Processing lexical ambiguity in sentential context: eye-tracking data from brain-damaged and non-brain-damaged individuals

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Abstract

The purpose of the present study was to identify general and syndrome-specific deficits in the lexical processing of individuals with non-fluent and fluent aphasia compared to individuals without cognitive, neurological or language impairments. The time course of lexical access, as well as lexical selection and integration was studied using a visual-world paradigm in three groups of Russian speakers: 36 individuals in the control group, 15 individuals with non-fluent aphasia and eight individuals with fluent aphasia. Participants listened to temporarily ambiguous sentences wherein the context biased the interpretation of an ambiguous word toward one of its two meanings. In half of the experimental sentences, a reanalysis was needed upon encountering the disambiguating phrase. The effect of the length of the intervening material between the ambiguous word and the disambiguation point was additionally monitored. All groups of participants showed intact lexical access under slowed speech rate, but non-fluent participants experienced difficulties with timely activation of multiple referents. At later stages of lexical processing, they additionally demonstrated a specific impairment of reanalysis. The deficit in participants with fluent aphasia was not focalized at any specific stage of lexical processing. Rather, the breakdown of lexical processes in fluent aphasia was likely related to difficulties with the inhibition of irrelevant lexical activation, which is further supported by the finding that increased phonological distance between the ambiguous word and ambiguity resolution was influential to the offline performance in this group.

1 Introduction

Language comprehension cannot be achieved outside of sentential context. Nonetheless, the first studies of lexical processing often involved isolated words – a necessary oversimplification that, for many decades, has served as a window to the intricate nature of lexical processing. A shift toward context-considerate language studies is now imperative to bridge the gap between these experimentally manipulated and naturally occurring language segments. Theoretical models typically divide word processing into three stages: lexical access, lexical selection and lexical integration (Friederici, Stenhauer & Frisch, 1999; Frauenfelder & Tyler, 1987; Marslen-Wilson, 1987, 1989). Critically, all three processes are constantly shaped by the surrounding context during language processing in a natural environment. At the lexical access stage, linguistic input activates a range of interrelated lexical units, with the amount of activation of a particular unit and its meanings being determined by the surrounding context and meaning frequency, among other factors. The meaning which was accessed first is then automatically selected (Duffy, Morris & Rayner, 1988; for alternative view, see Rayner & Frazier, 1989) and undergoes integration into context and a transformation into higher-order lexical-semantic and syntactic representations.

However, lexical processing is not necessarily restricted to the three stages described in many theoretical models. Sometimes integration of the selected meaning into its context fails, and the stages of lexical selection and integration are repeated to allow for the selection of a new meaning. That is, a reanalysis occurs. The present study has two primary aims: first, to investigate the time-course of lexical processing and reanalysis in non-brain-damaged speakers of Russian, as well at identifying factors that interfere with it (e.g., contextual bias, intervening phonological material). Additionally, driven by the idea that lexical processes are not uniform across all human populations, this paper focuses on the specific characteristics of lexical processing in individuals with language impairments related to stroke (i.e., non-fluent and fluent aphasia). In the following section, a brief summary of the data on lexical processing in populations without brain damage will be presented, followed by a review of studies on lexical processing in aphasia.

1.1 Lexical processing in populations without brain-damage

The mechanisms underlying lexical access in individuals without cognitive, neurological or language impairments have been a topic of extensive research. Several theoretical models appeared and later faded away with the emergence of new empirical evidence. Today, the available data (Sereno, 1995; Reichle, Pollatsek & Rayner, 2007; Weber & Crocker, 2012) seem to converge with the reordered access model introduced by Duffy et al. (1988). This model postulates that lexical access is exhaustive; that is, all word meanings are accessed during this stage of processing. However, access to meaning is not simultaneous, but rather ordered, i.e. determined by factors like context and meaning frequency. The importance of these factors to lexical access is now a well-accepted phenomena; the presence of a higher-frequency meaning or a stronger contextual bias towards one meaning induces faster lexical access (Sheridan & Reingold, 2012; Sereno, Brewer & O'Donnell, 2003). If factor values are balanced (i.e., meanings receive equal contextual support or meanings have similar frequencies of occurrence), lexical access may be delayed due to a pending conflict resolution (Dopkins, Morris & Rayner, 1992; Sheridan, Reingold & Daneman, 2009).

The next stage of lexical processing, lexical selection, has been less studied. In auditory word recognition, it has been monitored using cohort competitors, defined as words with overlapping initial phonemes. In such experiments, the conflict among activated cohort competitors is resolved with the help of the upcoming acoustic and top-down contextual information (Marslen-Wilson & Welsh, 1978). Interestingly, some evidence suggests that lexical selection and integration are in fact cascading processes (i.e., integration begins before the end of the selection process; Van den Brink, Brown & Hagoort, 2006; Van Petten et al., 1999; Van den Brink & Hagoort, 2004). The reason why lexical selection and integration may have generated less research interest separately could be that these stages are not easy to isolate and manipulate in experimental designs. In fact, in the reviewed studies, the terms "selection" and "integration" are frequently interchangeable. Nonetheless, these studies demonstrate that incoming phonetic and contextual information are critical factors in guiding lexical processing at later stages as well.

Finally, the reanalysis stage of lexical processing has been often investigated using ambiguous words. Reanalysis may be triggered in several ways, for example, it may take place when an ambiguous word has multiple meanings with different frequencies and the ambiguity is resolved towards the subordinate (less frequent) meaning. In this case, the more frequent meaning is selected first upon initially encountering the word but the attempt to integrate it into the context fails, thus necessitating reanalysis (Rayner & Duffy, 1986; Duffy et al., 1988; Rayner & Frazier, 1989; Sheridan et al., 2009). Alternatively, when the ambiguous word is balanced (i.e., has meanings with similar frequencies), the context comes into play. If the context initially biases the interpretation towards one meaning while the ambiguity is later resolved towards the other, reanalysis is also required (Rayner & Frazier, 1989). Reanalysis is typically associated with longer reading times, most likely, due to repeated access to different meanings (Rayner & Duffy, 1986; Duffy et al., 1988; Rayner & Frazier, 1989; Sheridan et al., 2009).

Interestingly, the possibility for reanalysis is always open. For example, Dahan and

Tanenhaus (2004) found that, in a visual-world study, participants shifted their gaze to the contextually incongruent referent immediately upon hearing the coarticulation that was consistent with it, but inconsistent with the contextually congruent referent. The lack of delay suggests that the human language processing system is constantly geared for reanalysis, because it remains highly sensitive to input even after the phonology and context have strongly converged on a given word candidate.

In sum, it appears that the three stages of lexical processing (i.e., access, selection and integration) cannot be definitively demarcated. Already during lexical access, selection starts based on the available information (e.g., frequency, context), possibly reflecting the fundamental psychological tendency to eliminate uncertainty. Lexical integration is linked with lexical selection. If a conflict arises, reanalysis is performed giving feedback to the new round of lexical processing. Nonetheless, it appears that clear-cut reference points for lexical processing include (1) initial lexical access, (2) late processing, i.e. lexical selection and integration, as well as ambiguity resolution, and (3) reanalysis. One can potentially dissociate the effects of factors such as frequency and contextual bias at different stages of lexical processing and across populations of individuals without cognitive, neurological or language impairments and in people with a language disorder such as aphasia. This framework is adopted in the present study.

1.2 Lexical processing in aphasia

Language impairments in aphasia often involve difficulties with lexical processing. The underlying deficit in lexical processing has been traditionally tied to the type of aphasia (Hagoort, 1993). For instance, deficits in non-fluent Broca’s and agrammatic aphasia, which is typically characterized by agrammatism and a lack of speech fluency, have been associated with impairments that are localized at specific stages of lexical processing. However, identification of these stages has been somewhat problematic; at times, lexical access has been reported to be impaired (Katz, 1988; Hagoort, 1993) whereas other studies have pointed to deficits with lexical selection and/or integration (Swaab, Brown & Hagoort, 1998; Grindrod & Baum, 2003). In fluent (Wernicke’s) aphasia, which is often described in terms of phoneme and word-level deficits but relatively spared syntax, deficits have been ascribed to all stages of lexical processing. More specifically, studies of fluent aphasia have reported atypical behaviour at all stages, including a faster-than-normal access to meanings and an inability to promptly suppress the activation of irrelevant referents (Prather, Zurif, Love & Brownell, 1997; Prather, Zurif & Love, 1992). One goal of the present study was to compare eye-movement behaviour in non-fluent and fluent aphasia during lexical processing in all of its stages (lexical access, late processing, ambiguity resolution and reanalysis) and to identify their syndrome-specific deficits.

1.2.1 Non-fluent (Broca’s and agrammatic) aphasia

Individuals with non-fluent aphasia have been reported to have an impairment in lexical processing, but the locus of this deficit with respect to the stages of lexical processing is still under debate. Two alternative accounts have been proposed: a slowdown in initial lexical processing (i.e., lexical access), or impaired late processing (i.e., lexical selection and/or integration). The first hypothesis received support from a series of priming studies. For example, Katz (1988) reported five participants with Broca's aphasia showing normal priming patterns, although their reaction times were significantly longer than in the control group. This delay in lexical access has been replicated in studies with Broca’s and agrammatic aphasic participants. Delays typically ranged from 400 ms (Thompson & Choy, 2009; Ferrill, Love, Walenski & Shapiro, 2012) to 1500 ms (Prather, Zurif, Stern & Rossen, 1992; Prather et al., 1997). Nonetheless, Hagoort (1993), in an auditory priming study, observed normal priming at 100- and 500-ms interstimulus intervals in Broca’s aphasia, but not at 1250-ms intervals, indicating that lexical access is spared and prompt (but see Hagoort [1997] where priming occurred at both 300 ms and 1400 ms, which is longer than the priming interval in control groups). Such inconsistency in results has recently received a tentative explanation: Love, Swinney, Walenski and Zurif (2008) reported that lexical access in individuals with non-fluent aphasia is delayed under normal (meaning, relatively fast) speech rates of auditorily presented stimuli, while under slower speech rates, it proceeds in a timely fashion. A direct precursor to the current study, the behavioral study by Friedmann and Gvion (2003) revealed that three agrammatic participants demonstrated chance performance when processing sentences that involved reanalysis. In these sentences, ambiguous words appeared in a context that biased interpretation toward the more frequent meaning but then ambiguity was resolved towards the less frequent meaning. In addition, phonological distance between the first presentation of an ambiguous word and the point of disambiguation was manipulated (being 2–3 words or 7–9 words). Friedmann and Gvion (2003) showed that the phonological manipulation did not influence performance of agrammatic participants. The authors attributed chance performance of individuals with agrammatic (non-fluent) aphasia to delayed access to the less frequent meaning, however, the results could also be consistent with other interpretations. For example, the effect might be explained by impaired selection or integration, or even impaired reanalysis, but the use of offline methods in the study could not allow for identification of the dysfunctional stage.

Experimental evidence for the second hypothesis (i.e., that attributes deficits to lexical selection or integration) has been more uniform. For instance, EEG-based experiments have shown that participants with Broca's aphasia activated both meanings of an ambiguous word in a restrictive context, but in contrast to control participants, failed to select the one that was congruous to the context within 100 ms after the offset of the word (Swaab et al., 1998). However, the process of lexical selection was completed 1250 ms after the offset. This suggests that participants with Broca's aphasia experience a delay in lexical selection (and, importantly, no delay in access), which may hinder subsequent integration. Similarly, in a biasing but non-restrictive context, individuals with non-fluent aphasia who performed a cross-modal semantic priming task have been shown to experience difficulties with lexical selection (Grindrod & Baum, 2003). In that study, non-fluent participants accessed both meanings of the ambiguous word at short interstimulus intervals, but control participants accessed only contextually appropriate meanings. The contextually appropriate meaning was successfully selected by individuals with aphasia only at longer interstimulus intervals. According to the authors, this indicates that participants with non-fluent aphasia experience difficulties with lexical integration, rather than a delay in lexical access. Similarly, in an eye-tracking study with agrammatic participants by Mack, Ji and Thompson (2013), it was found that prediction of upcoming arguments (which is involved in lexical integration) is impaired in agrammatic aphasia. Yet another line of evidence supporting the second hypothesis emerges from neuroimaging research. For instance, brain regions that are typically damaged in Broca's aphasia, including the left inferior frontal gyrus, have been shown to be responsible for selection between competing alternatives and integration of contextually appropriate meanings (Ihara, Hayakawa, Wei, Munetsuna & Fujimaki, 2007; Thompson-Schill, D'Esposito, Aguirre & Farah, 1997).

1.2.2 Fluent (Wernicke's and conduction) aphasia

Priming studies involving participants with Wernicke's aphasia have delineated the mechanics of lexical processing in this clinical population. Despite the limited number of such studies, a somewhat similar pattern comes into view: at first, lexical access resembles that of the control group but is followed by a breakdown in lexical processing at later stages. For instance, priming effects have been reported in participants with Wernicke's aphasia not only at 100 ms and 500 ms, which lies within normal range, but also at 1250-ms intervals (Prather et al., 1997; Prather et al., 1992) which hints at an inability to suppress activation. Additionally, individuals with Wernicke's aphasia were found to activate all cohort candidates (i.e., words that have overlapping onsets, like *hammock* and *hammer*) to a greater extent than individuals without brain damage, suggesting that their difficulties primarily concerned the timely inhibition of activated candidates (Janse, 2006; Yee, Blumstein & Sedivy, 2008; Mirman, Yee, Blumstein & Magnuson, 2011). In a similar vein, a study by Milberg, Blumstein and Dworetzky (1988) reported abnormally high levels of lexical activation in fluent aphasia. Their results showed that, in the control group, priming strength decreased for phonologically distorted primes, whereas the participants with fluent aphasia responded to all primes independent of the extent of their distortion. These studies demonstrate that in fluent aphasia, timely inhibition of irrelevant information might be impaired and thus processing at different levels, including phonological (Yee et al., 2008) and lexical (Prather et al., 1997), may be hindered.

Finally, in fluent conduction aphasia, which is characterized by impaired repetition and word-finding difficulties, Friedmann and Gvion (2003) reported specific damage to reanalysis when the phonological distance between word introduction and reanalysis was long (7–9 words), but not when it was short (2–3 words). The authors conclude that individuals with conduction aphasia fail to re-access the phonological form of a word in the long distance condition due to reduced phonological working memory span, but apart from that, their lexical processing has no pronounced impairments (see also Gvion & Friedmann, 2012).

Taken together, these findings suggest that the underlying disorder in fluent aphasia concerns later stages of lexical processing (i.e., impaired deactivation of contextually inappropriate meanings that could potentially hinder lexical selection and/or integration in Wernicke's aphasia, and inability to re-access the phonology of the word in conduction aphasia). Note, however, that according to Janse (2006), hampered inhibition of competing referents does not necessarily result in impaired lexical processing of the target one. Critically, no studies that we are aware of have investigated lexical processes in sentential context by participants with Wernicke's aphasia. Thus, what exactly happens in later processing stages remains an open question.

Alternatively, Mirman et al. (2011) proposed an intriguing account for deficits in Broca's and Wernicke's aphasia. They suggested that frontal and posterior regions form a dynamic balance, and damage to each of the regions leads to a behavioural pattern reflecting the functions of the intact region. Critically, frontal regions are typically associated with selection (Thompson-Schill et al., 1997; Ihara et al., 2007; Bedny, McGill & Thompson-Schill, 2008) and posterior regions are responsible for meaning activation (Bedny et al., 2008). Thus, damage to the left inferior frontal gyrus (often seen in Broca's aphasia) leads to impairment of response selection, and response probability becomes dependent solely on the activation. On the contrary, damage to the posterior lateral-temporal cortices (often seen in Wernicke's aphasia) leads to a threshold-like behavioural pattern with strong response to moderately activated entities and minimal response to weakly activated entities.

To reiterate, impairments in non-fluent aphasia seem to emerge during lexical selection and/or integration, since the evidence that concerns the delay in lexical access has been rather inconsistent. Whether or not the deficits in Wernicke’s aphasia can be confined to any specific stage of lexical processing, is an open empirical question that needs to be tested. The lack of studies of lexical processing in sentential context in Wernicke’s aphasia precludes us from making any strong predictions here. Based on both the impaired inhibition (Janse, 2006; Prather et al., 1997) and the impaired selection among competing alternatives (Mirman et al., 2011) hypotheses, we can predict that in Wernicke’s aphasia, the meanings of ambiguous words should receive stronger activation, with no or little differences between meanings. Because of severe impairments to selection processes, offline accuracy in this population should be low.

We also believe that the underlying deficits in non-fluent and fluent aphasia are qualitatively different (Yee et al., 2008) and would diverge in late processing. While in non-fluent aphasia the core deficit seems to concern lexical selection and/or integration, the deficits in fluent aphasia appear to stem from an imbalance in the activation of the target and inhibition of competing referents. We test this hypothesis in this study.

1.3 The present study

Research on lexical processing is tightly linked to the concept of lexical ambiguity since ambiguous words with two or more meanings represent an optimal tool unraveling different stages of lexical processing. The present study focuses on lexical processing of ambiguous words in a sentential context for individuals with and without brain-damage. Since one motivation of our study was to track changes in activation of word meanings during and after lexical access, we chose to employ contexts that, at some point, would require reanalysis. Since the effect of meaning-frequency on lexical access has previously been researched extensively (Sheridan & Reingold, 2012; Weber & Crocker, 2012; Sereno et al., 2003; Duffy et al., 1988), we opted for balanced ambiguous words (i.e., with meanings of equal frequencies). To induce reanalysis, we used manipulations with context whereby the context initially favored one meaning, while ambiguity was later resolved towards the other interpretation.

Of particular interest were anticipated deficits in late-stage processing in both fluent and non-fluent aphasia. We hypothesized that their deficits stem from different sources and although both would emerge at later stages of lexical processing, it might be possible to dissociate between them using an appropriate experimental design. The critical moment where performance of the groups was expected to diverge would be integration and reanalysis, when the context resolves previously induced ambiguity. If non-fluent participants have difficulties in selecting the appropriate meaning and integrating it into context, we would be able to find signs of such a deficit at the ambiguity resolution stage and, in particular, when reanalysis is required. Compared to control participants, individuals with non-fluent aphasia would not be able to integrate either of the preferred meanings, or the temporal dynamics of the integration would be impaired. On the other hand, we hypothesized that the fluent group would experience no problems with the selection and integration of the chosen meaning into the context, but would suffer from constant interference from multiple activated referents. Therefore, they were expected to show an imbalance in the activation of target and competitor and to give more erroneous responses overall.

An additional manipulation concerned the distance between the points of the first presentation of the ambiguous word and ambiguity resolution through the incorporation of semantically neutral linguistic material (a design adopted from Friedmann & Gvion, 2003) to further distinguish the performance of aphasic groups. We expected that long phonological distance would be especially disadvantageous to participants with fluent aphasia since they are characterized by an acoustic discrimination deficit (Ardila, 2010), as well as pervasive problems with inhibition (Yee, et al., 2008). Inhibition problems could lead to greater competition between activated lexical entities, delays in selection and a higher number of errors in this condition. At the same time we do not expect long phonological distance condition to influence lexical processing in the non-fluent aphasia group or control participants.

To summarize, the current study aimed to systematically investigate online mechanisms of lexical processing (access, selection and integration; reanalysis) in native speakers of Russian with and without aphasia using the benefits of the visual world paradigm, which allows for tracking the changes in the activation of word meanings. The use of balanced ambiguous words and temporarily ambiguous contexts serve as the optimal material for tracking online lexical processing.

In the control group, we expected that initial lexical access as well as selection and integration would be modulated by contextual bias. In individuals with non-fluent aphasia, we expected reduced sensitivity to contextual bias due to reported deficits with lexical selection and integration in this clinical population. We hypothesized a deficiency during reanalysis for the same reason. In the fluent group, a disruption at the selection and integration stages was also expected. More specifically, we anticipated that the overall activation of the meanings of the ambiguous word would be lower than in the control group due to the impaired inhibition of other referents from the story. More errors in the interpretation of stories were expected in individuals with fluent aphasia compared to the control or the non-fluent groups. Finally, the negative effect of increasing phonological distance between the ambiguity introduction and the disambiguation point was expected in fluent participants only, as caused by their specific difficulties with inhibition.

2 Method

2.1 Participants

Three experimental groups were tested: 36 control individuals (23 female; mean age 50 years, with no recorded history of neurological or psychiatric disorders) and 23 individuals with chronic aphasia due to a left hemisphere stroke, among which 15 participants had non-fluent aphasia (5 female; mean age 52 years) and 8 participants had fluent aphasia (4 female; mean age 56 years)[1].

The mean age in the group of participants with aphasia (PWA) did not significantly differ from that of the group of control participants ($t(67) = 1.74$, $p > .10$). Aphasic participants were recruited from the Center for Speech Pathology and Neurorehabilitation in Moscow, Russia. All participants were native speakers of Russian, right handed (premorbidly, in case of PWA), and had normal or corrected-to-normal hearing and vision.

For the two groups of aphasic individuals, the original aphasia type was diagnosed by a certified clinical psychologist, using Luria's Neuropsychological Investigation (Luria, 1966). The non-fluent group included individuals with a primary diagnosis of efferent motor aphasia (in some cases accompanied by afferent motor and/or dynamic aphasia), which is a rough equivalent of Broca's aphasia in terms of the Boston Aphasia Classification (Goodglass & Kaplan, 1983; see Ardila [2010] for a comparison of the two classifications), and is primarily distinguished by non-fluent output caused by the disruption in sequencing of speech movements, as well as agrammatism. The fluent group was limited to individuals diagnosed primarily with sensory aphasia (in several cases accompanied by acoustic-amnestic aphasia), generally corresponding to Wernicke's aphasia and characterized by fluent speech but deficient phoneme selection and discrimination. Aphasic participants selected for the current study were matched on the severity of their speech comprehension impairment, which was evaluated using the comprehension subtests (auditory text comprehension, word-picture and sentence-picture matching, and understanding of verbal instructions) of the Quantitative Assessment of Speech battery developed by Tsvetkova, Akhutina and Pylaeva (1981) and traditionally used in Russia for quantitative speech evaluation. The mean score of PWA on the test was 127 out of 150. These scores did not differ significantly between

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[1] For compatibility with previous clinical studies, in this paper we refer to the participants with aphasia as fluent and non-fluent, although they were originally classified into aphasia types according to Luria's classification (Luria, 1966).

groups, according to the Wilcoxon rank sum test ($W = 83$, $p > .10$). Individual demographic, neuroradiological (when available) and linguistic data of the PWA are presented in Table 1 in the Appendix.

2.2 Materials

Experimental materials of the study consisted of 20 short audio stories (linguistic stimuli), and 20 visual panels (visual stimuli) depicting four referents from the story. In addition, 20 similar filler stories, irrelevant to experimental manipulations, and 20 similarly organized visual panels for them were used. The general presentation design (an audio story and a visual panel with four referents) was adopted from Sussman and Sedivy (2003).

Linguistic stimuli. Each of the 20 experimental stories consisted of three short sentences followed by a comprehension question, e.g.:

(1) It took the technician an hour to get ready for the repair works.
Eventually he found a screw.
(a) Togda on pochinil *kran* s tekuschej vodoj.
Then he fixed *crane/tap* with leaking water
'Then he fixed the crane/tap with leaking water.'
(b) Togda on pochinil *kran* s uzhe nadoevshej sosedyam, postojanno i gromko tekuschej vodoj.
Then he fixed *crane/tap* with annoying the-neighbors, permanently and loudly leaking water
'Then he fixed the crane/tap that was leaking permanently and loudly, and annoyed the neighbors.'
Gde *kran* otremontirovannyj tehnikom?
Where *crane/tap* fixed by-technician?
'Where is the crane/tap the technician fixed?'

In the first sentence, the protagonist of the story (in the example above, *technician*) was introduced. The second sentence introduced the foil (*screw*). The third, critical sentence contained an ambiguous word with two meanings[2] (*kran* in Russian means both 'tap' and 'crane') and a further phrase (*leaking water*), which resolved the ambiguity toward the target meaning ('tap') making the competitor meaning ('crane') irrelevant for the current context. The question probed understanding of the resolved ambiguity and asked about the target meaning of the ambiguous word (*kran* as 'tap').

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[2] If an ambiguous word had three or more meanings, the first two mentioned in the dictionary (Kuznetsov, 2009) were used.

Within each story, the protagonist's name, the foil and the ambiguous word were matched on length and frequency and their initial phonemes did not overlap. Half of the ambiguous words were classified in the dictionary as homonymous, thus having separate lexical entries, and half as polysemous, thus representing a single lexical entry with multiple meanings (Kuznetsov, 2009). Given the subtlety of such division and mixed evidence on the role of meaning relatedness in lexical processing (see, e.g., Hino, Kusunose & Lupker, 2010), in the present study the two groups of ambiguous words were examined together. Ambiguous words that were used in the current study were selected from a pretest that evaluated the relative frequency of the two meanings of 73 ambiguous words. Fifty volunteers received a list of short sentences that contained a lexically ambiguous word in a disambiguated context. They were instructed to estimate how often they use/hear/read each word in the given meaning. Twenty balanced ambiguous words were selected, such that the difference in the reported frequencies of their two meanings was within one standard deviation.

Two experimental manipulations were used in the study. First, we manipulated the contextual bias toward the target versus the competing meaning of the ambiguous word. Although neither of the two potential meanings could be completely ruled out prior to the ambiguity resolution, half of the experimental items (n = 10) contained ambiguous words biased by prior context toward the target meaning, and half towards the competitor meaning. Biasing was preliminarily tested in a sentence completion questionnaire filled out by 48 Russian speakers who did not take part in the main experiment. The experimental stories were visually presented up to the critical word (in this case, *kran*) with the ambiguity remaining unresolved. The task was to complete the story with a short phrase which first came to the participant's mind. The obtained responses were classified as either target- or competitor-related by two professional linguists, who are native Russian speakers. The results confirmed that, in half of the stories, interpretation of the ambiguous word was biased towards the target meaning, whereas the other half favored the competitor meaning. Therefore, sentences that had ambiguity which was initially biased to the competitor meaning but then resolved towards the target meaning, would require reanalysis. It should be noted that contexts did not contain words that could prime the biased meaning of an ambiguous word. In both conditions, preference for the biased meaning reached statistical significance as confirmed by the Mann-Whitney U test for target bias in items 1–10 ($V = 53$, $p < .05$) as well as for competitor bias in items 11–20 ($V = 45$, $p < .05$). There was no significant difference in bias strength between target and competitor bias conditions, as calculated using subjective ratings for bias direction (Wilcoxon signed rank test, $V = 35$, $p > .01$).

The second experimental manipulation concerned the length of the phonological material intervening between the ambiguous word and the ambiguity resolution phrase (i.e., phonological distance). In the short-distance condition, ambiguity was immediately resolved (see[1a]); in the long-distance condition ambiguity was resolved after an extended modifier containing four to six words (see[1b]). The long and short conditions did not differ in terms of bias strength (based on subjective ratings for bias direction; Mann-Whitney U test, $W = 174$, $p > .05$).

To avoid a repetition effect, experimental stories were assigned to two lists. Each list contained 10 experimental stories with a target bias and 10 stories with a competitor bias, but only one version of them – either in the short-distance or in the long-distance condition – with an equal number of stories per condition. Each list also included 20 filler stories containing no ambiguity, 10 per condition, with conditions equally distributed across lists, e.g.:

(2) ‘Before the competition, an athlete was swimming in the pool.
Suddenly he felt an arm ache.
His coach became worried.
Who was worried?/Who was swimming in the pool?’

The order of experimental and filler stories (40 in total) was pseudo-randomized so that the conditions were evenly spread across the list to avoid effects of learning or attention loss. The stories were recorded by a male native Russian speaker with a mean speech rate of three syllables per second (mean speech rate in spoken Russian is five syllables per second, see Stepanova, 2013). We chose the slowed speech rate for stimuli presentation to find out whether in non-fluent aphasia there are deficits in lexical processing independent of delayed lexical access found in several studies (Ferrill et al., 2012; Thompson & Choy, 2009; Prather et al., 1997; Prather et al., 1992).

Visual stimuli. For each story, a visual panel was designed. Figure 1 depicts the visual panel accompanying the experimental story about the tap. A panel included four black-and-white images: a picture of the protagonist (‘technician’), a picture of the foil (‘screw’), and two referents corresponding to the target meaning (*kran* as ‘tap’) and the competitor meaning of the ambiguous word (*kran* as ‘crane’). All pictures were drawn by the same artist and were consistent in size (8.5 x 8.5 cm; 1000 x 1000 pixels) and style. Each picture was positioned in one the four corners of the panel, and the four types of referents appeared in any of the corners with equal probability across the experiment. The background of the panel was gray, and each picture occupied 32.5% of the panel’s area in width and height.

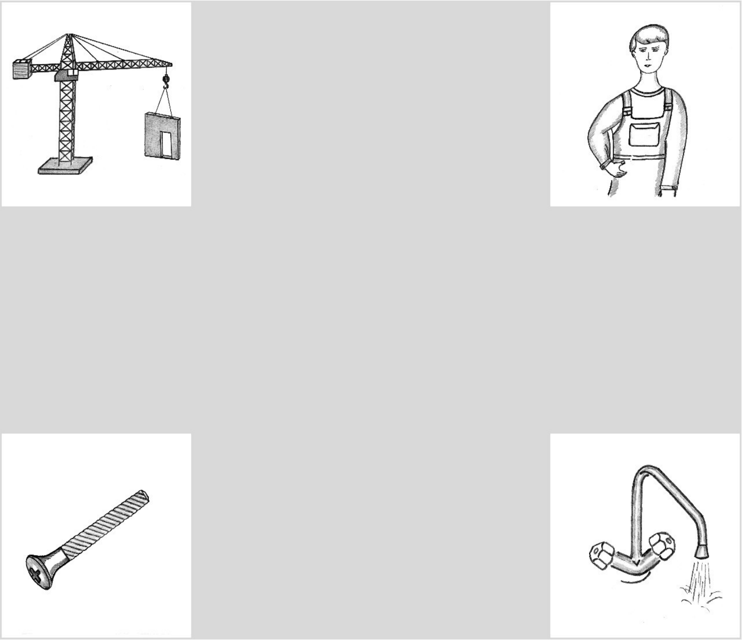

Figure 1. An example of the visual panel for an experimental story.

2.3 Procedure

Participants were tested individually and were seated in a comfortable position at an appropriate viewing distance (60 cm) from the computer screen. Their eye movements were recorded using an LC Technologies Eyegaze (Fairfax, VA, USA) remote pupil centre/corneal reflection system with a sampling rate of 60 Hz (16.7 milliseconds). An automatic calibration procedure was completed prior to stimuli presentation. A chin rest was used to restrict participants' head movements during the calibration and experimental testing. Stimuli were presented with custom developed software.

Five practice trials preceded the experiment and were repeated when PWA performed poorly on these trials. Each trial started with a fixation cross in the center of a gray screen for 300 milliseconds (ms). The audio story and the corresponding visual panel were then presented simultaneously. Audio was recorded in wav format (16 bit, mono, 44.1 kHz), and played over loudspeakers. The visual panel remained on the screen during the entire sentence presentation and for another 5000 ms after the sentence ended. Participants were instructed to listen to the story and to answer the comprehension question by fixating the picture that corresponded to the referent of their choice until the screen with a cross appeared (5000 ms after the end of the question). The choice of the response procedure was based on specific needs of PWA, who often experience right-sided hemiparesis or fine motor skill damage. This limitation restricts the use of buttons and manipulators while eye movements are intact and less prone to fatigue for the PWA. Eye-movements have been shown to be robust for detecting PWA’s behavioral choice (Ivanova & Hallowell, 2012). While this response procedure could lead to increased attention to the meanings of ambiguous words in our study, it can not independently influence the difference in activation of the meanings.

The experimenter monitored participants’ eye-tracking performance on a second screen and regulated the presentation of the trials, making a recalibration or offering a short break when required. The whole experiment took approximately 30–35 minutes (including 10–15 minutes for calibrating the eye-tracker and training the participant to perform the task).

2.4 Analysis

In order to track activation of the relevant referents (corresponding to the target and the competitor meanings of an ambiguous word) over time, two critical temporal regions were defined in the last sentence of the experimental stories, time-locked to the presentation onset of an ambiguous word in the ambiguous context, and to that of the ambiguity resolution phrase (see Table 2). Both critical regions included a pause between the actual linguistic materials they comprised and the next region. In addition, a third response region of 5000 ms duration was time-locked to the end of the last word of the story. The onset of each region was measured by two independent raters who were trained linguists and native speakers of Russian. These measurements were performed for each sentence individually on the basis of the oscillo- and spectrograms of the audio files in Sound Forge software (Sound Forge, 2010). Boundaries of the regions were shifted 200 ms downstream to account for planning and execution of saccadic movements (Matin, Shao & Boff, 1993).

Table 2

Regions of analysis in the experimental stories.

	Region 1		Region 2		Response region
Togda on pochinil	*kran*	*s / s uzhe nadoevshej sosedyam, postojanno i gromko*	*tekuschej vodoj.*	*Gde kran otremontirovannyj tehnikom?*	5000 ms pause
Then he fixed	crane/tap	with / with annoying neighbors, permanently and loudly	leaking water.	Where crane/tap fixed by-technician?	

Behavioral responses to comprehension probes were considered correct if the number of frames with looks to the target was greater than the number of frames with looks to any other picture in the visual panel within the specified response region. Further statistical analyses were performed on correct trials only, since the number of incorrect trials was insufficient to yield significant results.

The independent variable that is often measured in eye-tracking language studies is the proportion of fixation durations to different referents in the visual panel (Dickey & Thompson, 2009; Hanne, Sekerina, Vasishth, Burchert & De Bleser, 2011). However, the raw proportions of fixation durations that were extracted from our data were not normally distributed ($D = .5$, $p < .001$ for all groups of participants, as assessed with the Kolmogorov-Smirnov test of normality) which hindered further t-test analyses. Since our data followed a bimodal distribution, we opted for the empirical logit regression analysis that has recently gained popularity as a tool for analysing eye-tracking data (Barr, 2008; Sekerina & Trueswell, 2011; Mack et al., 2013). The main advantage of this technique is that time is treated as a continuous variable. In addition, random effect terms can be introduced into the model to account for variation across experimental items and participants. The latter is especially useful during investigations of data from individuals with aphasia because of their greater inter-subject variability. Below we report the transformations of data that preceded regression analysis, as well as the details of the empirical logit regression itself.

Regarding data preprocessing, only frames constituting a fixation were extracted for the analysis. A fixation was defined as a prolonged look to the same point (with six pixels horizontal and four pixels vertical tolerance) on the screen (at least 100 ms, or six consecutive frames), as in, for example, Dickey and Thompson (2009). Following Barr (2008), eye data frames were then arranged into 50 ms time bins aggregated by subjects and experimental conditions. Then the proportion of eye data frames corresponding to fixations on the target and the proportion of eye data frames corresponding to fixations on the competitor (relatively to all data frames included in analysis) were transformed using empirical logit function (Barr, 2008). In addition, the difference between the transformed scores on the target and the competitor was computed (Sekerina & Trueswell, 2011).

Consequently, three empirical logit regression models were computed with the three dependent variables: transformed target scores, transformed competitor scores, and difference between transformed target and competitor scores. This was driven by the goal of providing information not only on the advantage of the target over the competitor, but also on the dynamics of fixations on the target and the competitor per se. The models were computed using the lmer() function from the ‘lme4’ statistical package (Bates, Bolker, Maechler & Walker, 2013). Independent variables, which entered the models as fixed effects, included Time (in seconds) that elapsed from the onset of the region (treated as a continuous variable), Group (control/non-fluent/fluent), Bias (target/competitor) and Phonological distance (short/long). Beside the main effects, the models included two-way interactions (Group x Time, Group x Bias, Group x Phonological Distance) and three-way interactions (Group x Time x Phonological Distance, Group x Bias x Time, Group x Bias x Phonological Distance), which was driven by the expectation that time, bias and phonological distance could affect the three groups of participants in different ways. The models included random intercepts and slopes for all fixed effects by participants and by experimental items to account for variability across participants and conditions (Barr, Levy, Scheepers & Tily, 2013). The categorical variables were contrast-coded (sum coding scheme), so that their influences could be interpretable as main effects (for details on main effects and coding, see Barr, 2013). The reference levels were: control group in the Group variable, target bias in the Bias variable and short condition in the Phonological Distance variable. Following suggestions by Mack et al. (2013), the Time variable was centered. This ensured that the main effects of the other variables represent the effects that are observed halfway through the time window, and not anticipatory effects at the beginning of the region. The three separate models were implemented in each of the two defined regions of the experimental stories. Statistical analysis was carried out in R (R Development Core Team, 2013).

The dependent measures map onto our hypothesized deficits in the following way. First, the proportion of fixations to the target in the response region is a proxy of accuracy. Based on this measure, participant responses were marked as correct or incorrect, and their overall processing abilities were evaluated. Increase in fixations to a given referent over time corresponds to the increase in activation. The exact interpretation of activation patterns is tied to the region of interest. To illustrate, during the first presentation of the ambiguous word, failure to timely increase the activation (to the level of the control group) would point to difficulties with lexical access. During ambiguity resolution, however, this measure should be interpreted as a reanalysis impairment. Increased activation of non-target referents would point to difficulties with inhibition.

3 Results

Accuracy of comprehension probes registered in the Response region in three groups of participants are presented first, followed by empirical logit regression analysis performed separately on each of the other two critical regions of interest.

3.1 Accuracy

To ensure that the results in each group were not due to chance, we performed a binomial test comparing the number of frames where the target was fixated to the number of frames where the competitor was fixated in the response region. All three groups of participants performed above chance on the comprehension probes: $p < .001$ in the control and the non-fluent groups, and $p < .05$ in the fluent group. Chance performance was set at 50%, since there were two potential referents that could be chosen when probed by the ambiguous word in the comprehension question, e.g., ‘Where is the *crane/tap* the technician fixed?’. However, a difference was found in the proportion of correct responses between groups. Control participants responded correctly 96% of the time but as the Mann-Whitney test demonstrated, the non-fluent group performed significantly poorer than the control group (79% correct, $W = 129524$, $p < .001$), and the fluent group was characterized by the poorest performance (60% correct, which is significantly lower than both the control group [$W = 73166$, $p < .001$] and the non-fluent group [$W = 28892$, $p < .001$]).

We also compared the performance of each group in the short and long phonological distance conditions. The control group had a correct response rate of 96% in the short condition, and 97% in the long condition, with no difference between conditions ($G = .18$, $p > .10$). The non-fluent participants had a correct response rate of 81% in the short condition and 77% in the long condition, but the accuracy rates in the two conditions were not significantly different ($G = .73$, $p > .10$), while being above chance ($p < .001$ in both conditions, binomial test). Finally, the fluent participants correctly responded 67% of the time in the short condition and 54% of the time in the long condition. While the accuracy rates in the two conditions were not significantly different ($G = 2.7$, $p = .10$), the performance in the long-distance condition did not differ from chance ($p > .10$), while in the short-distance condition, it was above chance ($p < .01$).

3.2 Logit regression analyses

3.2.1 Ambiguous word introduction

The number of frames with looks to the target and to the competitor referents, as well as advantage of the target over the competitor at the first presentation of the ambiguous word in the ambiguous context, were computed for in Region 1. Figure 2 illustrates the proportion of time bins where gaze was located on the target or on the competitor images across groups and conditions. Note that the choice of 1-1200 ms time window in Figure 2 was motivated by convenience and coherence of presentation. Since too few items had regions that lasted longer than 1200 ms, the means of later time bins could be taken for a meaningful change in eye-movement behaviour, while in reality these were based on three to four measurements only.

Parameters and estimates of the model are summarized in Table 3 in the Appendix.

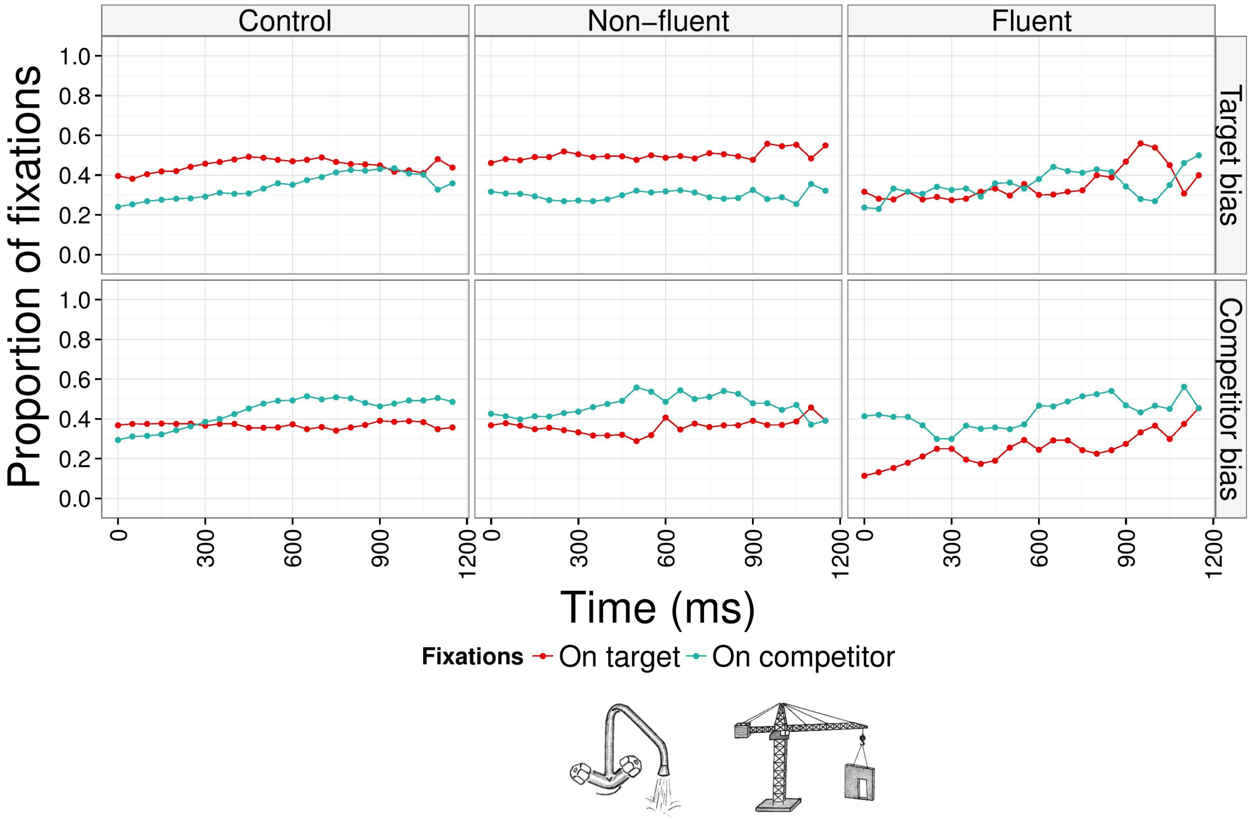

Figure 2. Proportions of frames with fixations on the target vs. competitor images in Region 1 across groups and bias conditions in 50 ms bins.

A main effect of Group was observed in the analysis of fixations on the target: overall, individuals with fluent aphasia fixated the target image less than control participants did, while individuals with non-fluent aphasia did not differ from either of the other two groups, showing a transitional pattern. As for the temporal dynamics of fixating the target and the competitor in Region 1, a main effect of Time was revealed, with fixations on both the target and the competitor images increasing over time in Region 1. In addition, the analysis of fixations on the competitor revealed that the factor of Time interacted with Group: individuals with non-fluent aphasia showed a slower increase of competitor fixations over time as compared to the control and the fluent groups. This means that in all groups, activation of both meanings of an ambiguous word increased upon its presentation in the ambiguous context, although the target meaning activation was overall reduced in the fluent group, and the activation of the competitor meaning, which was equally relevant in the ambiguous context, did not gradually increase in the non-fluent group to the extent exhibited by the other two groups.

Importantly, the main effect of Bias was found to be significant, with a higher probability of fixating the target than the competitor in the target bias condition and a higher probability of fixating the competitor than the target in the competitor bias condition. The target advantage analysis directly contrasting the number of fixations on the target and on the competitor also revealed a main effect of Bias, the positive coefficient indicating an increase in target advantage in the target bias condition in comparison to the competitor bias condition. This shows that during an ambiguous word presentation individuals with fluent and non-fluent aphasia, as well as control participants, demonstrated equal sensitivity to the contextual bias by fixating the target more when the context is biased to the target meaning of an ambiguous word and fixating the competitor more when the context is biased to the competitor meaning. No other significant main or interaction effects were found.

3.2.2 Ambiguity resolution

Similarly, fixations on the target and on the competitor images and the target advantage over the competitor during the stage of ambiguity resolution were examined for in Region 2, containing the phrase which resolved the previously introduced ambiguity toward the target meaning (see Figure 3 for the illustration of the revealed effects and Table 4 in the Appendix for statistical results). In this case, the choice of the time window was motivated by the coherence of presentation, as in the ambiguous word introduction region.

A main effect of Group was found both in the analysis of fixations on the target and in the target advantage analysis: individuals with fluent aphasia fixated the target less than control participants, and their target advantage scores were also lower than in the control group. Meanwhile, the non-fluent group did not differ from either of the other groups (however they tended to show lower target advantage scores than the control group, $p = .07$); control participants fixated the competitor significantly less than individuals with fluent and non-fluent aphasia did, with the two clinical groups not differing on this parameter. A main effect of Time was also found, with increased fixations on the target, declining competitor fixations, and consequently an increasing target advantage over time. In addition, the interaction between Time and Group was revealed: individuals with fluent aphasia showed a smaller increase of fixations on the target, and smaller decrease of fixations on the competitor over time, and thus a lower increase of target advantage over time as compared to control participants; the non-fluent did not differ from either of the other two groups. This means that all groups of participants looked increasingly more at the target image and less at the competitor image when the ambiguity was being resolved, but the overall amount of the relevant (target) meaning activation and its increase over time was reduced in the fluent group. Furthermore, the control participants inhibited the irrelevant (competitor) meaning more than both groups of individuals with aphasia did.

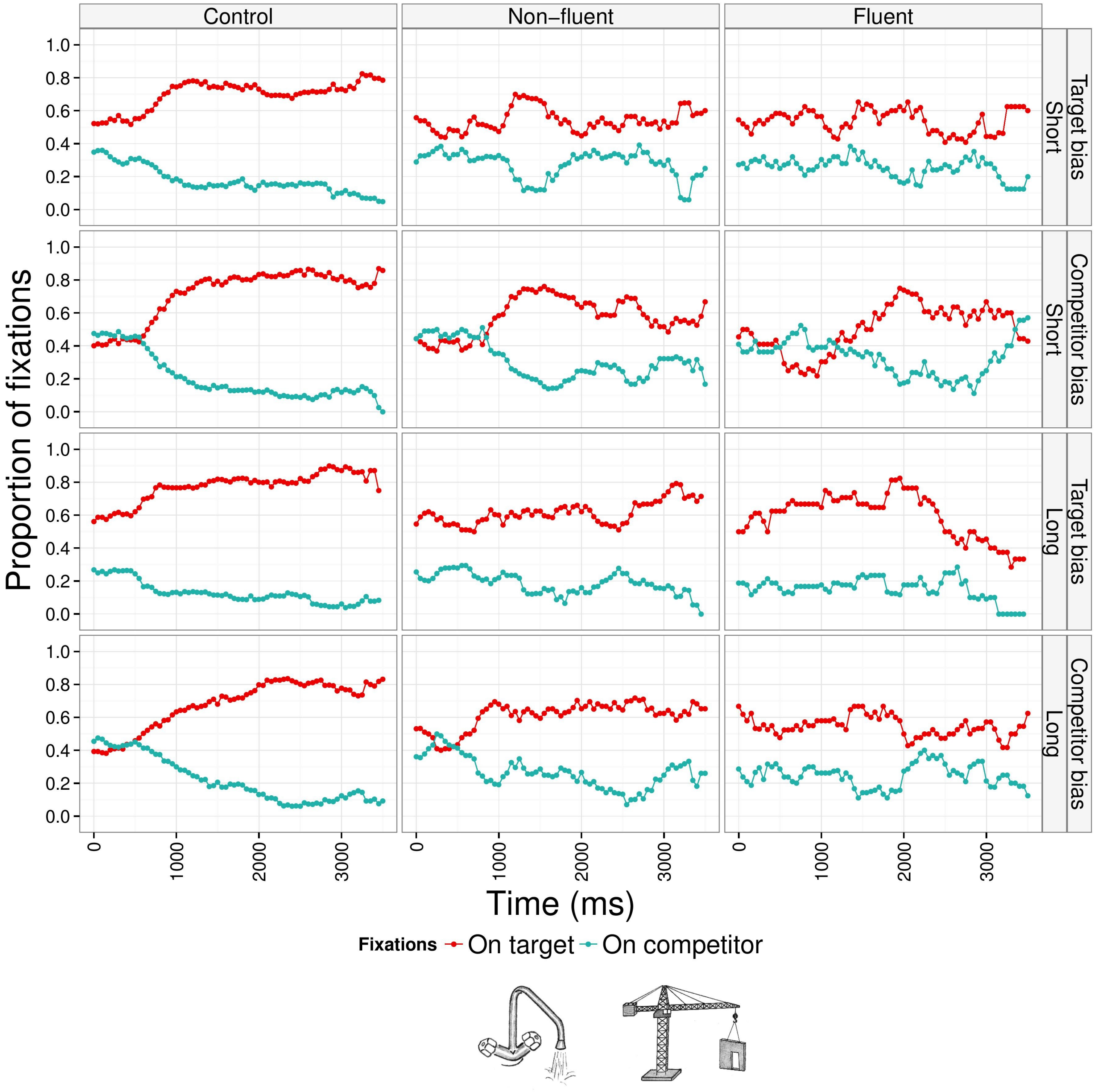

Figure 3. Proportions of frames with fixations on the target vs. competitor images in Region 2 across groups and bias and length conditions in 50 ms bins.

The competitor fixations analysis also revealed main effects of Bias: all participants demonstrated decreased competitor fixations in the target bias condition, which resulted in a target advantage tending to be greater in the target bias condition than in the competitor bias condition (the effect did not reach significance). Thus, when the ambiguity was being resolved, the irrelevant (competitor) meaning was equally more inhibited in all groups of participants if the previous context was biased toward the relevant (target) meaning. Moreover, Phonological Distance was found to affect fixations on the competitor (in the target scores analysis the effect was marginally significant): overall, participants exhibited a greater likelihood of fixating the competitor and a trend toward a smaller likelihood of fixating the target in the short condition in comparison to the long condition; this significantly affected the target advantage in the short condition, causing it to be smaller in comparison to the long condition.

In addition, three-way interactions of Group x Bias x Time and Group x Bias x Phonological Distance were found significant in Region 2. The two-way interaction between Bias and Time was only significant for the control participants: target fixations increased and competitor fixations decreased more slowly over time in this group, resulting in a smaller target advantage increase over time in the target bias condition in comparison to the competitor bias condition. The same interaction in the PWA groups approached significance. Similarly, the interaction between Bias and Phonological Distance was only found to be significant in the control group; in the target bias condition, the probability of fixating the target was higher and the probability of fixating the competitor was lower given long distance in comparison to short distance, which significantly affected the target advantage in the target bias condition: it was lower when the phonological distance was short. These findings suggest that when control participants resolve ambiguity, they activate the relevant meaning and inhibit the irrelevant meaning faster and to a greater extent if the previous context was biased to the irrelevant meaning. Also, given the bias of the context toward the relevant meaning, the intervening phonological materials enhanced its overall advantage over the irrelevant meaning in the control group.

4 Discussion

The present study used the visual-world eye-tracking-while-listening paradigm to investigate the dynamics of lexical access and ambiguity resolution in Russian participants with and without aphasia. We examined processing of ambiguous words in a biased context. Our main research question was how lexical access performed and how further selection, integration and reanalysis proceed in aphasic and non-aphasic individuals. In addition, we monitored the effects of contextual bias and phonological distance in all three participant groups.

4.2 Group performance

4.2.1 Control group

In line with our predictions, the control group demonstrated sensitivity to the direction of contextual bias (i.e., whether the context biased the listener to choose the target or, alternatively, the competitor), which guided all steps of the lexical processing. During lexical access, at the point of ambiguous word introduction, control participants activated both meanings more than other referents. As expected, controls looked more at the referent whose meaning was biased by the preceding context. Moreover, the influence of contextual bias was found to extend beyond the stage of lexical access. Control participants successfully resolved ambiguity at the disambiguation region in all conditions by fixating upon the relevant referent significantly more than the alternative, irrelevant meaning of the ambiguous word. The magnitude of the relevant referent advantage was the same irrespective of contextual bias but in the condition that required reanalysis, it increased faster (as seen from the interaction between the Bias and Time factors in the disambiguation region). We attribute this difference to the baseline effect: at the beginning of the analysis window, the rate of fixations to the target in the competitor bias condition was lower and therefore led to a greater increase than in the target bias condition in the same amount of time.

We also found a significant effect of the length of intervening phonological material between the first presentation of the ambiguous word and the ambiguity resolution point. This difference was manifested during ambiguity resolution, so that the participants were less likely to fixate the target when the phonological distance was short. Interestingly, the effect of Phonological Distance also interacted with Bias in the control group: in the target bias condition, the target advantage increased more efficiently when the phonological distance was long. Note that these two conditions differed in phonological distance but did not differ in the biasing strength of preceding contexts (see Section 2.2), and therefore, the stronger target advantage could not be attributed to the semantics of the intervening material. Also note that research in syntactic ambiguity demonstrates that the distance between an ambiguous noun phrase and the point of disambiguation affects the ease of reanalysis in healthy population (Ferreira & Henderson, 1991; Christianson et al., 2006): the longer the distance to disambiguation, the more difficult the reanalysis is. An analogous effect could also be present during lexical ambiguity resolution: the longer the listener holds to a particular interpretation, the more active the biased meaning gets, and the less active the unbiased meaning becomes. According to the literature on syntactic ambiguity mentioned above, the reanalysis should be more difficult in the long condition than in the short, and the observed increase in fixations could be linked to a greater processing load during reanalysis. A similar pattern has been reported by Van Orden, Limbert, Makeig and Jung (2001) in a visuospatial memory study that used eye-tracking which showed that fixation frequency was correlated with cognitive workload. As further indirect evidence, the error rate in the non-fluent group in the long condition that required reanalysis was greater than in the short condition (27% versus 20%), but the difference was not statistically significant. Unfortunately, we did not measure pupil dilation, as this common measure of cognitive effort could bring new evidence to the case.

4.2.2 PWA groups

We anticipated that participants with aphasia would exhibit general and syndrome-specific patterns. Overall, neither of the clinical groups was expected to experience delays in lexical access given the slowed speech rate. The predicted general deficit was an impairment of later processing stages in comparison to the control group. However, due to different hypothesized causes of this deficit for individuals with non-fluent and fluent aphasia, different patterns of its manifestation were also expected. In particular, previous literature suggested that selection and integration problems are responsible for a large part of the lexical deficit in non-fluent aphasia (Swaab et al., 1998; Grindrod & Baum, 2003), while impaired inhibition of irrelevant meanings is its major contributor in fluent aphasia (Janse, 2006; Yee et al., 2008). We tested this hypothesis directly by monitoring the process of ambiguity resolution and reanalysis in all participant groups. The obtained data support syndrome-specific explanations of lexical difficulties in participants with aphasia, and additionally shed light on the role of contextual bias, as well as intervening phonological material in lexical processing in non-fluent and fluent aphasia.

During lexical access in the word introduction stage when the two meanings of an ambiguous word should be normally activated, the eye-tracking behavior of individuals with aphasia resembled that of the control group: all participants demonstrated equal sensitivity to the contextual bias by fixating the target more when the context was biased to the target meaning of an ambiguous word and fixating the competitor more when the context was biased to the competitor meaning. The ability of non-fluent aphasic individuals to respond to the contextual bias was of special interest in our study since, in some previous studies, lexical selection in fluent aphasia was questioned (Swaab et al., 1998; Grindrod & Baum, 2003). Our finding that the non-fluent group was as sensitive to contextual bias as the control group suggests that lexical selection is preserved in non-fluent aphasia. The lack of sensitivity to context reported in previous studies could be confounded by factors like the wrap-up effect, since the critical ambiguous word was presented in a sentence-final position (see Rayner, Kambe & Duffy, 2000; Fallon, Peelle & Wingfield, 2006), or by the severity of aphasia. For example, in the study by Swaab et al. (1998), six out of twelve participants with Broca's aphasia were diagnosed with a moderate-to-severe language impairment; in the study by Grindrod and Baum (2003) the severity of aphasia was not specified. Our results suggest that participants with non-fluent aphasia are, on the whole, sensitive to contextual manipulations; moreover, they can perform lexical selection in biased ambiguous contexts without delays relative to the control group under slowed speech rate. We therefore conclude that the difficulties with the processing of contexts do not constitute a core deficit in non-fluent aphasia.

Iindividuals with non-fluent aphasia activated a biased meaning more than a non-biased one as did the control group and the fluent aphasic group, and the activation of the target did not differ between the groups, but the activation of the competitor increased more slowly in nonfluent aphasic participants than in the other two groups. Interestingly, independent of the preceding context's bias toward target or competitor, it was always the competitor that was activated more slowly. General difficulties associated with the timely activation of multiple referents might therefore be hypothesized in the non-fluent group, which is in line with findings on reduced lexical activation in Broca's aphasia by Utman, Blumstein and Sullivan (2001).

Our results are also consistent with the studies that found a normal pattern of lexical access in fluent aphasia (Yee et al., 2008; Prather et al., 1997). However, one difference between fluent and control participants was detected, namely the underactivation of the target meaning. Taking into account that the target meaning was less activated in all regions of analysis, we attribute this result to higher levels of lexical interference among activated referents and difficulties with their inhibition in fluent aphasia (Janse, 2006), rather than to specific impairments to lexical access.

To summarize, both clinical groups demonstrated context-sensitive and timely lexical access under slowed speech rate, but each aphasic group diverged slightly from the control group in its own way. In the non-fluent group, a slower rise in the activation of competitor referents could be attributed to the reported difficulties with simultaneous activation of multiple referents, while in the fluent group, it likely stems from the main underlying deficit of this group, disrupted inhibition, which is observed in other stages as well. Critically, the examination of target advantage did not detect any differences between the groups in the stage of lexical access – the difference between fixations on target and competitor was similar in all groups. Therefore, we view the discussed deviations as minor and insufficient for any claim that lexical access per se is impaired in either fluent or non-fluent aphasia under slowed speech rate.

A major motivation behind our study was to dissociate the deficits at late stages of lexical processing reported in fluent and non-fluent aphasia. For this purpose, in half of our experimental stories, we incorporated material that would require reanalysis at a later point. Reanalysis was tied to the disambiguation region where the information critical to the identification of the target meaning was made available. When this information was confronted with the preceding context, reanalysis was required. In line with our predictions, the impairments at later stages of lexical processing were detected in both PWA groups. However, the sources for these impairments were hypothesized to be different. The obtained results suggest that the performance of the PWA groups with respect to reanalysis confirms the prediction.

In the group of non-fluent participants we must conclude that reanalysis was impaired, due to lower accuracy rates and a tendency towards lower target advantage scores in the reanalysis region. Although online patterns of further reanalysis were similar in the control and PWA groups, these might be unstable. This interpretation is consistent with the role of left inferior frontal gyrus, often damaged in Broca's area, that is involved in selection between competing alternatives (Ihara et al., 2007; Thompson-Schill et al., 1997) and reanalysis (Novick, Trueswell & Thompson-Schill, 2005). These findings provide further support for the accounts that ascribe major deficits in non-fluent aphasia to later stages of lexical processing.

A different pattern was characteristic of the fluent group in the present study. We found consistent evidence pointing to difficulties with inhibition of the irrelevant referent and to higher levels of lexical interference in this group. Importantly, this feature could not be relevant to one specific stage of lexical processing, because it seems to undermine all stages. We did not find any evidence of difficulties specifically related to late lexical processing in fluent participants. Therefore, a lesser activation of the target and a greater activation of the competitor echoes through all stages of analysis including ambiguity resolution, which minimizes the possibility that late lexical processing is focally disrupted in fluent aphasia. Considering all of the evidence, spared sensitivity to context during lexical access and control-like behavior during reanalysis suggest that those processes are at least partially spared in fluent aphasia. However, the processing system of individuals with fluent aphasia is characterized by a constant "noise" resulting from impaired inhibition of irrelevant referents. This interference influences all stages of lexical processing, beginning with lexical access and accumulating through later stages. This disrupts the offline performance in the condition with the most "noise"; that is, under high phonological load (see the relevant discussion below).

Therefore, previously reported results about lexical deficits in aphasia were only partially confirmed in the present study: in non-fluent aphasia, the impairment is centralized at the reanalysis stage, while in fluent aphasia, no stage seems to be specifically disrupted, but lexical processing suffers from an impaired inhibition of irrelevant meanings. It should be noted that research on lexical processing in a sentential context in fluent aphasia is almost non-existent, and to our knowledge, we are the first to show that there is no specific disruption of any of the lexical processing stages in fluent aphasia (at least, under slowed speech rate). Rather, the obtained data show that the deficit in fluent aphasia is spread over all stages of lexical processing and seems to stem from difficulties with lexical inhibition.

As expected, phonological distance did specifically disrupt performance of the fluent group as reflected in the offline accuracy measure. Our results are in line with the study by Friedmann and Gvion (2003) that reported deficient processing in individuals with conduction aphasia under high phonological load. These findings also conform the fluent participants' key deficit that was identified above – an inability to appropriately inhibit irrelevant activation, which in turn leads to higher levels of lexical interference (note that the activation of the target in this group was also weaker; Janse, 2006; Yee et al., 2008) and augmented "noise" levels. Note that the direction of the online and offline effects for the group of fluent participants was reversed: during online processing of long-distance sentences, they looked more at the target, just as control participants did, whereas offline their performance was at chance level in the response region. Thus, processing across a long phonological distance was difficult for the fluent group, but when they succeeded in processing, they behaved just like control participants. The lack of significant differences between the fluent and other groups in online processing of long- and short-distance conditions could be attributed to a high number of incorrect responses in the fluent group that lead to the exclusion of a large number of data points from the analysis (46% and 33% in long and short conditions, accordingly).

Finally, participants with aphasia gave fewer correct offline responses overall, compared to the control group. The reduced efficiency of responding to the comprehension question, which targeted the success of ambiguity resolution, corresponded to a higher activation of the competitor during ambiguity resolution in both PWA groups relative to the control participants. Higher competition between activated meanings and hence a higher error rate was expected specifically in the group of fluent participants, which is in line with their presumed difficulties with irrelevant meaning inhibition. However, the non-fluent group also demonstrated poorer performance than the control group. We suggest that one of the sources of the observed offline deficit in non-fluent aphasia is inefficient reanalysis. More specifically, the relevant meaning might be correctly selected during reanalysis, but not fully integrated into the interpretation of the story, and in that case the second presentation of the ambiguous word in the comprehension question could trigger reactivation of the other, already irrelevant meaning and induce their competition at the response stage. This explanation echoes the suggestion of Thompson and Choy (2009) who related the impaired offline comprehension failure of agrammatic, non-fluent individuals in syntactic tasks to their aberrant lexical integration.

Note that our results are also compatible with the framework of Mirman et al. (2011). According to their theory, Wernicke's aphasia would show equally strong response to moderately and high activated entities (ambiguous word's meanings) and thus, no (or smaller) difference between in the pattern of activation of the ambiguous word's meanings (resulting in low accuracy rates). In our study, there was a reliable difference in the activation of the two meanings with the activation of target consistently smaller, whereas the activation of competitor was often higher than that in the other groups. Indeed, accuracy was the lowest among the groups. In Broca's aphasia, no specific processing impairments would be expected, since if the representations are activated based on the lexical input, the most active representation will also be the correct answer.

To conclude, in the presented eye-tracking-while-listening study, contextual bias was found to be a factor that universally affects lexical access not only in control populations, but also in fluent and non-fluent aphasia. Generally, all groups of participants demonstrated equal sensitivity to context and timely lexical access under slowed speech rate. The fact that non-fluent participants in our study successfully responded to contextual manipulations has important implications for theories of lexical processing in aphasia, since it suggests that contextual insensitivity reported in non-fluent aphasia may have been previously confounded with other variables (e.g., experimental design, differences across subjects). However, we propose that this group experiences difficulties with timely activation of multiple referents. Despite the similarities between the online patterns of reanalysis in the control and PWA groups, we suggest that reanalysis is impaired in the non-fluent group, based on lower accuracy rates and a tendency towards lower target advantage scores in the reanalysis region. We conclude that sensitivity to context and lexical selection are intact in non-fluent aphasia, as suggested by the online eyetracking measure, while activation of multiple referents might be hindered. Another deficit in lexical processing in non-fluent aphasia occurs in the late processing stages, and more precisely, during reanalysis.

Regarding participants with fluent aphasia, this study provides evidence that lexical selection and integration are mostly spared in this aphasia type and no stage of lexical processing is disrupted per se. On the contrary, the breakdown in lexical processing in fluent aphasia is likely related to the difficulties with inhibition and an increased level of lexical interference (i.e., “noise” in the processing system). Intervening phonological material between the points of ambiguous word introduction and ambiguity resolution should be regarded as an additional source of interference, consistent with the effect of phonological distance on the offline performance of the fluent group. Moreover, the influence of phonological distance found in the online performance of all participants (i.e., increased fixations on targets in the long condition), which we interpreted as evidence of a higher processing load, is interesting and prompts further investigation.

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Appendix

Demographic and language-testing data of participants with aphasia.

Table 1

Demographic and language-testing data of participants with aphasia.

Participant	Age	Gender	Onset	Score	Aphasia type	Neuroimaging information
NFL 01	28	M	5	137.5	Dynamic, motor	Lesion in left MCA distribution, hemorrhagic in putamen and posterior limb of internal capsule, ischemic in parietal lobe.
NFL 02	46	M	12.5	120	Efferent motor	Left ischemic CVA in MCA distribution.
NFL 03	50	M	25	137	Motor	Left ischemic CVA, large left hemisphere lesion involving temporal and parietal areas.
NFL 04	69	M	35	122	Dynamic, efferent motor	Ischemic lesion involving left temporal and parietal areas.
NFL 05	75	F	29	100.5	Efferent motor, dynamic	Left MCA infarct involving frontal, temporal and parietal areas.
NFL 06	67	M	11	140	Efferent motor	Left ischemic CVA in cortical branches of MCA.
NFL 07	55	F	8.5	132	Motor	NA
NFL 08	48	M	32	141	Motor	NA
NFL 09	57	F	12	122.5	Motor	CVA in left ACA and MCA.
NFL 10	46	M	18	140	Motor	Left MCA infarct, with lesion involving frontal, temporal and parietal areas, with partial cortical atrophy of inferior regions of pre- and postcentral, supramarginal and insular gyri.
NFL 11	55	F	12	138.5	Motor	Lesion after CVA in left ACA and MCA distribution.
NFL 12	38	M	2	118	Efferent motor, dynamic	Lesion in the left frontal lobe.
NFL 13	55	M	3	124.5	Motor	Lesion in the left MCA distribution involving both grey and white matter of temporal and parietal areas including insular and posterior portion of superior temporal gyri.
NFL 14	61	M	3	140.5	Motor	Lesion in left frontal lobe with cortical atrophy involving inferior and partially middle frontal gyri with extension to insular gyri.

NFL 15	25	F	18	138	Efferent motor	NA
FL 16	49	F	3	122	Sensory, acoustic-amnestic	Postischemic, ischemic lesions in left frontal region.
FL 17	59	F	10	126	Sensory, acoustic-amnestic	CVA in the left temporal lobe.
FL 18	45	F	2	109	Sensory	Lesions after left CVA in cortical branches of MCA moderate vascular encephalopathy.
FL 19	59	M	8	129.5	Sensory	CVA in the left temporal lobe.
FL 20	46	F	4	140.5	Sensory, acoustic-amnestic	Left ischemic CVA in MCA distribution involving the basal ganglia.
FL 21	59	M	6	123	Sensory	Lesion after CVA in left MCA distribution invovlving both grey and white matter of parietal and occipital areas, with partial cortical atrophy of angular and superior temporal gyri.
FL 22	62	M	14	108.5	Sensory, acoustic-amnestic	Postischemic cystic cavity in the left hemisphere.
FL 23	71	M	3	102.5	Sensory, acoustic-amnestic	NA

Notes: Onset = months post-onset; Score = score on comprehension test (out of 150); NFL = participants with non-fluent aphasia; FL = participants with fluent aphasia; M = male; F = female; NA = no data available. Aphasia type was classified according to Luria's classification (Luria, 1966).

Table 3

Empirical logit analysis for Region 1: Model parameters and significance values.

	Target advantage				Target scores				Competitor scores			
	Coefficient estimate	Standard error	*T* value	*P* value	Coefficient estimate	Standard error	*T* value	*P* value	Coefficient estimate	Standard error	*T* value	*P* value
Intercept	-0.076	0.159	-0.479	0.632	-0.491	0.073	-6.695	<0.001*	-0.445	0.092	-4.830	<0.001*
Time	-0.166	0.246	-0.679	0.497	0.410	0.132	3.111	0.002*	0.496	0.123	4.049	<0.001*
Fluent	-0.366	0.262	-1.400	0.162	-0.270	0.121	-2.233	0.026*	0.023	0.152	0.149	0.881
Non-fluent	0.157	0.219	0.717	0.473	0.106	0.101	1.043	0.297	-0.026	0.127	-0.202	0.840
Target Bias	0.588	0.153	3.857	<0.001*	0.236	0.072	3.277	0.001*	-0.224	0.070	-3.194	0.001*
Time × Fluent	0.417	0.406	1.028	0.304	0.427	0.219	1.947	0.052	0.042	0.204	0.206	0.837
Time × Non-fluent	0.271	0.339	0.800	0.423	-0.114	0.180	-0.630	0.528	-0.466	0.169	-2.762	0.006*
Fluent × Target Bias	-0.262	0.251	-1.041	0.298	-0.078	0.119	-0.657	0.511	0.145	0.116	1.251	0.211
Non-fluent × Target Bias	0.265	0.211	1.257	0.209	0.110	0.100	1.108	0.268	-0.151	0.097	-1.559	0.119
Time × Fluent × Target Bias	0.025	0.555	0.045	0.964	-0.217	0.300	-0.723	0.470	-0.106	0.266	-0.398	0.691
Time × Non-fluent × Target Bias	0.411	0.401	1.024	0.306	0.146	0.212	0.687	0.492	-0.286	0.189	-1.514	0.130
Time × Control × Target Bias	0.174	0.252	0.693	0.489	0.045	0.133	0.340	0.734	-0.126	0.118	-1.063	0.288

Notes: significant results are marked with *.

Table 4

Empirical logit analysis for Region 2: Model parameters and significance values.

	Target advantage				Target scores				Competitor scores			
	Coefficient estimate	Standard error	*T* value	*P* value	Coefficient estimate	Standard error	*T* value	*P* value	Coefficient estimate	Standard error	*T* value	*P* value
Intercept	1.802	0.143	12.597	<0.001*	0.432	0.081	5.358	<0.001*	-1.073	0.064	-16.812	<0.001*
Time	0.372	0.098	3.783	<0.001*	0.170	0.056	3.015	0.003*	-0.204	0.047	-4.311	<0.001*
Fluent	-0.583	0.236	-2.474	0.013*	-0.304	0.133	-2.285	0.022*	0.165	0.105	1.571	0.116
Non-fluent	-0.356	0.197	-1.803	0.071	-0.163	0.112	-1.460	0.144	0.128	0.088	1.458	0.145
Target Bias	0.194	0.106	1.838	0.066	0.030	0.051	0.588	0.557	-0.139	0.050	-2.829	0.005*
Short condition	-0.285	0.106	-2.700	0.007*	-0.096	0.051	-1.879	0.060	0.147	0.050	2.994	0.003*
Time × Fluent	-0.433	0.162	-2.678	0.007*	-0.262	0.093	-2.823	0.005*	0.234	0.078	2.999	0.003*
Time × Non-fluent	-0.108	0.136	-0.798	0.425	-0.026	0.078	-0.333	0.739	0.040	0.065	0.612	0.541
Fluent × Target Bias	0.026	0.174	0.148	0.882	-0.002	0.084	-0.027	0.978	-0.026	0.081	-0.322	0.748
Non-fluent × Target Bias	-0.077	0.146	-0.525	0.600	-0.021	0.070	-0.307	0.759	0.041	0.068	0.605	0.545
Fluent × Short condition	-0.247	0.174	-1.421	0.155	-0.140	0.084	-1.657	0.098	0.086	0.081	1.066	0.286
Non-fluent × Short condition	0.089	0.146	0.612	0.541	0.093	0.071	1.327	0.184	0.015	0.068	0.215	0.830
Time × Fluent × Short condition	0.120	0.176	0.700	0.484	0.072	0.084	0.861	0.389	-0.049	0.086	-0.572	0.567
Time × Non-fluent × Short condition	-0.163	0.125	-1.307	0.191	-0.036	0.061	-0.601	0.548	0.018	0.063	0.278	0.781
Time × Control × Short condition	-0.083	0.080	-1.038	0.299	-0.037	0.039	-0.973	0.331	0.029	0.040	0.713	0.476
Time × Fluent × Target Bias	-0.249	0.172	-1.454	0.146	-0.149	0.084	-1.775	0.076	0.027	0.086	0.309	0.757
Time × Non-fluent × Target Bias	-0.221	0.125	-1.764	0.078	-0.063	0.061	-1.031	0.302	0.104	0.063	1.649	0.099
Time × Control × Target Bias	-0.347	0.080	-4.322	<0.001*	-0.169	0.039	-4.370	<0.001*	0.146	0.040	3.626	<0.001*
Fluent × Target Bias × Short condition	-0.006	0.239	-0.024	0.981	-0.056	0.111	-0.500	0.617	-0.020	0.112	-0.179	0.858
Non-fluent × Target Bias × Short condition	-0.049	0.174	-0.282	0.778	-0.001	0.081	-0.011	0.991	0.040	0.081	0.498	0.618
Control × Target Bias × Short condition	-0.244	0.112	-2.177	0.030*	-0.134	0.052	-2.588	0.010*	0.119	0.052	2.283	0.022*

Notes: significant results are marked with *.

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