, 720-732.

Reitan, R. (1958). Validity of the trail making test as an indicator of organic brain disease. Perceptual & Motor Skills, 8, 271-276.

Sung, J.E., McNeil, M. R., Pratt, S. R., Dickey, M. W., Fassbinder, W., Szuminsky, N. J., Kim, A., & Doyle, P. J. (2011). Real-time processing in reading sentence comprehension for normal adult individuals and persons with aphasia. *Aphasiology, 25*, pp 57-71.

Trueswell, J.C., Tanenhaus, M.K. & Kello, C. (1993). Verb-specific constraints in sentence processing: Separating effects of lexical preference from garden-paths. *Journal of Experimental Psychology: Learning, Memory & Cognition*, **19**, 528-553.

Wechsler, D. (1981). Wechsler adult intelligence scale-revised (WAIS-R).

Table1. Demographic and descriptive measures for the Control Participants

NC Group	Age (Years)	Education (Years)	Gender	PICA-%ile WAB –AQ**	Digit Span - Forward	Digit Span - Backward	TMT - A	TMT - B
1	50	16	M	35	10	6	16	43
2	58	13	F	45	11	10	19	36
3	69	12	M	50	11	12	21	51
4	41	12	M	25	10	9	12	40
5	55	14	F	25	7	7	19	49
6	80	14	M	10	11	12	52	100
7	55	16	M	30	8	6	37	97
8	56	16	F	30	9	6	33	87
9	83	16	M	15	10	8	33	69
10	85	18	F	25	8	8	33	81
11	76	12	M	10	6	4	47	108
12	77	18	M	60	11	8	34	85
13	80	12	M	35	8	7	61	81
14	78	12	F	15	8	6	19	54
15	54	16	M	35	7	6	24	59
16	25	14	M	----**	25**	**	21	48
17	42	16	M	----**	30**	**	19	84
18	60	16	F	----**	47**	**	25	66
19	63	16	F	----**	44**	**	19	46
20	69	18	M	----**	28**	**	19	56
21	73	16	F	----**	28**	**	32	80
22	69	16	F	----**	34**	**	33	67
23	54	7	M	----**	76**	**	28	90
24	57	18	F	----**	44**	**	24	70
25	60	18	F	----**	95**	**	34	55
26	61	16	F	----**	56**	**	27	59
27	50	18	F	----**	110**	**	17	30
28	62	18	M	----**	24**	**	18	47
29	64	15	F	----**	57**	**	38	59
Mean	62	15	F;14/ M;15	29.7	9/ 49.9**	7.7	28	65
SD	14	3		14.5	1.7/ 25.9**	2.3	11	21

PICA=Porch index of Communicative Ability (Porch, 2001); M=Male; F=Female; TMT=Trail Making Test (Reitan, 1958); Digit Span=maximum recalled items; *=WAB (Western Aphasia Battery Aphasia Quotient); **=WAIS-III digit span score -memory scale form 1.

Table 2. Demographic and descriptive measures for Participants With Aphasia

NC Group	Age (Years)	Education (Years)	Gender	PICA-%ile WAB – AQ**	Digit Span - Forward	Digit Span - Backward	TMT -A	TMT - B	NC Group
1	55	16	F	81	362	7	4	33	114
2	75	14	F	79	369	8	5	56	143
3	47	14	F	72	36	2	4	26	103
4	50	18	F	90	19	4	4	64	128
5	58	17	M	71	57	7	4	52	144
6	42	18	M	66	37	4	2	27	157
7	63	16	M	69	48	4	2	40	247
8	71	10	F	71	48	2	2	99	257
9	67	13	F	74	492	6	4	142	468
10	64	15	M	75	73	5	5	34	193
11	54	18	F	30	22	8	4	41	55
12	37	16	M	38	76	2	2	233	>300
13	59	18	M	62	20	1	1	191	>300
14	54	14	M	60	154	1	2	85	282
15	57	14	M	52	24	0	2	120	>300
16	52	15	M	88*	-	7**	**	31	81
17	66	21	M	86.8*	-	0**	**	76	176
18	71	25	M	32.7*	-	0**	**	61	122
19	59	17	M	79.3*	-	6**	**	62	132
20	66	17	M	80.8*	-	27**	**	37	123
21	60	16	M	19.16*	-	0**	**	31	65
22	72	18	M	77.4*	-	0**	**	40	124
23	47	12	M	92.8*	-	31**	**	52	61
24	51	16	M	92.4*	-	70**	**	35	76
25	68	20+	M	91*	-	40**	**	43	137
Mean	59	16	F:7/M:18	PICA: 66 *WAB: 74	122	4.1 18.1**	3.1	68	172
SD	10	3			154	2.7 23.6**	1.3	52	100

PICA=Porch index of Communicative Ability (Porch, 2001); MPO=Months Post Onset; M=Male; F=Female; TMT=Trail Making Test (Reitan, 1958); Digit Span=maximum recalled items; *=WAB (Western Aphasia Battery Aphasia Quotient); **=WAIS-III digit span score - memory scale form 1.

Table 3. Examples of each sentence structure

CRTT_R-Fade	
	Touch the red square and the green circle
	Touch the big red square and the little green circle
	Put the red square above the green circle
	Put the big red square above the little green circle
	Put the red square to the left of the green circle
	Put the big red square to the left of the green circle
CRTT_R active/passive	
	The red square has touched the green circle
	The bid red square has touched the little green circle
	The red square was touched by the green circle
	The big red square was touched by the little green circle

Table 4. Fixed-effects coefficients in a mixed-effects model fitted to the log-transformed reading times for color adjectives for control participants and PWA, with phrase length, participant group, and overall CRTT-R score as added fixed effects

	Estimate[1]	hpd lower[2]	hpd upper[2]	p[3]
Phrase Length	0.0678	0.0159	0.1095	0.0062
Group	-0.3648	-1.3897	0.6230	0.4466
CRTT-R-overall	-0.0893	-0.1672	-0.0431	0.0012
Group by Phrase Length	0.0752	0.0034	0.1474	0.0418

[1]estimated coefficient
[2] hpdlower/higher: 95% Highest Posterior Density (hpd) intervals based on 10,000 Markov chain Monte Carlo samples
[3] p: two-tailed mcmc probability.Mcmc estimates are based on 10,000 samples

Table 5. Fixed-effects coefficients in a mixed-effects model fitted to the log-transformed reading times for color adjectives for control participants, with phrase length and overall CRTT-R score as added fixed effects

	Estimate[1]	hpd lower[2]	hpd upper[2]	p[3]
Phrase Length	0.0723	0.0125	0.1240	0.0128
CRTT-R-overall	-0.0904	-0.1633	-0.0479	0.0002

[1]estimated coefficient
[2] hpdlower/higher: 95% Highest Posterior Density (hpd) intervals based on 10,000 Markov chain Monte Carlo samples
[3] p: two-tailed mcmc probability.Mcmc estimates are based on 10,000 samples

Table 6. Fixed-effects coefficients in a mixed-effects model fitted to the log-transformed reading times for color adjectives for PWA, with phrase length and overall CRTT-R score as added fixed effects

	Estimate[1]	hpd lower[2]	hpd upper[2]	p[3]
Phrase Length	0.0665	0.0012	0.1276	0.0498
CRTT-R-overall	-0.0611	-0.1257	-0.0417 0.	0002

[1]estimated coefficient
[2] hpdlower/higher: 95% Highest Posterior Density (hpd) intervals based on 10,000 Markov chain Monte Carlo samples
[3] p: two-tailed mcmc probability.Mcmc estimates are based on 10,000 samples

Table 7. Fixed-effects coefficients in a mixed-effects model fitted to the log-transformed reading times for color adjectives, with digit span forward added to the precious model (Table 4)

	Estimate[1]	hpd lower[2]	hpd upper[2]	p[3]
Phrase Length	0.0687	0.0208	0.1119	0.0036
Group	-0.7169	-1.7831	0.1613	0.1124
CRTT-R-overall	-0.0875	-0.1575	-0.0389	0.0018
Digit Span Forward	-0.0888	-0.1153	-0.0577	0.0001
Group by Phrase Length	0.0752	0.0034	0.1474	0.0418

[1]estimated coefficient
[2] hpdlower/higher: 95% Highest Posterior Density (hpd) intervals based on 10,000 Markov chain Monte Carlo samples
[3] p: two-tailed mcmc probability.Mcmc estimates are based on 10,000 samples

Table 8. Fixed-effects coefficients in a mixed-effects model fitted to the log-transformed reading times for color adjectives for control participants and PWA, with phrase length, PICA overall score and digit span forward as added fixed effects

	Estimate[1]	hpd lower[2]	hpd upper[2]	p[3]
Phrase Length	0.0641	-0.0068	0.1372	0.0848
PICA overall score	-0.0014	-0.1471	0.1350	0.9400
Digit Span Forward	-0.1806	-0.2693	-0.0853	0.0004

[1]estimated coefficient
[2] hpdlower/higher: 95% Highest Posterior Density (hpd) intervals based on 10,000 Markov chain Monte Carlo samples
[3] p: two-tailed mcmc probability.Mcmc estimates are based on 10,000 samples