Reduced semantic context and signal-to-noise ratio increase listening effort as measured using functional near-infrared spectroscopy

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Conflicts of Interest

The authors declare no conflicts of interest.

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Abstract

Objectives: Understanding speech in noise can be highly effortful. Decreasing the signal-to-noise ratio (SNR) of speech increases listening effort, but it is relatively unclear if decreasing the level of semantic context does as well. The current study used functional near-infrared spectroscopy (fNIRS) to evaluate two primary hypotheses: (1) listening effort (operationalized as oxygenation of the left lateral PFC) increases as the SNR decreases and (2) listening effort increases as context decreases.

Design: Twenty-eight younger adults with normal hearing completed the Revised Speech Perception in Noise (R-SPIN) Test, in which they listened to sentences and reported the final word. These sentences either had an easy SNR (+4 dB) or a hard SNR (-2 dB), and were either low in semantic context (e.g., "Tom could have thought about the *sport*") or high in context (e.g., "She had to vacuum the *rug*"). PFC oxygenation was measured throughout using fNIRS.

Results: Accuracy on the R-SPIN Test was worse when the SNR was hard than when it was easy, and worse for sentences low in semantic context than high in context. Similarly, oxygenation across the entire PFC (including the left lateral PFC) was greater when the SNR was hard, and left lateral PFC oxygenation was greater when context was low.

Conclusions: These results suggest that activation of the left lateral PFC (interpreted here as reflecting listening effort) increases to compensate for acoustic and linguistic challenges. This may reflect the increased engagement of domain-general and domain-specific processes subserved by the DLPFC (e.g., cognitive control) and IFG (e.g., predicting the sensory consequences of articulatory gestures), respectively.

Introduction

When listening conditions are challenging, such as in the presence of background noise, listeners may need to work especially hard as they attempt to maintain levels of speech understanding. This process is known as listening effort, defined as “the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a [listening] task” (Pichora-Fuller et al. 2016, p. 10S). Listening effort is of considerable interest to clinicians, as people with hearing loss may experience elevated listening effort despite normal pure-tone thresholds (Plack et al. 2014). Such elevated listening effort can lead to cognitive consequences such as reduced memory for what you are listening to (McCoy et al. 2005) as well as social consequences such as withdrawal from situations in which listening is effortful (Pichora-Fuller et al. 2015). These consequences have motivated researchers to investigate the conditions under which listening effort is elevated. In the current study, we use a silent neuroimaging method known as functional near-infrared spectroscopy (fNIRS) to measure listening effort. In particular, we consider how listening effort is affected by the level of background noise (acoustic challenge) and the level of semantic context (linguistic challenge).

Listening Effort and Background Noise

The factor most often shown to affect listening effort is the acoustic challenge of speech. This is frequently dictated by the level of background noise relative to target speech, or signal-to-noise ratio (SNR), where a decreasing SNR indicates increasing noise relative to speech. Comprehending speech in noise (e.g., competing talkers) presents a unique set of challenges to listeners. For instance, energetic masking occurs when target speech and noise fall within the same critical band, rendering target speech less available due to physical interactions that are taking place in the periphery (Fletcher & Galt 1950). Another form of masking is informational, broadly defined as any form of masking that is not energetic (Durlach 2006). This is usually characterized by interference from sounds that are similar to the target, thus making them difficult to separate perceptually (Brungart 2001).

These unique sources of masking place a load on cognitive processes that support stream segregation to separate target speech from the noise (e.g., based on spectral cues), selective attention to the speech over the noise, and perceptual closure to "fill in" any portions of the speech that were occluded by the noise (e.g., based on linguistic or general world knowledge; Mattys et al. 2012; Johnsrude & Rodd 2016). This processing load causes listening to become more effortful, as has been demonstrated using several types of measures (for a review of measures, see McGarrigle et al. 2014). These include subjective (i.e., self-reported listening effort; Rudner et al. 2012; Johnson et al. 2015), behavioural (e.g., reaction time, secondary-task performance; Sarampalis et al. 2009; Houben et al. 2013; Wu et al. 2016), and peripheral physiological measures (e.g., pupil dilation; Kramer et al. 1997; Zekveld et al. 2010), all of which report increased listening effort as the SNR decreases. However, once the SNR becomes sufficiently challenging, listeners are increasingly likely to disengage, leading to a decrease in listening effort (Pichora-Fuller et al. 2016; Peelle 2018; Herrmann & Johnsrude 2020).

Important questions have been raised about the above measures of listening effort. For instance, these measures do not usually correlate with one another, suggesting that they may not measure the same construct (Strand et al. 2018; Alhanbali et al. 2019; Strand et al. 2020). Another method to study listening effort involves neuroimaging, which offers a more direct look at the recruitment of cognitive resources to support listening (Evans & McGettigan 2017; Peelle 2018; Herrmann & Johnsrude 2020). In contrast, subjective, behavioural, and peripheral physiological measures of listening effort are more likely to be confounded by internal or external factors (e.g., perceived task performance in the case of self-reported listening effort; Moore & Picou 2018; for discussion, see Rovetti et al. 2019). Thus, it is unsurprising that a review by Ohlenforst et al. (2017) concluded that neural measures of listening effort—specifically functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), the only neuroimaging methods considered—may be uniquely suited to detect increases in listening effort resulting from hearing loss. Given these strengths, many recent studies of effortful listening have opted to employ neuroimaging methods.

The Neural Basis of Listening Effort

Effortful listening in noise is marked by increased activation of two primary brain networks (Alain et al. 2018; Peelle 2018). The first network is the domain-general multiple-demand system (Duncan 2010; Camilleri et al. 2018), which can be divided into two sub-networks (Dosenbach et al. 2008): the cingulo-opercular network, composed of dorsal cingulate, inferior frontal, and anterior insula regions (Dosenbach et al. 2006; Eckert et al. 2009); and the frontoparietal network, composed of brain areas along the dorsolateral prefrontal cortex (DLPFC) and intraparietal sulcus (Ptak 2011; Marek & Dosenbach 2018). The second network to support speech perception in noise is a domain-specific speech processing network specialized for speech and language, including the inferior frontal gyrus (IFG), premotor cortex, and inferior parietal lobule (Hickok & Poeppel 2007; Rauschecker & Scott 2009).

When it comes to the multiple-demand system, the cingulo-opercular network becomes active when we are motivated to understand speech, and when cognitive control (i.e., goal-directed behaviour) is needed to monitor and optimize our performance (Vaden et al. 2013; Vaden et al. 2015). This network may then signal activation of the fronto-parietal network (Botvinick et al. 2004), including the DLPFC, which directs attention to relevant information and suppresses irrelevant information (Eckert et al. 2016). Numerous fMRI studies have previously found that the DLPFC becomes more active as the SNR decreases (Sharp et al. 2006; Eckert et al. 2008; Wong et al. 2008), as have positron emission tomography studies (Salvi et al. 2002; Scott et al. 2004). EEG studies have also investigated listening in noise, such as Wisniewski et al. (2015), who found that frontal alpha power increased as the SNR decreased.

As for the speech processing network, these brain areas are theorized to perform several functions to support speech perception in noise. First, they may contribute verbal working memory, allowing unclear speech to be held in memory as it undergoes further processing (Fedorenko et al. 2012; Rönnberg et al. 2013; Peelle & Wingfield 2016; Peelle 2018). Second, because this network is also responsible for speech production, it may predict the sensory consequences of articulatory gestures in such a way that it helps to disambiguate what is being heard (Hervais-Adelman et al. 2012; Du et al. 2016; Skipper et al. 2017). Third and finally, the IFG in particular likely contributes higher-level linguistic processing, such as drawing on prior linguistic and world knowledge to aid in perceptual closure (Davis & Johnsrude 2003; Wild et al. 2012; Johnsrude & Rodd 2016). Numerous fMRI studies have found that the (usually left) IFG becomes more active as the SNR decreases (Adank et al. 2012; Vaden et al. 2013; Du et al. 2014), which was also confirmed by a meta-analysis from Alain et al. (2018).

Listening Effort and Semantic Context

In addition to SNR and other factors that change the acoustic challenge of speech, the linguistic content of speech can also affect processing load. One such linguistic factor is the level of semantic context present to facilitate speech perception. For instance, in a sentence such as "The boy likes to look at the snow," little semantic context is present to help the listener predict the final word. Thus, if the final word is unclear (e.g., due to occlusion from background noise), the listener has to consider thousands of candidate words, which together comprise the lexical search space (Wagner et al. 2016b). The larger the lexical search space, the more mental conflict—or lexical competition—is experienced as the listener determines the correct interpretation (Luce & Pisoni 1998; Dahan et al. 2001). In contrast, in the sentence “The boy rolled around in the snow,” the final word is highly predictable based on the context of the sentence, as there are only so many candidates that are semantically coherent (e.g., grass, mud, sand). Thus, semantic context reduces the lexical search space and, as a result, lexical competition (McClelland & Elman 1986; Strand et al. 2013).

Pupillometry studies have reported that overcoming lexical competition requires considerable listening effort (Kuchinsky et al. 2013; Wagner et al. 2016b). It is thus sensible to assume that decreased semantic context, which would increase lexical competition, would also lead to increased listening effort, likely by increasing the load on higher-level linguistic processes that support “filling in” occluded speech (Johnsrude & Rodd 2016). However, the literature is mixed on this question. Numerous studies have found that listening effort is increased when context is decreased, including studies of self-reported listening effort (Johnson et al. 2015; Holmes et al. 2018), dual-task performance (Pichora-Fuller et al. 1995; Johnson et al. 2015), and pupil dilation (Winn 2016; Lau et al. 2019; Kadem et al. 2020). In contrast, other studies have found that listening effort is not influenced by context, including two studies of dual-task performance (Tun et al. 2009; Desjardins & Doherty 2014) and one of pupil dilation (Borghini & Hazan 2020). One study even found that self-reported listening effort decreases when context is lower (Lau et al. 2019). It should be noted that in addition to the exact measures used to probe listening effort, these studies varied in their populations and stimuli, meaning their results are difficult to compare. Nevertheless, no one of these factors seems to predict whether or not context affects listening effort.

Only a handful of studies have manipulated the semantic context of speech while measuring the brain. For instance, Davis et al. (2011) found that the left IFG was more active when participants listened to sentences presented in speech envelope and spectrum noise with low context than high context, at least up until the point where the SNR became very hard. Zekveld et al. (2012) described similar left IFG activation when participants listened to sentences (both in clear and speech-shaped stationary noise) that were preceded by semantically-unrelated cue words rather than semantically-related cue words. However, these two studies contradict Obleser et al. (2007), who reported greater left IFG and DLPFC activation when participants listened to noise-vocoded sentences with high context than low context. As with studies involving non-neural measures, the results of these neuroimaging studies are difficult to compare given the diversity of methods employed. Thus, even when it comes to the neural assessment of listening effort, it is unclear whether decreased context increases listening effort.

Functional Near-Infrared Spectroscopy

Apart from fMRI, another neuroimaging method that may be suitable to study listening effort is fNIRS. fNIRS works by using light sources to emit near-infrared light into the cortex. On the basis of how much of that light is scattered back and measured by light detectors, the concentration of oxygen in the cortex (i.e., brain activity) can be inferred (Izzetoglu 2012). As with fMRI, fNIRS is sensitive to the hemodynamic response, which may take up to 10 s or even longer to evolve after task onset (Miezin et al. 2000). For many years, fNIRS measurement of the PFC has been used to effectively assess cognitive effort and workload during a variety of tasks (Ayaz et al. 2012; Harrivel et al. 2013; Fishburn et al. 2014). Thus, it is unsurprising that fNIRS has recently been used to measure listening effort, operationalized as the recruitment of prefrontal brain areas that are associated with effortful listening (Wijayasiri et al. 2017; Lawrence et al. 2018; Rowland et al. 2018; Rovetti et al. 2019; Zhou et al. accepted). Indeed, fNIRS is well-suited to study speech and language, as it is silent (for discussion of fMRI and scanner noise, see Peelle et al. 2010), tolerant of motion artefacts (Metzger et al. 2017), and resistant to interference from nearby electronic equipment (e.g., hearing assistive devices; Van de Rijt et al. 2016; Rovetti et al. 2019).

One of the first fNIRS studies to measure listening effort was Wijayasiri et al. (2017), who found that the left IFG was most active when participants were presented with noise-vocoded speech that was challenging to perceive accurately but still intelligible (as opposed to clear or unintelligible speech), but only when they attended to this speech rather than a distractor. These results replicated earlier findings obtained with fMRI (Wild et al. 2012). More recently, Rowland et al. (2018) monitored the PFC of participants while listening to complex, naturalistic stimuli ranging in a variety of acoustic features, including SNR (which ranged from -16 dB to +25 dB). Although PFC activation was found to be significantly correlated across participants, there was no effect of SNR on activation in any part of the PFC. This could be due to the considerable variability of the stimuli (e.g., the environments in which the noise was recorded). This was the only fNIRS study to assess the effect of SNR on listening effort, and thus no fNIRS study has found a relationship between these variables. In addition, no fNIRS study has assessed whether semantic context (or any other linguistic factors) affects listening effort.

The Current Study

To address the shortcomings in the literature described above, we recruited 28 younger adults with normal hearing to complete the Revised Speech Perception in Noise (R-SPIN) Test, in which participants listen to sentences presented among background noise and reported the final word. Two independent variables were manipulated: the SNR (+4 dB [easy] or -2 dB [hard]) and the level of semantic context (low or high). We used fNIRS to measure oxygenation in four subregions of the PFC, defined by their position along the coronal plane: the left lateral PFC, left medial PFC, right medial PFC, and right lateral PFC. The lateral PFC subregions includes the DLPFC and IFG, while the medial PFC subregions includes the frontopolar cortex (Liu et al. 2017). Left lateral PFC oxygenation was our operationalization of listening effort, as the left DLPFC and IFG tend to be recruited in response to acoustic and linguistic challenge (Scott et al. 2004; Davis et al. 2011; Du et al. 2014). We predicted that (1) left lateral PFC oxygenation (i.e., listening effort) would increase as the SNR decreased and (2) left lateral PFC oxygenation would increase as semantic context decreased.

Materials and Methods

Participants

Data are reported for 28 normal-hearing younger adults, who were recruited from undergraduate psychology courses and the community. Participants had ages ranging from 18 to 35 years (M = 24.1, SD = 5.07) and pure-tone averages (PTA; measured as the binaural average at 500, 1000, 2000, and 4000 Hz) ranging from 0.63 to 16.88 dB HL (M = 8.03, SD = 4.18), indicating that all had normal hearing. Data were collected from five additional participants, but they were replaced for the following reasons: having a PTA greater than 25 dB HL (n = 1); being older than 35 years of age (n = 1); learning English after the age of seven (n = 1); and experimenter error resulting in their data not being saved (n = 2). The sample size was selected based on a power analysis done in R version 4.0.3 (R Core Team 2020) with the package “Superpower” version 0.1.0 (Lakens & Caldwell 2019). This number was sufficient to detect effects of SNR and context on left lateral PFC oxygenation with 80% power, assuming a moderate correlation across conditions (*r* = .5) and small-medium effect sizes (*d* = 0.4; Zekveld et al. 2012; Johnson et al. 2015; Holmes et al. 2018; Lau et al. 2019).

Design

The experiment was based on a three-factor within-subject design. The independent variables were PFC subregion (left lateral, left medial, right medial, or right lateral), R-SPIN Test SNR (+4 dB [easy] or -2 dB [hard]), and R-SPIN Test semantic context (low or high). The dependent variables were R-SPIN Test accuracy (expressed as a proportion) and oxygenation (expressed in arbitrary units). Listening effort was operationalized as oxygenation of the left lateral PFC. No other measures of listening effort were used. The study was approved by the Research Ethics Board at Ryerson University (protocol number 2017-187).

Tasks and Measures

R-SPIN Test. Stimuli consisted of 100 clips of spoken sentences obtained from lists 5 and 7 of the R-SPIN Test (Bilger et al. 1984). These clips ranged from 9.03 to 12.18 s in duration (*M* = 10.54, *SD* = 0.46). Participants were instructed to listen to these clips and repeat back the final word of each sentence. If they could not identify the final word, they were instructed to guess or say “pass.” The speech was spoken by a male with a North American accent, and the background noise—playing throughout the entire clip—was 12-talker babble (six male and six female voices reading aloud). Each clip began with a spoken stimulus number (e.g., “Number one”) to aid the later review of responses by the experimenter. After that number, the sentence itself was spoken, and then a few seconds were present before the end of the clip to give participants a chance to repeat back the final word. The sentences either contained a low or high degree of contextual information that would help to identify the final word of each sentence (e.g., "Tom could have thought about the *sport*" or "She had to vacuum the *rug*").

The 100 sentences were divided into two 50-sentence lists (one low context, one high context). Participants were presented with a list of one context level followed by a list of the other context level (e.g., low context followed by high context). In addition, the first 25 sentences of both lists had one SNR and the last 25 sentences of both lists had the other SNR (e.g., easy SNR followed by hard SNR within each of the two lists). Thus, each participant was presented with four blocks of 25 sentences, with each block just over 250 s. The two context orders and two SNR orders were counterbalanced across participants. This gave rise to four block orders, each completed by seven participants. For example, a participant may have completed the blocks in the following order: (1) easy SNR/high context, (2) hard SNR/high context, (3) easy SNR/low context, and (4) hard SNR/low context.

fNIRS. Figure 1 shows the layout of the fNIR Imager 1100 (fNIR Devices, LLC, Potomac, USA), the apparatus with which we collected PFC oxygenation data. This is a 16-channel continuous wave optical neuroimaging system, which emits near-infrared light of 730 nm and 850 nm into the forehead. Cognitive Optical Brain Imaging Studio version 1.4 (Ayaz & Onaral 2005) was the platform used to control the acquisition of light intensity data, completed at a sampling rate of 2 Hz. In each channel, oxygenation was calculated as the difference between the concentrations of oxygenated and deoxygenated hemoglobin (HbO − HbR). This composite measure—known as the change in cerebral oxygen exchange—is highly sensitive, as it captures both the increase in HbO and the decrease in HbR that accompanies brain activation (Kato et al. 1993; Liang et al. 2016; Saleh et al. 2018; Pinti et al. 2019). Left lateral PFC oxygenation was calculated as the average of oxygenation in channels 1–4, left medial PFC oxygenation channels

5–8, right medial PFC oxygenation channels 9–12, and right lateral PFC 13–16, all as in prior studies with a similar apparatus (Aranyi et al. 2015; Cavazza et al. 2015; Liang et al. 2016; Montgomery et al. 2017; Anderson et al. 2018; Rovetti et al. 2019, 2021).

Listening effort was operationalized as oxygenation of the left lateral PFC, as this region has previously been found to become more active in response to acoustic and linguistic challenge (Scott et al. 2000; Wong et al. 2008; David et al. 2011; Zekveld et al. 2012; Du et al. 2014; Wijayasiri et al. 2017). Left lateral PFC activation also decreases once task demands exceed the listeners' cognitive capacity (Davis & Johnsrude 2003; Wild et al. 2012), as is also true of listening effort (Peelle 2018; Herrmann & Johnsrude 2020). Our previous fNIRS studies to successfully measure cognitive effort and listening effort have operationalized it in the same way (Rovetti et al. 2019, 2021). This operationalization is meant to align with the definition of listening effort being used: "the deliberate allocation of mental resources to overcome obstacles in goal pursuit when carrying out a [listening] task" (Pichora-Fuller et al. 2016, p. 10S). In other words, listening effort is being defined as the recruitment of cognitive resources to support listening, whereas other studies may instead be interested in the subjective experience of listening being effortful or some other definition (Herrmann & Johnsrude 2020; Strand et al. 2020).

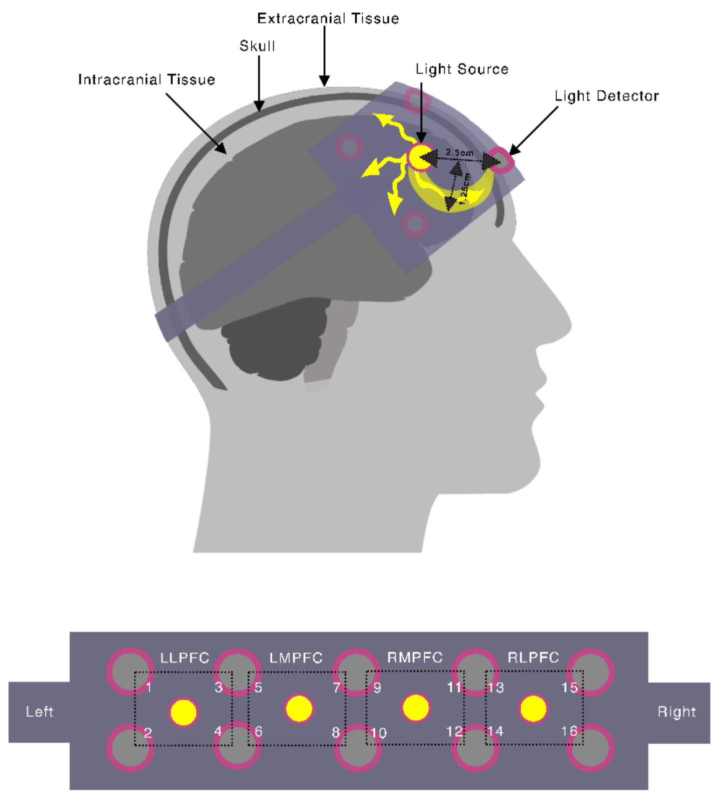

Figure 1. The fNIRS sensor pad was secured to participants' foreheads (top). This sensor pad had 10 light sources (grey circles) and four light detectors (yellow circles), which defined 16 channels in which oxygenation was measured (numbered in white; bottom). These 16 channels were grouped into four PFC subregions (black boxes): LLPFC = left lateral PFC, LMPFC = left medial PFC, RMPFC = right medial PFC, RLPFC = right lateral PFC. Figure adapted from Rovetti et al. (2019).

Procedure

Upon arrival in the lab, participants were given a detailed description of the study, provided written informed consent, and completed prescreen and demographic questionnaires. Participants were then seated in a double-walled sound-attenuated chamber where they completed pure-tone audiometric testing using a Grason-Stadler GSI 61 audiometer. They next put on Sennheiser HD 518 headphones and were given an explanation of the task. Windows Media Player was then used to play two practice R-SPIN Test sentences, which were presented at 72 dB SPL and with no background noise. Once participants expressed an understanding of the task, the fNIRS sensor pad was affixed to and centred on their foreheads above the eyebrows, aligned with the FpZ location according to the international 10-20 system (Homan et al. 1987). Adjustments were then made to the sensor pad placement and device settings (e.g., detector gain) to optimize signal quality (for details, see Rovetti et al. 2019, 2021).

Before the very first block, a 10-s baseline was recorded, over which participants were instructed to relax and remain still. Windows Media Player was used to present the R-SPIN Test blocks, with the order determined by the counterbalancing scheme (for details, see Tasks and Measures). A block design was chosen to reduce the influence of noise unrelated to brain activity (Cui et al. 2011). At the start of each block, the experimenter pressed a key to manually place a "marker" in the data acquisition platform. This gave a timestamp to the start of the block and allowed it to later be selected and exported at the data processing stage. Once a block began, the rate of stimulus presentation was automatic, with the next clip immediately following the last. Speech was presented at 72 dB SPL across all blocks and the level of noise was determined by the SNR. A one-way audio monitor was used by the experimenter to listen to and score the accuracy of participants' responses in real time, and their responses were also recorded for later review. There was no set break between blocks; once the next block was prepared by the experimenter (approximately 10 s), the participant could begin the next block whenever they were ready (on average, there was approximately 20 s between the end of one block and the start of the next). After completing all blocks, participants were debriefed.

Data Processing

Using fNIRSoft Professional version 4.6 (Ayaz 2010), the following pre-processing steps were applied to the light intensity data: (1) finite impulse response linear phase low-pass filtering (order = 20, cut-off frequency = 0.1 Hz) to reduce physiological and equipment noise (e.g., heartbeat), (2) removal of motion artefacts using the sliding-window motion artefact removal algorithm (window size = 10 s, upper threshold = 0.025 nm, lower threshold = 0.003 nm; Ayaz et al. 2010), (3) manual rejection of channels whose raw signal values fell below 400 mV (suggesting light detector obstruction) or exceeded 4000 mV (suggesting light detector saturation), (4) conversion of light intensity data to oxygenation data using the modified Beer-Lambert law (Kocsis et al. 2006), (5) and baseline correction of each channel according to the mean of that channel's 10-s baseline recorded at the start of the experiment.

In post-processing, channels were also rejected if more than 50% of their data were missing across all conditions (e.g., due to motion artefacts). The mean number of channels rejected per participant, of 16 in total, was 2.64 (SD = 1.85). Means were similar among the four PFC subregions, although the right lateral PFC had the highest rate of channel rejection (left lateral: M = 0.61; left medial: M = 0.50; right medial: M = 0.46; right lateral: M = 1.07). When a channel was rejected for a participant, it was rejected across all conditions. For each block, oxygenation in each channel was calculated as the mean from 10 s into the block (to allow the hemodynamic response a chance to evolve in response to the task) until 250 s after the start of the block. Oxygenation in each PFC subregion was then calculated by averaging together oxygenation from the four channels that comprise it, or fewer in cases where channels were rejected. These pre- and post-processing steps are almost identical to Rovetti et al. (2019, 2021), with the only difference being that linear detrending was not used in the current study. With all participants completing two conditions of one context level followed by two conditions of the other context level, using linear detrending to eliminate signal drift over time would have also eliminated the effect of context, as it also tied to time.

Statistical Analyses

All statistical analyses were done using R version 4.0.3. Analysis of variance (ANOVA) was conducted using the package "ez" version 4.4.0, with Greenhouse–Geisser adjustment of degrees of freedom applied to effects that failed Mauchly's test of sphericity. These analyses were used to assess the effects of SNR and semantic context on accuracy; and SNR, context, and PFC subregion on oxygenation. Analyses of oxygenation considered all trials, including those in which participants answered "pass," which represented 8.11% of all responses. Effect sizes for follow-up paired-samples *t*-tests were calculated using the package "lsr" version 0.5. The package "rmcorr" version 0.4.1 (Bakdash & Marusich 2017) was used to conduct exploratory repeated-measures correlational analyses, a technique that calculates the within-subject association between two variables, equivalent to multilevel modelling with intercepts (but not slopes) allowed to vary randomly across participants. In particular, these analyses assessed whether, as accuracy changed on a within-subject basis from condition to condition, oxygenation in any PFC subregion changed along with it. Figure 1 was created in Adobe Photoshop version 20.0; Figures 2 and 3 were created in R using the packages "tidyverse" version 1.3.0, "grid" version 4.0.3, and "gridExtra" version 2.3; and Figure 4 was created in MATLAB version 9.9.

Results

Data and code for the analyses reported can be found at the following link: https://osf.io/pavtd/

R-SPIN Test Accuracy

Figure 2 shows accuracy as a function of SNR and context (averaged across participants). A repeated-measures 2 (SNR) × 2 (context) ANOVA found significant main effects of SNR (F[1,27] = 334, $p < .001$, $\eta_G^2 = .45$) and context (F[1,27] = 159, $p < .001$, $\eta_G^2 = .50$) on accuracy, with accuracy worse when the SNR was hard than when the SNR was easy, and worse when context was low than when context was high. There was also a significant interaction between SNR and context on accuracy (F[1,27] = 22.1, $p < .001$, $\eta_G^2 = .076$). Paired-samples *t*-tests were used to compare the effect of context on accuracy at each SNR. This found that accuracy was significantly worse when context was low both when the SNR was easy (low context: $M = 0.69$, $SD = 0.13$; high context: $M = 0.90$, $SD = 0.13$; t[27] = -10.7, $p < .001$, $d = 2.02$) and when the SNR was hard (low context: $M = 0.34$, $SD = 0.11$; high context: $M = 0.72$, $SD = 0.20$; t[27] = -10.4, $p < .001$, $d = 1.96$). The interaction was driven by the larger effect of context on accuracy when the SNR was hard (0.38) than when the SNR was easy (0.21).

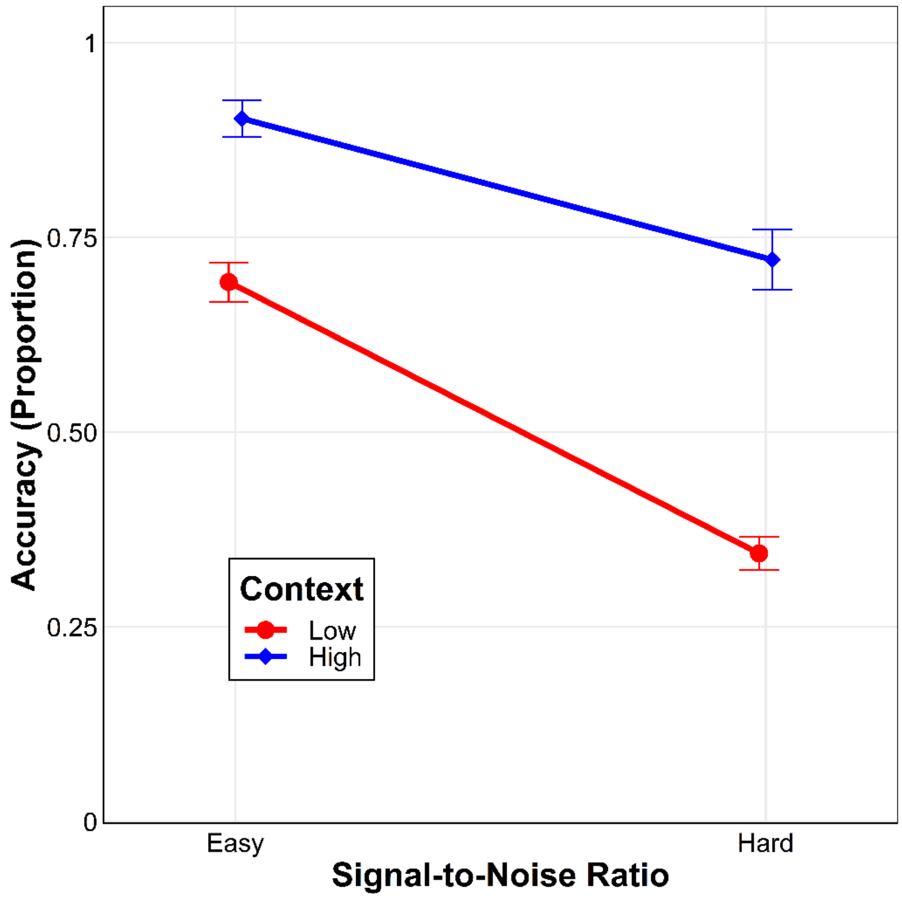

Figure 2. Accuracy was better when the SNR was easy than when the SNR was hard, and was better when semantic context was high than when the context was low. The effect of SNR was greater when context was low. Error bars show the standard errors of the mean.

Recall that half of our sample completed the low-context conditions followed by the high-context conditions, and the other half high-context followed by low-context. Since the order in which these context levels were completed could have affected the strategy that participants used, we also explored effect of context order (low-high or high-low) on accuracy using a mixed 2 (SNR; within-subject) × 2 (context; within-subject) × 2 (context order; between-subject) ANOVA. However, there was no effect of context × context order (F[1,26] = 0.68, p = .42, η_G^2 = .005) or any other significant effects involving context order (ps > .15).

Oxygenation

Figure 3 shows the timecourse of oxygenation in each PFC subregion for all conditions (averaged across participants). Looking at these timecourses, it is evident that oxygenation is fairly stable over time. The main exception is the first 10–30 s of each condition, which is approximately the time it takes for the hemodynamic response to evolve in response to the demands of the task. This lag provides some validation for our decision to exclude the first 10 s of data when calculating block means (see Data Processing). The increase in oxygenation at the very start of each block may reflect the increase in cingulo-opercular network activity that accompanies task onset (Eckert et al. 2016), which may in turn trigger the activation of brain areas that we are able to measure (e.g., the DLPFC and IFG). For the easy conditions, oxygenation then decreases, hitting a trough after the 50 s mark. It then ramps up again until 150 s, at which point it plateaus for the remainder of the block. This may reflect an ongoing recalibration of cognitive resources to meet the relatively low task demands without recruiting more than is necessary. In contrast, for the hard conditions, oxygenation remains relatively high and steady throughout, likely reflecting their higher task demands.

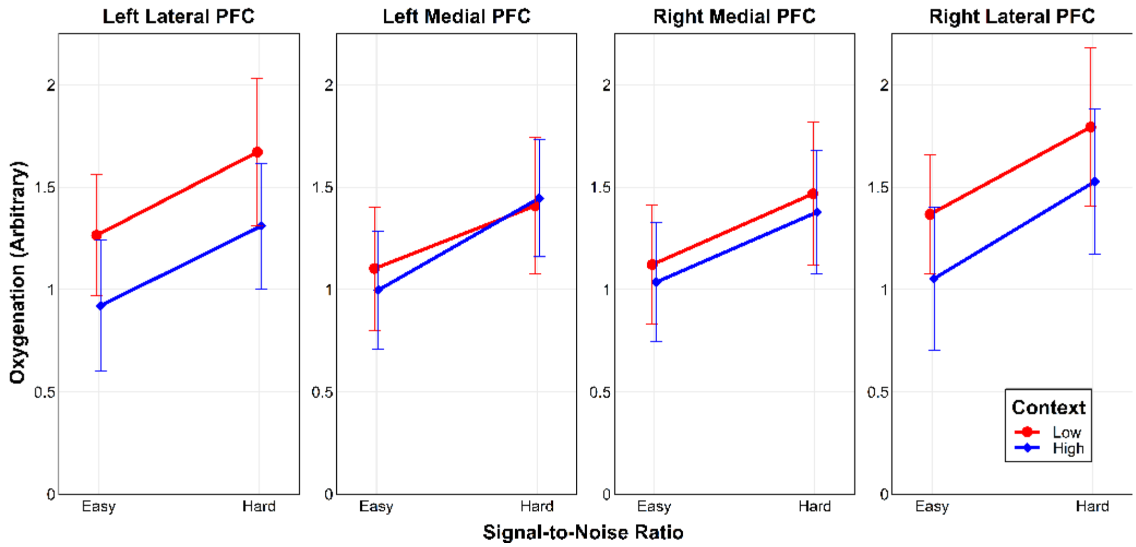

Figure 3. Oxygenation in all four PFC subregions was fairly stable over time in each block, with the exception of the first 10–30 s over which oxygenation started to evolve in response to task demands. After this period, differences between blocks become readily apparent. Oxygenation is in arbitrary units, since continuous wave fNIRS is unable to measure the absolute concentration of oxygen. The zero mark on the y-axis indicates the level of oxygenation at baseline.

A repeated-measures 2 (SNR) × 2 (context) x 4 (PFC subregion) found a significant main effect of SNR on oxygenation ($F[1,27] = 26.9$, $p < .001$, $\eta_G^2 = .014$), with oxygenation greater when the SNR was hard than when the SNR was easy. There was no effect of context ($F[1,27] = 1.66$, $p = .21$, $\eta_G^2 = .003$), PFC subregion ($F[3,81] = 0.36$, $p = .68$, $\eta_G^2 = .002$), SNR × context ($F[1,27] = 0.043$, $p = .84$, $\eta_G^2 = .00004$), or SNR × context × PFC subregion ($F[3,81] = 0.63$, $p = .57$, $\eta_G^2 = .00009$) on oxygenation. Although the effect of context × PFC subregion on oxygenation was not significant, it trended toward significance ($F[3,81] = 3.05$, $p = .050$, $\eta_G^2 = .002$), suggesting that the effect of context may have differed by PFC subregion. Given our prediction that oxygenation in only the left lateral PFC would show an effect of context (as well as SNR), we decided to follow up this marginal interaction.

Figure 4 shows mean oxygenation in each PFC subregion as a function of SNR and context (averaged across participants and time within each block). We analyzed oxygenation in each PFC subregion separately using repeated-measures 2 (SNR) × 2 (context) ANOVAs. In each PFC subregion, there was a significant effect of SNR on oxygenation (*p*s < .001), with oxygenation greater when the SNR was hard. There was a significant effect of context on oxygenation in the left lateral PFC ($F[1,27] = 4.87$, $p = .036$, $\eta_G^2 = .011$), with oxygenation greater when context was low. This effect of context was not present in the other PFC subregions (*p*s > .17). SNR did not interact with context in any PFC subregion (*p*s > .55). Given that oxygenation often continued to evolve for longer than just 10 s (see Figure 3), we also re-analyzed each PFC subregion after cutting off the first 30 s of each block. This re-analysis yielded the same results: a significant effect of SNR in each PFC subregion (*p*s < .001) and an effect of context in only the left lateral PFC ($F[1,27] = 4.71$, $p = .038$, $\eta_G^2 = .011$).

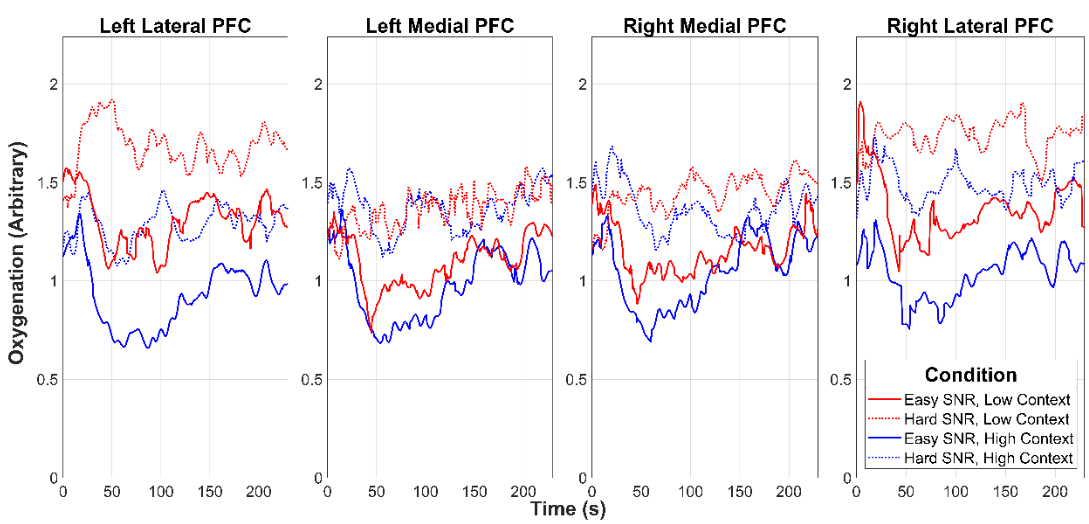

Figure 4. Oxygenation in all four PFC subregions was greater when the SNR was hard than when the SNR was easy, but only the left lateral PFC oxygenation was reduced when context was high. Error bars show the standard errors of the mean.

As with accuracy, we explored whether oxygenation in each PFC subregion may have been affected by context order using a mixed 2 (SNR; within-subject) × 2 (context; within-subject) × 2 (context order; between-subject) ANOVA. There was no effect of context × context order on oxygenation in the left lateral PFC (F[1,26] = 0.067, p = .80, η_G^2 = .0002), left medial PFC (F[1,26] = 0.050, p = .83, η_G^2 = .0001), right medial PFC (F[1,26] = 0.099, p = .76, η_G^2 = .0002), or right lateral PFC (F[1,26] = 1.06, p = .31, η_G^2 = .003). However, there was a significant effect of SNR × context × context order on oxygenation in all PFC subregions but the right lateral (ps < .043). Upon further exploration, these interactions appeared to be driven by larger effects of SNR in the first context level than the second level, regardless of whether that first level was low or high. This may be due to fatigue effects. There were no other significant effects involving context order in any PFC subregion (ps > .092).

Relationship Between Accuracy and Oxygenation

Two exploratory analyses further probed the relationship between accuracy and PFC oxygenation. First, paired-samples *t*-tests found that accuracy did not differ between easy SNR/low context and hard SNR/high context conditions (in other words, the conditions in which one factor was favourable and the other was unfavourable; t[27] = -0.95, p = .35, d = 0.18). Likewise, left lateral PFC oxygenation also did not differ between these two conditions (t[27] = -0.30, p = .77, d = 0.06). Means were also very similar across these conditions for both accuracy (easy SNR/low context: M = 0.69, SD = 0.13; hard SNR/high context: M = 0.72, SD = 0.20) and left lateral PFC oxygenation (easy SNR/low context: M = 1.26, SD = 1.57; hard SNR/high context: M = 1.31, SD = 1.62). Second, a repeated-measures correlational analysis found that accuracy was significantly negatively correlated with left lateral PFC oxygenation, meaning that across conditions, as accuracy became worse, left lateral PFC oxygenation increased (r_{rm}[83] = -

.37, $p < .001$). Although not quite as strong, this negative correlation was also present in the right lateral PFC ($r_{rm}[83] = -.27$, $p = .011$) and right medial PFC ($r_{rm}[83] = -.25$, $p = .022$), but it did not reach significance in the left medial PFC ($r_{rm}[83] = -.20$, $p = .063$).

Discussion

Speech Understanding (Accuracy)

We found that when the SNR was decreased, accuracy on the R-SPIN Test became worse. In other words, as the level of background noise increased relative to speech, speech understanding deteriorated. Furthermore, speech understanding also deteriorated when sentences contained less semantic context (i.e., when the final word was less predictable). These results are consistent with a large body of research (Kalikow et al. 1977; Sarampalis et al. 2009; Wilson et al. 2012; Johnson et al. 2015) and demonstrate that the acoustic challenge of speech (e.g., the SNR) as well as the linguistic challenge of speech (e.g., the level of context) can both influence speech understanding. In addition, we found that context had a greater positive impact on speech understanding when the SNR was hard. This is consistent with Pichora-Fuller et al. (1995), who concluded that if masking is not severe enough, speech can be sufficiently well understood using lower-level processing, which results in a smaller effect of context.

Listening Effort (Oxygenation)

Effect of SNR on Listening Effort. In line with our prediction, we found that when the SNR was decreased, left lateral PFC oxygenation increased. In other words, as the level of background noise increased, participants exerted more listening effort. This is consistent with a large body of research, including studies using subjective (Rudner et al. 2012), behavioural (Sarampalis et al. 2009; Houben et al. 2013), peripheral physiological (Zekveld et al. 2010), and neural measures (Scott et al. 2004; Du et al. 2014). For instance, Du et al. (2014) reported increased activation of the left IFG (among other brain areas) as the level of broadband noise increased. Although prior studies employing fNIRS have found effects of noise vocoding on listening effort (Wijayasiri et al. 2017), the current study is the first to show an effect of SNR on listening effort. This is in contrast to Rowland et al. (2018), an fNIRS study that did not find this effect. The discrepancy in findings across the two studies may be due to the considerable variability in the stimuli that Rowland et al. (2018) used; for instance, their noise was taken from 17 different real-world environments (e.g., a busy café, a swimming pool, a moving car). In contrast, the stimuli used in the current study were relatively well controlled.

The left lateral PFC subregion may have been more active at the harder SNR to support processes such as stream segregation, selective attention, and perceptual closure, all of which help listeners overcome masking from background noise (Mattys et al. 2012; Johnsrude & Rodd 2016). This subregion includes the left DLPFC, part of the multiple-demand system, and the left IFG, part of the speech processing network (Liu et al. 2017). The DLPFC was likely recruited to implement cognitive control by selectively attending to the target speech and suppressing distracting noise (Eckert et al. 2016). In addition, the IFG may have contributed verbal working memory, which would allow any unclear aspects of the sentences (e.g., the final word) to be held in memory for further processing (Peelle & Wingfield 2016; Peelle 2018). Such further processing could include two other proposed functions of the speech processing network: predicting the sensory consequences of articulatory gestures (Hervais-Adelman et al. 2012; Du et al. 2016) and higher-level linguistic processing. In the case of the latter function, the IFG likely used prior linguistic knowledge to support perceptual closure (Davis & Johnsrude 2003; Wild et al. 2012). For instance, if noise occluded a portion of the final word in the sentence “Tom could have thought about the -ort,” our knowledge of words and syntax could help us arrive at “sport” as a viable candidate, rather than a non-word such as “gort” or a word that is unlikely syntactically such as “short” (Ganong 1980; Bashford et al. 1992).

Interestingly, as the SNR decreased, oxygenation increased across all four subregions of the PFC, not just the left lateral PFC. This result is not likely due to the limited spatial resolution of fNIRS, since our context manipulation in the current study, as well as other manipulations in our prior research (Rovetti et al. 2021), have used the same fNIRS apparatus to find effects localized to specific PFC subregions. It is not uncommon for studies of effortful listening to report activation of the right DLPFC and IFG (Salvi et al. 2002; Wong et al. 2008; Zekveld et al. 2014), which likely perform a similar function to their left-sided counterparts. In the case of the IFG, it has been proposed that right-sided activation may reflect compensatory cognitive resource recruitment to support speech understanding in especially challenging conditions (Bidelman & Howell 2016). Similarly, studies of effortful listening (Dimitrijevic et al. 2019) and cognitive workload (Ayaz et al. 2012) have found activation of the medial PFC (e.g., frontopolar cortex). This may also reflect compensatory activation in challenging conditions (Pochon et al. 2002). However, it should be noted that such compensation has yet to be well characterized in the context of effortful listening (see Herrmann & Johnsrude 2020).

Effect of Semantic Context on Listening Effort. In line with our prediction, we found that when semantic context was lower, oxygenation in the left lateral PFC (but not other PFC subregions) increased. In other words, as context rendered speech less predictable, listening effort increased. This is consistent with some prior studies using subjective (Holmes et al. 2018), behavioural (Johnson et al. 2015), peripheral physiological (Kadem et al. 2020), and neural measures of listening effort (Davis et al. 2011). For instance, Davis et al. (2011) found that activation of the left IFG was greater when participants listened to sentences low in context, but only for SNRs of -2 dB or easier. Given that -2 dB was the hardest SNR that we used, their results are broadly consistent with ours. The current study was the first to use fNIRS to assess the effect of semantic context (or any other linguistic factor) on listening effort.

The left IFG may have been more active for low-context sentences to compensate for the lack of contextual constraint, which in turn increases processing load (Vitello & Rodd 2015; Johnsrude & Rodd 2016). This brain area has been proposed to resolve lexical competition by using prior knowledge to make predictions about incoming speech, which are then compared to acoustic representations of speech in the superior temporal gyrus (Sohoglu et al. 2012). Activity of the (usually left) IFG has also been found to increase in response to other linguistic challenges, such as semantic ambiguity (Bekinschtein et al. 2011), syntactic ambiguity (Tyler et al. 2011), syntactic complexity (Obleser et al. 2011), and syntactic incorrectness (Herrmann et al. 2012). It is also possible that with less context to enable higher-level linguistic processing, this may have increased the load on other forms of processing (Johnsrude & Rodd 2016), including those associated with the DLPFC such as cognitive control.

To understand the higher-level linguistic processing described above, recall that the greater lexical competition of low-context sentences means that participants likely relied heavily on their knowledge of words and syntax (Ganong 1980; Bashford et al. 1992), as these are some of the only linguistic strategies that would support the comprehension of low-context sentences (see Effect of SNR on Listening Effort). In contrast, for high-context sentences, participants could also rely on conditional word frequencies and general knowledge of the word, as the rich context renders such processing useful (Warren 1970; Bashford et al. 1992; Johnsrude & Rodd 2016). For instance, if noise occlusion of the final word caused a sentence to be heard as “She had to vacuum the -ug,” this final word would be difficult to identify based solely on knowledge of words and syntax given the number of viable candidates (e.g., mug, bug, drug). However, with the preceding context offer by the sentence, identifying the word ("rug") becomes trivial. In the current study, the lexical search process may have thus been more effortful for low-context sentences than high-context sentences, or perhaps it simply required more time, with more cognitive resources recruited overall (Wagner et al. 2016a).

Relationship Between Speech Understanding and Listening Effort

In an exploratory analysis, we found that speech understanding did not differ between the easy SNR/low context and hard SNR/high context conditions, suggesting that acoustic and linguistic factors can offset one another in support of speech understanding (Johnsrude & Rodd 2016). Interestingly, this was also true for listening effort, which like speech understanding did not differ between easy SNR/low context and hard SNR/high context conditions. A second exploratory analysis found that as speech understanding deteriorated across conditions (i.e., within subjects rather than between subjects), left lateral PFC oxygenation (i.e., listening effort) increased. This relationship was also found in the right lateral PFC and right medial PFC, but not in the left medial PFC. Speech understanding has previously been found to have this relationship with non-neural measures of listening effort (Zekveld et al. 2010; Holmes et al. 2018; but see Winn & Peece 2020). This further suggests a compensatory response of the PFC as listening conditions become more challenging (Davis & Johnsrude 2003).

Limitations and Future Directions

Some limitations of the current study relate to fNIRS and the specific apparatus employed. For instance, the limited spatial resolution of fNIRS means that we were not able to distinguish activation of the DLPFC and IFG. The specific apparatus used is also limited to measurement of the PFC. This, coupled with the penetration depth limits of fNIRS, meant that we were unable to measure other brain areas of interest beyond the PFC, such as the anterior cingulate cortex (Eckert et al. 2016), premotor cortex (Peelle et al. 2018), and inferior parietal lobule (Alain et al. 2018). In addition, the fNIRS apparatus used does not include short separation channels, which can account for blood flow in extracranial tissue (Brigadoi & Cooper 2018). Event-related analyses were also not possible given the block design, and thus incorrect trials could not be analyzed separately from "pass" trials. Finally, our results may not generalize to other measures of listening effort, particularly self-reported listening effort (Herrmann & Johnsrude 2020), given that different measures frequently fail to correlate with one another and are often proposed to measure different constructs (Strand et al. 2018; Alhanbali et al. 2019; Strand et al. 2020). Nevertheless, the lack of a convergent measure of listening effort may be considered a limitation of the current study, particularly a measure that, like fNIRS, is purported to measure the recruitment of cognitive resources to support listening (e.g., pupillometry).

In the future, studies should continue to assess the effect of semantic context on listening effort, as there is still much to be clarified. One problem is that studies have been highly variable in their methodology, including their stimuli and the measures of listening effort used, which may explain why they differ in their conclusions. For instance, the effect of context may depend on the nature of the sentences and how they are processed (Winn & Peece 2020) or on the severity of masking (Davis et al. 2011; Johnson et al. 2015). When it comes to the measures of listening effort used, different approaches have disagreed about the effect of context (c.f. Desjardins & Doherty 2014; Holmes et al. 2018). However, rather than genuinely disagreeing, it is possible that each of these measures reflects a different dimension of effortful listening (e.g., the recruitment of cognitive resources versus the subjective experience of effort). To address these concerns, future studies should consider using more diverse stimuli, a wider range of

SNRs, and multiple measures, with the aim of determining the conditions under which context reduces listening effort. Finally, future fNIRS studies could employ event-related designs (Lawrence et al. 2021); more channels covering frontal, temporal, and parietal areas; as well as short-separation channels subjected to general linear modeling to better account for physiological noise.

Conclusions

In sum, the current study was the first fNIRS study to find that oxygenation of the PFC, including the left lateral PFC, increases as SNR decreases. It was also the first study to assess whether semantic context affects PFC oxygenation, and indeed we found that oxygenation in the left lateral PFC is greater when listening to sentences with little to no context, as opposed to sentences rich in context. We interpret these results to mean that listening effort (i.e., the recruitment of cognitive resources to support listening) increases when listening to speech with greater background noise and less context, likely to compensate for the challenges that they impose on speech perception. These results highlight the fact that speech intelligibility alone does not offer a complete picture of one's listening experience, and that ease of processing can be influenced by linguistic factors (e.g., context) in addition to acoustic factors (e.g., SNR). They also support the utility of fNIRS to measure listening effort, and perhaps support its candidacy as a clinical tool to gain a more complete picture of patients' hearing health.

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