



Short Communication

Bilingual speech-in-noise: Neural bases of semantic context use in the native language



Alexis Hervais-Adelman ^{a,*,1}, Maria Pefkou ^{a,1}, Narly Golestani ^{a,b}

^aBrain and Language Lab, Department of Clinical Neuroscience, University Medical School, 1 Rue Michel-Servet, CH-1211 Geneva, Switzerland

^bInstitute of Cognitive Neuroscience, University College London, 17 Queen Square, WC1N 3AR London, UK

ARTICLE INFO

Article history:

Accepted 26 January 2014

Available online 3 March 2014

Keywords:

Bilingualism

fMRI

Backward priming

Semantic context

Speech-in-noise

Angular gyrus

ABSTRACT

Bilingual listeners comprehend speech-in-noise better in their native than non-native language. This native-language benefit is thought to arise from greater use of top-down linguistic information to assist degraded speech comprehension. Using functional magnetic resonance imaging, we recently showed that left angular gyrus activation is modulated when semantic context is used to assist native language speech-in-noise comprehension (Golestani, Hervais-Adelman, Obleser, & Scott, 2013). Here, we extend the previous work, by reanalyzing the previous data alongside the results obtained in the non-native language of the same late bilingual participants. We found a behavioral benefit of semantic context in processing speech-in-noise in the native language only, and the imaging results also revealed a native language context effect in the left angular gyrus. We also find a complementary role of lower-level auditory regions during stimulus-driven processing. Our findings help to elucidate the neural basis of the established native language behavioral benefit of speech-in-noise processing.

© 2014 Elsevier Inc. All rights reserved.

1. Introduction

Behavioral evidence shows speech-in-noise is more easily comprehended in the native compared to the non-native language of bilinguals (Shi, 2010). Using the Speech Perception in Noise (SPIN) paradigm (Kalikow, Stevens, & Elliott, 1977), in which the predictability of the final word in sentences is manipulated, this native language advantage has been shown to arise from better use of higher-level linguistic *contextual information* in the native than in the non-native language (Florentine, 1985; Mayo, Florentine, & Buus, 1997; Shi, 2010). Using a word-level task in which the first word of semantically related or unrelated word pairs is embedded in different levels of noise, it has further been shown that semantic context contributes to this behavioral native-language advantage (Golestani, Rosen, & Scott, 2009).

A small number of functional magnetic resonance imaging (fMRI) studies have examined the neural underpinnings of the use of linguistic context or of prior information in the comprehension of degraded speech, though only in the native language. Using the SPIN sentences, Obleser, Wise, Alex Dresner, and Scott (2007)

showed that high-predictability sentences elicited greater activation in the left angular and left inferior frontal gyri (IFG) at intermediate levels of speech intelligibility. In a follow-up study, simpler noise-vocoded sentences were used, where semantic expectancy was manipulated. Greater left angular gyrus activation was found when semantic expectancy was higher, and this effect appeared to be greatest when sentences were degraded such that they were comprehensible but challenging (Obleser & Kotz, 2010). A third fMRI study addressed the question of prior information on the perception of degraded sentences, and found greater activation of the left angular and middle temporal gyri when degraded sentences were preceded by their nondegraded versions, thereby enabling extraction of semantic information (Clos et al., 2012). Fourth, in a recent fMRI study by our group, semantically related or unrelated word pairs were presented, in which the first word was embedded in noise (Golestani, Hervais-Adelman, Obleser, & Scott, 2013). We found relatively greater left angular gyrus activation in the presence of semantic contextual information, and this context effect was greater at high than low SNRs, consistent with the findings of Obleser and Kotz (2010). Finally, Zekveld, Rudner, Johnsrude, Heslenfeld, and Rönnerberg (2012) recently examined how related or unrelated single-word cues influence the processing of degraded sentences. They found no evidence for modulation of neural responses during speech-in-noise processing for related over unrelated or over control, nonword cues. However, they reported that individuals with better working

* Corresponding author. Present address: Brain and Language Lab, Department of Clinical Neuroscience, University of Geneva, 1 Rue Michel-Servet, CH-1211 Geneva, Switzerland.

E-mail address: alexis.adelman@unige.ch (A. Hervais-Adelman).

¹ These authors contributed equally to this work.

memory were better at using related cues, and this was associated with diminished superior temporal gyrus and IFG activation and increased right medial frontal cortex activation.

In the present experiment, we extend the fMRI study described above (Golestani et al., 2013) to the non-native language of late bilinguals, with the goals of replicating the behavioral native-language context benefit (Golestani et al., 2009), and of establishing, for the first time, neural evidence for the native-language specificity of this context effect. The neural basis of speech-in-noise processing has so far not been examined in both languages of bilinguals. Here, we reanalyzed previously reported data obtained in the native language (French) of our nine participants along with new data obtained in their second, late-learned 'non-native' language (English). Participants performed a forced-choice visual recognition task on the first of two auditorily-presented semantically related or unrelated words, where the first, 'target' word was embedded in different levels of noise (SNRs: -7, -6, -5 dB, and no noise). Behaviorally, we predicted relatively better performance at higher SNRs, on semantically related trials, and in the native language. Consistent with Golestani et al. (2009), we also predicted a behavioral benefit of semantic context at the lower SNRs (c.f. (Golestani et al., 2009; Mayo et al., 1997), but only in the native language. In the imaging data, we predicted modulation of left angular gyrus activation by semantic context, specifically in the native language. We also expected to find complementary involvement of lower-level auditory regions, during more stimulus-driven processing (i.e. during semantically unrelated trials, in which no supporting semantic information is available, c.f. Golestani et al., 2013) in both languages of participants.

2. Results

2.1. Behavioral results

Reaction time (RT) and accuracy data for each condition are presented in Fig. 1. A 3-way (language by context by SNR) repeated-measures ANOVA on the RTs excluding incorrect trials revealed, as predicted: (1) a main effect of language ($F_{(1, 8)} = 29.84$,

$p = 0.001$, partial- $\eta^2 = 0.79$), with faster RTs in the native compared to the non-native language, (2) of SNR ($F_{(3, 24)} = 54.74$, $p = 0.001$, partial- $\eta^2 = 0.87$), with faster RTs at relatively higher SNRs, and (3) of context ($F_{(1, 8)} = 42.92$, $p = 0.001$, partial- $\eta^2 = 0.57$), with faster RTs on related compared to unrelated conditions (see Fig. 1). There was a significant 2-way interaction between language and SNR ($F_{(3, 24)} = 3.03$, $p = 0.049$, partial- $\eta^2 = 0.27$). There was also a significant 3-way language by context by SNR interaction ($F_{(3, 24)} = 4.08$, $p = 0.018$, partial- $\eta^2 = 0.34$). Post-hoc pairwise comparisons on the cells of this 3-way interaction revealed that, as predicted, there was an effect of semantic context in French only and at the lowest SNR only ($F_{(1, 8)} = 10.35$, $p = 0.0001$) (i.e. there was no significant advantage nor disadvantage of semantic context at any other SNR in either language), and examination of the means (mean RT related = 757 ms, mean RT unrelated = 847 ms) revealed that this context effect reflected faster performance on the semantically related compared to the unrelated trials (n.b. that the critical p -value for $\alpha = 0.05$ for eight tests is 0.006, using a Bonferroni correction). Thus, at the lowest SNR of -7, we observe a benefit of semantic context on RTs in the native language only.

Accuracy values ranged from 77% to 86% correct in the conditions containing noise (mean = 82% and SD = 1.6%), demonstrating that performance was well above chance (on a binomial distribution with $p = 0.5$, equivalent to random responding, the probability of scoring 77% correct by chance, over 30 trials = 0.002). A 3-way (language by context by SNR) repeated-measures ANOVA showed a main effect of language ($F_{(1, 8)} = 13.40$, $p = 0.006$, partial- $\eta^2 = 0.63$), with relatively better performance in the native language, and a main effect of SNR ($F_{(3, 24)} = 41.85$, $p = 0.001$, partial- $\eta^2 = 0.84$), with better performance on relatively higher SNRs (Fig. 1c and d).

2.2. Imaging results

Unless otherwise indicated, all results described were significant at a whole-brain familywise error corrected level of $p < 0.05$. Table 1 lists the peak voxels of the effects described below.

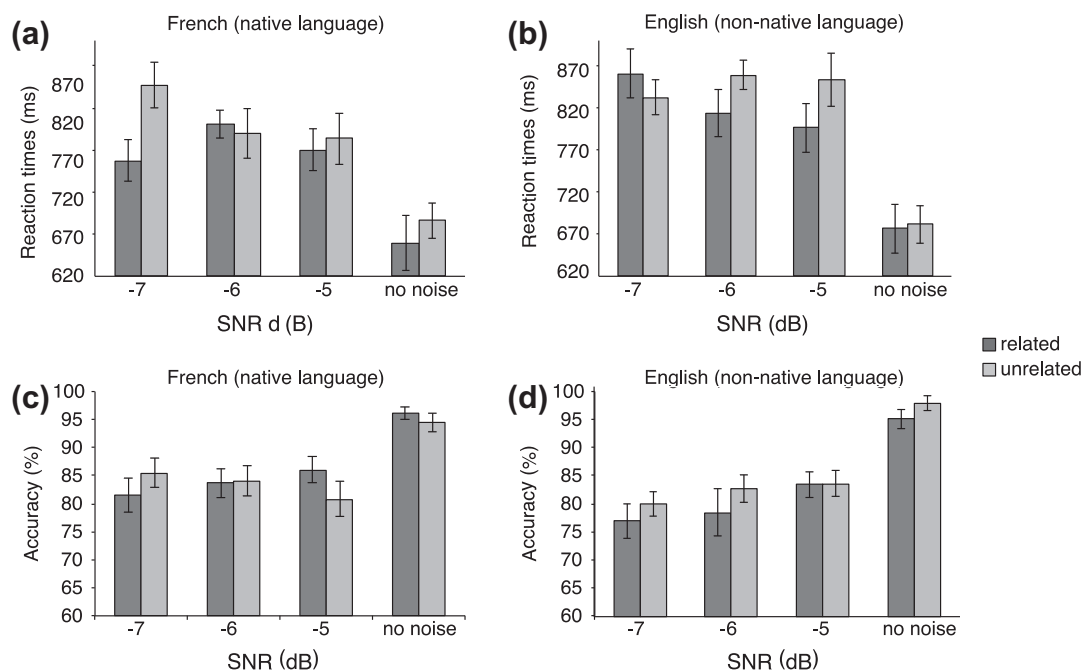


Fig. 1. Mean reaction times for behavioral responses across the group in French (a) and English (b). Error bars indicate the standard error of the mean (SEM). Note that in this and the next figures, the data obtained in the French condition have been previously reported in Golestani et al. (2013).

The main effect of SNR revealed activation in a network highly similar to, but more extensive than (the experiment had more power since twice as many trials were included) the related experiment by Golestani et al. (2013). These are presented in Supplementary Table 1 and Supplementary Fig. 1, but will not be discussed further.

We found a significant main effect of semantic context in the left angular gyrus, and, at a less conservative threshold (uncorrected $p = 0.001$, and cluster-extent threshold, $k = 100$), in its right hemisphere homologue (see Fig. 2a), with relatively greater activation of these regions during related trials. There was also an effect of context in the right mid-superior temporal sulcus (STS)/middle temporal gyrus (MTG), driven by relatively greater activation on unrelated trials.

There was no main effect of language, nor were there any 2-way interactions at whole-brain corrected levels. We had predicted that activation in the left angular gyrus would be modulated by semantic context, in the native but not the non-native language. Motivated by this a priori hypothesis, we carried out a region of interest (ROI) analysis in the language by context interaction, using Marsbar (Brett, Anton, Valabregue, & Poline, 2002). The ROI consisted of a 10 mm sphere, at a left angular gyrus location which was determined independently of our data. The centre of the ROI (MNI co-ordinates: $-44, -62, 37$) was determined by taking the mean of peak activation loci of left angular gyrus findings from three independent studies having shown the involvement of this region in using linguistic context or prior information during degraded speech perception (Clos et al., 2012; Obleser & Kotz, 2010; Obleser et al., 2007) and of a fourth study showing greater recruitment of this region during the processing of semantically related compared to unrelated word pairs (Chou et al., 2006). Supplementary Table 2 provides an overview of these studies, and the respective x, y, and z coordinates of their left angular gyrus findings. This analysis revealed that there was a significant language-by-context interaction within the region ($p = 0.048$), with an impact of context in the native language only (see Fig. 2b).

There was a significant three-way interaction between context, SNR and language, in the right cerebellum, the left planum temporale, and the left postcentral gyrus. There were trends for an interaction in the right post-central gyrus, the right anterior cingulate cortex, the middle cingulate gyrus, and the left thalamus (see Fig. 2c). In all of these regions, the interaction is driven by relatively greater recruitment during related than unrelated trials at lower than at higher SNRs in English. In French, the opposite pattern holds, with relatively greater recruitment during related than unrelated trials at higher compared to lower SNRs.

3. Discussion

Here, we replicated the previously-reported behavioral finding (Golestani et al., 2009) that listeners benefit from semantic context in their native but not in their non-native language when listening to speech-in-noise. We also examined the neural basis of this differential semantic context effect in the two languages of late bilingual individuals, by reanalyzing data obtained for French stimuli previously reported by Golestani et al. (2013) together with new data obtained in the same participants in their non-native language. To date, the neural basis of using linguistic context and prior information in processing degraded speech has only been examined in the native language of individuals (Clos et al., 2012; Golestani et al., 2013; Obleser & Kotz, 2010; Obleser et al., 2007; Zekveld et al., 2012), with existing studies showing involvement of several regions but most converging regarding the involvement of the left angular gyrus. Here, we extend the recently-reported left angular gyrus modulation by semantic context (Golestani et al., 2013), by showing that this effect is specific to the native language of late bilinguals. We found that the left angular gyrus is more strongly recruited during semantically related than unrelated conditions during challenging speech-in-noise perception, and that this effect is specific to the native language of participants. We also found a complementary role of lower-level auditory regions during stimulus-driven processing. There was greater activation of the right mid-STG/MTG when semantic context was lacking and hence word identification depended more heavily upon successful extraction of prelexical acoustic and phonetic information, in both languages of late bilinguals.

The left angular gyrus is known to play a role in semantic processing (Seghier, Fagan, & Price, 2010), and in executive demanding semantic tasks (Noonan, Jefferies, Visser, & Lambon Ralph, 2013). It has also been found to be implicated in subliminal semantic priming (Diaz & McCarthy, 2007), and in relatedness judgments when word pairs are semantically related compared to when they are unrelated (Chou et al., 2006). The present data, demonstrating a language-by-context interaction in the left angular gyrus, suggest that its involvement during challenging degraded speech processing may be language-specific, occurring mainly in the proficient language. Successful semantic access is a prerequisite of the facilitatory effect of semantic context on speech-in-noise perception. It is likely that semantic access is less effortful in the native language, in which speech processing is more automated than in a less proficient non-native language. Non-native speech processing, particularly when the language is later-learned and not proficiently spoken, is less well-established due to a lack of automaticity and also to the need for concurrent inhibition of a

Table 1

Results of fMRI analyses, showing peak voxels, cluster extents and Z-scores for listed contrasts, thresholded at uncorrected $p < 0.001$, and a cluster extent threshold of 100 voxels. Entries marked with * are significant at a family-wise error corrected $p < 0.05$. The most significant voxel of each cluster is denoted in bold. Local maxima are detailed only for clusters that extended beyond the region of the peak voxel.

Structure	Cluster extent (voxels)	MNI coordinates (x, y, z mm)	Z-Score
<i>Main effect of semantic context</i>			
*Left angular gyrus	620	$-46, -66, 36$	4.99
Right middle temporal gyrus	196	$54, -10, -16$	4.42
Right angular gyrus/Right inferior parietal lobule	272	$54, -56, 40$	4.09
<i>Context by SNR by language interaction</i>			
*Right superior cerebellum (lobule VI)	1167	$18, -52, -26$	6.43
*Left postcentral gyrus	2960	$-46, -20, 40$	5.55
Left superior temporal gyrus		$-52, -26, 10$	5.19
Left thalamus	259	$-12, -24, 0$	4.65
Anterior cingulate gyrus (left and right)	505	$12, 26, 24$	4.64
Right precentral gyrus	262	$40, -22, 62$	4.28
Anterior cingulate gyrus (left and right)	225	$-2, -18, 42$	3.98

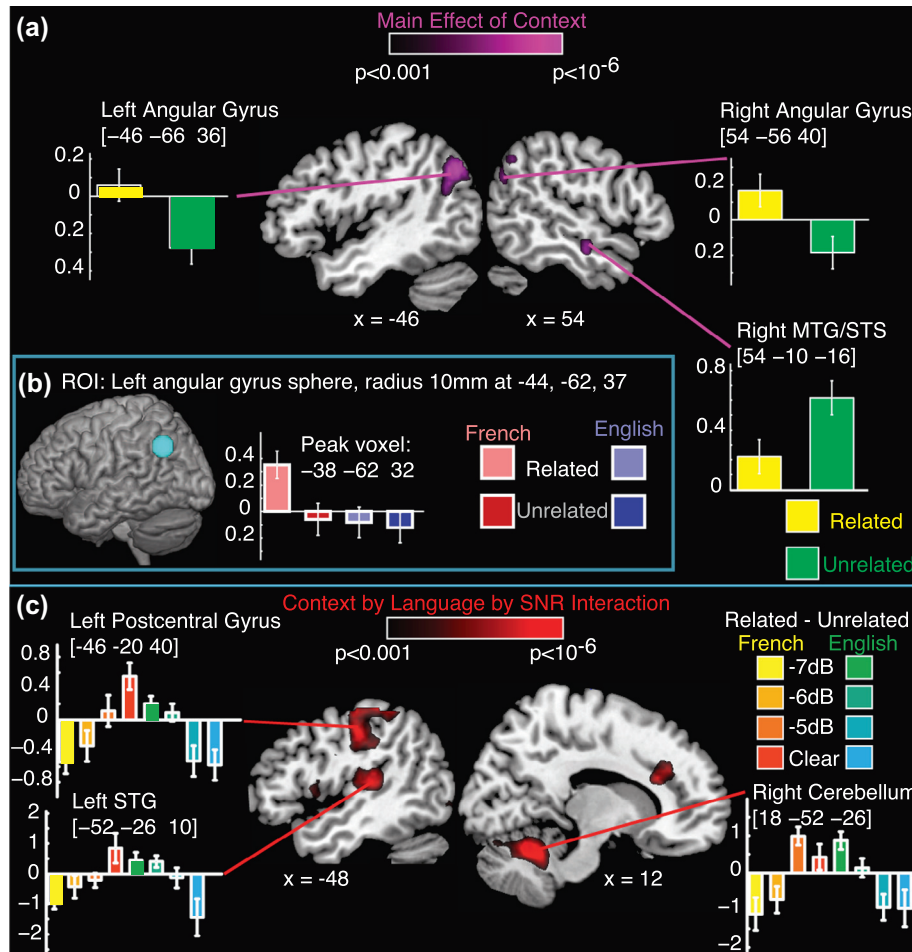


Fig. 2. (a) Main effect of semantic context. Bar plots represent mean contrast estimates for the related and unrelated conditions, collapsed across language and SNR at selected local maxima. (b) Language by context interaction, the spherical 10 mm-radius ROI centred at MNI-space co-ordinates of -44, -62, 37 is shown in cyan. Bar plots illustrate the mean contrast estimates at the voxel in the ROI at which the language by context interaction is most significant. (c) SNR by context by language interaction. Bar plots represent mean difference in contrast estimates for related vs unrelated conditions. Error bars indicate standard error of the mean, adjusted for repeated-measures comparisons (as described in Loftus & Masson, 1994).

dominant native language (Abutalebi & Green, 2007; Hervais-Adelman, Moser-Mercer, & Golestani, 2011; Rodriguez-Fornells, De Diego Balaguer, & Muentz, 2006). It is thus possible that during acoustically-challenging speech perception in the non-native language, neural and cognitive resources are lacking for an automated and efficient engagement of semantic processing in the left angular gyrus, and that the benefits of semantic context are absent due to capacity limitations. This interpretation is consistent with reports that semantic priming effects vary as a function of proficiency, being more reliable in a more proficient language (Phillips, Segalowitz, O'Brien, & Yamasaki, 2004). Our behavioral results are also consistent with this; we find faster response times in the native than in the non-native language during this retroactive semantic priming paradigm.

Last, we found evidence that the presence of noise modulates the effect of context in the brain differently in the native compared to the non-native language of late bilinguals. This 3-way interaction is found in the right cerebellum, the left planum temporale, and the left postcentral gyrus. It appears that in these regions, the impact of relatedness is greatest at lower SNRs in the non-native language (English), and at higher SNRs in the native language (French).

Several of the regions revealed in this interaction are implicated in speech and language processing. Graph theoretical analysis of the asymmetry of cortical oscillations measured with EEG and fMRI

at rest has indicated that the somatosensory cortex (i.e. including the post-central gyrus) is part of a core network of speech-sensitive regions (Giraud & Poeppel, 2012). There is also extensive evidence for cerebellar involvement in language processing (Ackermann & Hertrich, 2000; Ackermann, Mathiak, & Riecker, 2007), and for auditory cortex involvement in lower-level, phonetic aspects of speech processing (Jancke, Wustenberg, Scheich, & Heinze, 2002; Osnes, Hugdahl, Hjelmervik, & Specht, 2011). It is possible that in the non-native language, the above network of regions is more 'taxed' during relatively more degraded auditory word processing when a congruent semantic context is present due to greater semantic interference in this less proficiently spoken language (c.f. Golestani et al., 2009, for a similar explanation of behavioral findings). In the native language however, these same regions appear to be more strongly recruited when semantic context is present when there is little or no noise compared to when speech is degraded. Within the auditory cortex, this interpretation suggests that during auditory word processing *especially* under intelligible conditions, semantic context may facilitate lower-level, phonetically and acoustically based processing, but only in the native language. This interpretation is compatible with the idea that at least in certain brain regions, there exists 'additivity' of the semantic and phonetic levels of speech (i.e. a facilitatory effect of one on the other); such a facilitatory mechanism in the auditory cortex is complementary to the compensatory role in the left angular gyrus,

which appears to play a role in extracting semantic information when speech input is degraded.

More generally, the differential response patterns in the left auditory cortex, the right cerebellum, and the left post-central gyrus suggest different neural mechanisms underlying the use of semantic information during the processing of easily-intelligible versus suboptimal speech in the native versus non-native languages in bilinguals. The exact mechanism of such a differential mechanism remains to be elucidated in future studies.

Our results have implications for understanding the neural bases of speech processing in bilinguals, who in real-life situations often have more difficulty in understanding noisy speech in their non-native compared to their native language. We provide evidence that left angular gyrus involvement in utilizing semantic context to assist speech-in-noise processing is specific to the native language. We propose that involvement of this higher-level component of the language network in utilizing semantic context during the perception of noisy speech is more easily promoted in the native than the non-native language due to more automated semantic access based on better-established representations. A number of studies show evidence suggesting more automated processing (manifest as relatively lower brain activation) of native than non-native languages (Chee, Hon, Lee, & Soon, 2001; Stein et al., 2009). Hence, it is possible that during effortful (i.e. noisy) non-native language processing, neural and cognitive resources are lacking for an automated and efficient engagement of top-down semantic and linguistic integration mechanisms that could otherwise facilitate processing. This view is compatible with the limited capacity theory of cognitive processing, whereby during the performance of a particular task, attentional mechanisms select among competing mental processes (Handy, 2000; Posner & Presti, 1987). Likewise, it is also compatible with the view that the brain has to trade-off, or to balance out neural resources in a manner that is dependent on cognitive load (Arsalidou, Pascual-Leone, Johnson, Morris, & Taylor, 2013). It remains to be tested whether with the acquisition of greater levels of proficiency in the non-native language, neural resources will be liberated, enabling recruitment of the left angular gyrus for utilization of linguistic context in assisting degraded speech comprehension, and for enabling semantic priming more generally.

4. Methods

Nine native French speakers (3 men), who were late learners of English were tested in this study. More information about the participants and their language backgrounds can be found in the related paper by Golestani et al. (2013). Detailed information about stimuli and about the experimental procedure can also be found in the related paper. A forced-choice visual recognition task on the first of two auditorily-presented semantically related or unrelated words was employed, where the first, 'target' word was embedded in different noise levels. French semantically related and unrelated word pairs were selected from the database of Ferrand and Alario (1998), and English word pairs were selected from the University of South Florida Free Association Norms (Nelson, McEvoy, & Schreiber, 1998). In each language, two sets of stimuli were generated (two sets of 520 word pairs) such that in list '1', a specific target (e.g. 'parrot') was followed by a related prime (e.g. 'bird'), and that in list '2', it was followed by an unrelated prime (e.g. 'cake') (see Supplementary Table 3 for examples of items). The number of syllables of the prime, target, and foil were matched across languages. Word frequency information was taken from the 'Lexique' database for the French words (<http://www.lexique.org>, New, Pallier, Brysbaert, & Ferrand, 2004), and from the University of South Florida Free Association Norms database for

the English words (Nelson et al., 1998). Phonological neighborhood density (ND) of the primes was not matched between languages. Mean ND was higher in French than English stimuli [2-sample *t*-test: $t(521) = 2.92$, $p = 0.04$, French mean (s.d.) = 17.37 (22.919) and English mean (s.d.) = 13.87 (14.856)]. We checked for the presence of correlations between ND and RT, and found none (in French, Pearson's $r = 0.05$, $p = 0.423$; in English, Pearson's $r = 0.037$, $p = 0.56$). For accuracy, there was a low but significant negative correlation between ND and accuracy in French (Pearson's $r = -0.198$, $p = 0.001$), and no correlation between ND and accuracy in English (Pearson's $r = 0.013$, $p = 0.838$). Given that higher ND appears to make the task harder (in French), the difference in ND between the two languages may have reduced the facilitatory effects of semantic context in French. Nevertheless we still find significantly superior performance in French than English in terms of both RT and accuracy.

The fMRI protocol was identical to that reported in Golestani et al. (2013). Here, two additional runs containing English stimuli were included per participant, to complement the previously-reported runs containing French stimuli. There were four scanning runs in total (two in French and two in English), and language was alternated between scanning runs, while counterbalancing for starting language across participants.

The following factors were manipulated: language (French = native language and English = non-native language), semantic context (related and unrelated), SNR (no noise, -7 dB, -6 dB, -5 dB). Null events were also included, resulting in a total of 17 conditions. There were 30 related and 30 unrelated word pairs at each of the four SNRs (i.e. 30 stimuli per condition), resulting in a total of 120 related and 120 unrelated word pairs per language (i.e. 240 word pairs in total per language), for a total of 480 trials for each participant. Language and SNR were blocked into mini-blocks of 5 trials each, and 'relatedness' was pseudo-randomly mixed (ensuring that equal numbers of related and unrelated trials occurred within each pairing of language and SNR) within mini-blocks in order to ensure that participants would not adopt different response strategies across relatedness conditions. Scanning lasted approximately 52 min per participant.

Data preprocessing steps and the first level fixed-effects analyses were identical to those reported in Golestani et al. (2013). The analysis of group data was achieved by entering the parameter estimates for each of the 16 conditions from each participant into a single random effect model. Using the contrast vectors described by Henson and Penny (2005), an analysis of variance (ANOVA) with three factors (language: 2 levels; context: 2 levels; SNR: 4 levels) was carried out on the imaging data to test for the main effects of language, context and SNR, and interactions between the three. In order to test for regions that show a response that is modulated by SNR, we carried out a correlational analysis in which we sought a linear effect of SNR. However, because the SNR = ∞ in the clear condition, SNR values were transformed into a measure of the proportion of signal and noise in the mixture (proportion of signal in stimulus: no noise = 1, SNR -5 dB = 0.3162, SNR -6 dB = 0.2512, SNR -7 dB = 0.1995). The transformed values were then used as a contrast vector to find any regions showing a response that was reliably positively or negatively linearly correlated with SNR. Unless otherwise stated, all results reported are significant at a whole-brain family-wise error (FWE) corrected level of $p < 0.05$. Coordinates of peak activations are in the MNI (Montreal Neurological Institute) space.

Acknowledgments

We wish to thank Rhonda Amsel for statistical advice. This work was supported by a Marie Curie International Incoming Fellowship under the European Commission's FP6 framework to N.G., and by a

Swiss National Science Foundation grant awarded to N.G. We also thank two anonymous reviewers for their insightful comments and helpful suggestions.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.bandl.2014.01.009>.

References

- Abutalebi, J., & Green, D. (2007). Bilingual language production: The neurocognition of language representation and control. *Journal of Neurolinguistics*, 20, 242–275.
- Ackermann, H., & Hertrich, I. (2000). The contribution of the cerebellum to speech processing. *Journal of Neurolinguistics*, 12(2), 95–116.
- Ackermann, H., Mathiak, K., & Riecker, A. (2007). The contribution of the cerebellum to speech production and speech perception: Clinical and functional imaging data. *Cerebellum*, 6(3), 202–213.
- Arsalidou, M., Pascual-Leone, J., Johnson, J., Morris, D., & Taylor, M. J. (2013). A balancing act of the brain: Activations and deactivations driven by cognitive load. *Brain and Behavior*, 3(3), 273–285.
- Brett, M., Anton, J., Valabregue, R., & Poline, J. (2002). *Region of interest analysis using an SPM toolbox*. Paper presented at the 8th international conference on functional mapping of the human brain, Sendai, Japan.
- Chee, M. W., Hon, N., Lee, H. L., & Soon, C. S. (2001). Relative language proficiency modulates BOLD signal change when bilinguals perform semantic judgments. Blood oxygen level dependent. *Neuroimage*, 13(6 Pt 1), 1155–1163.
- Chou, T. L., Booth, J. R., Bitan, T., Burman, D. D., Bigio, J. D., Cone, N. E., et al. (2006). Developmental and skill effects on the neural correlates of semantic processing to visually presented words. *Human Brain Mapping*, 27(11), 915–924.
- Clos, M., Langner, R., Meyer, M., Oechslin, M. S., Zilles, K., & Eickhoff, S. B. (2012). Effects of prior information on decoding degraded speech: An fMRI study. *Human Brain Mapping*. Epub ahead of print.
- Diaz, M. T., & McCarthy, G. (2007). Unconscious word processing engages a distributed network of brain regions. *Journal of Cognitive Neuroscience*, 19(11), 1768–1775.
- Ferrand, L., & Alario, X. (1998). Normes d'associations verbales pour 366 noms d'objets concrets. *L'Année Psychologique*, 98, 689–739.
- Florentine, M. (1985). *Speech perception in noise by fluent, non-native listeners*. Paper presented at the proceedings of the acoustical society of Japan.
- Giraud, A. L., & Poeppel, D. (2012). Cortical oscillations and speech processing: Emerging computational principles and operations. *Nature Neuroscience*, 15(4), 511–517.
- Golestani, N., Hervais-Adelman, A., Obleser, J., & Scott, S. K. (2013). Semantic versus perceptual interactions in neural processing of speech-in-noise. *Neuroimage*, 79, 52–61.
- Golestani, N., Rosen, S., & Scott, S. K. (2009). Native-language benefit for understanding speech-in-noise: The contribution of semantics. *Bilingualism-Language and Cognition*, 12(3), 385–392.
- Handy, T. C. (2000). Capacity theory as a model of cortical behavior. *Journal of Cognitive Neuroscience*, 12(6), 1066–1069.
- Henson, R. N., & Penny, W. D. (2005). ANOVAs and SPM. London: Institute of Cognitive Neuroscience. Wellcome Department of Imaging Neuroscience.
- Hervais-Adelman, A., Moser-Mercer, B., & Golestani, N. (2011). Executive control of language in the bilingual brain: Integrating the evidence from neuroimaging to neuropsychology. *Frontiers in Psychology*, 2, 234.
- Jancke, L., Wustenberg, T., Scheich, H., & Heinze, H. J. (2002). Phonetic perception and the temporal cortex. *NeuroImage*, 15(4), 733–746.
- Kalikow, D. N., Stevens, K. N., & Elliott, L. L. (1977). Development of a test of speech intelligibility in noise using sentence materials with controlled word predictability. *The Journal of the Acoustical Society of America*, 61(5), 1337–1351.
- Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subjects designs. *Psychonomic Bulletin & Review*, 1(4), 476–490.
- Mayo, L. H., Florentine, M., & Buus, S. (1997). Age of second-language acquisition and perception of speech in noise. *Journal of Speech, Language, and Hearing Research*, 40(3), 686–693.
- Nelson, D. L., McEvoy, C. L., & Schreiber, T. A. (1998). *The University of South Florida word association, rhyme, and word fragment norms*. <<http://www.usf.edu/FreeAssociation/>>.
- New, B., Pallier, C., Brysbaert, M., & Ferrand, L. (2004). Lexique 2: A new French lexical database. *Behavior Research Methods, Instruments and Computers*, 36(3), 516–524.
- Noonan, K. A., Jefferies, E., Visser, M., & Lambon Ralph, M. A. (2013). Going beyond inferior prefrontal involvement in semantic control: Evidence for the additional contribution of dorsal angular gyrus and posterior middle temporal cortex. *Journal of Cognitive Neuroscience*.
- Obleser, J., & Kotz, S. A. (2010). Expectancy constraints in degraded speech modulate the language comprehension network. *Cerebral Cortex*, 20(3), 633–640.
- Obleser, J., Wise, R. J., Alex Dresner, M., & Scott, S. K. (2007). Functional integration across brain regions improves speech perception under adverse listening conditions. *Journal of Neuroscience*, 27(9), 2283–2289.
- Osnes, B., Hugdahl, K., Hjelmervik, H., & Specht, K. (2011). Increased activation in superior temporal gyri as a function of increment in phonetic features. *Brain and Language*, 116(2), 97–101.
- Phillips, N. A., Segalowitz, N., O'Brien, I., & Yamasaki, N. (2004). Semantic priming in a first and second language: Evidence from reaction time variability and event-related brain potentials. *Journal of Neurolinguistics*, 17, 237–262.
- Posner, M. I., & Presti, D. E. (1987). Selective attention and cognitive control. *Trends in Neurosciences*, 10(1), 12–17.
- Rodriguez-Fornells, A., De Diego Balaguer, R., & Muentz, T. F. (2006). Executive control in bilingual language processing. *Language Learning*, 56, 133–190.
- Seghier, M. L., Fagan, E., & Price, C. J. (2010). Functional subdivisions in the left angular gyrus where the semantic system meets and diverges from the default network. *Journal of Neuroscience*, 30(50), 16809–16817.
- Shi, L.-F. (2010). Perception of acoustically degraded sentences in bilingual listeners who differ in age of English acquisition. *Journal of Speech Language and Hearing Research*, 53(4), 821–835.
- Stein, M., Federspiel, A., Koenig, T., Wirth, M., Lehmann, C., Wiest, R., et al. (2009). Reduced frontal activation with increasing 2nd language proficiency. *Neuropsychologia*, 47(13), 2712–2720.
- Zekveld, A. A., Rudner, M., Johnsrude, I. S., Heslenfeld, D. J., & Rönnberg, J. (2012). Behavioral and fMRI evidence that cognitive ability modulates the effect of semantic context on speech intelligibility. *Brain and Language*.