The relevance of the availability of visual speech cues during adaptation to noise-vocoded speech

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Abstract

Purpose: This study first aimed to establish whether viewing specific parts of the speaker's face (eyes or mouth), compared to viewing the whole face, affected adaptation to distorted - noise-vocoded - sentences. Second, this study also aimed to replicate results on processing of distorted speech from lab-based experiments in an online setup.

Method: We monitored recognition accuracy online while participants were listening to noise-vocoded sentences. We first established if participants were able to perceive and adapt to audiovisual 4-band noise-vocoded sentences when the entire moving face was visible (AV Full). Four further groups were then tested: a group in which participants viewed the moving lower part of the speaker's face (AV Mouth), only see the moving upper part of the face (AV Eyes), could not see the moving lower or upper face (AV Blocked), and a group where participants saw an image of a still face (AV Still).

Results: Participants repeated around 40% of key words correctly and adapted during the experiment but only when the moving mouth was visible. In contrast, performance was at floor level, and no adaptation took place, in conditions when the moving mouth was occluded.

Conclusions: The results show the importance of being able to observe relevant visual speech information from the speaker's mouth region, but not the eyes/upper face region, when listening and adapting to distorted sentences online. Second, the results also demonstrated that it is feasible to run speech perception and adaptation studies online, but that not all findings reported for lab studies replicate.

Key words: Adaptation, audiovisual speech, noise-vocoded speech; speech perception.

Introduction

We often interact with others in suboptimal listening situations, e.g., in a crowded cafeteria, at a busy railway station, or when interacting online over a poor audio and/or video connection. Indeed, most of us can cope with these distortions, although speech recognition performance tends to be attenuated compared to clear listening conditions. For example, listeners can adapt to distortions of the speech signal. Such perceptual adaptation can occur in a relatively short time frame: listeners can improve their response speed and accuracy after exposure to fewer than 30 distorted sentences. Such rapid adaptation has, for example, been reported for noise-vocoded speech (Davis et al., 2005; Hervais-Adelman et al., 2008) accented (Adank et al., 2010; Banks et al., 2015b, 2015a; Brown et al., 2020), and time-compressed speech (Peelle & Wingfield, 2005; Sebastián-Gallés et al., 2000).

Much of the research on rapid adaptation used noise-vocoded speech, which is an artificial distortion of the speech signal in which harmonic components are replaced with bands of noise. The distorted signal has lost much of the final spectral and harmonic detail, but amplitude modulation information is largely preserved (Shannon et al., 1995). The speech signal is first divided into separate frequency bands (generally between 4 and 32). Next, the amplitude envelope is extracted, which is subsequently used to manipulate a broadband carrier signal. This type of distortion has been used as a simulation of how speech and other sounds are transmitted in people with a cochlear implant (Faulkner et al., 2000; Rosen et al., 1999), which is an implanted device that restores hearing in those who have severe or complete hearing loss. When normal-hearing listeners are exposed to noise-vocoded speech they generally show adaptation (i.e., improvement in speech perception performance over time). It is generally more difficult to understand noise-vocoded speech with a lower number of frequency bands (4 or 6) than a higher number of bands (Dorman et al., 1997; Faulkner et al., 2000; Sohoglu et al., 2014).

Most studies on adaptation to distorted speech published to date focused on adaptation to noise-vocoded speech used auditory-only stimuli. However, being able to see as well as hear the speaker can considerably improve perception of different types of distorted speech (e.g., speech in background noise), a phenomenon referred to as the *audiovisual benefit* (Erber, 1975; MacLeod & Summerfield, 1987; Sumby & Pollack, 1954). Listeners benefit from the availability of visual cues and are thought to integrate them with auditory speech cues, which then in turn improves speech perception performance. The audiovisual benefit has also been studied for perceptual adaptation to noise-vocoded speech (Banks et al., 2020; Bernstein et al., 2013; Kawase et al., 2009; Pilling & Thomas, 2011; Wayne & Johnsrude, 2012). Pilling & Thomas (2011) and Banks et al. (2020) compared adaptation to noise-vocoded sentences with and without audiovisual speech cues. When visual speech cues were made available, listeners adapted more than for auditory-only conditions, although the audiovisual benefit was smaller and earlier in Banks et al., peaking after exposure to 75 out of 90 sentences. Similar results were reported by Bernstein et al. (3013), who report that the presence of visual speech cues leads to more adaptation to noise-vocoded syllables. Wayne & Johnsrude (2012) also investigated adaptation to noise-vocoded sentences providing audiovisual cues as feedback during a period of training and found that audiovisual feedback didn't benefit adaptation any more than clear (i.e., not noise-vocoded) feedback; however, they did not directly compare degraded audiovisual and audio-only conditions as in Pilling & Thomas (2011) and Banks et al (2020). Current evidence thus indicates that concurrent visual speech cues can thus benefit listeners during rapid adaptation to distorted speech. However, it remains unclear whether it is only visual cues from the mouth that benefit listeners, or whether cues from other parts of the face (e.g., eyes), or the whole face, are also useful in helping listeners adapt.

Several speech perception studies using eye-tracking demonstrated that listeners look more at a speaker's mouth during perception of speech in noise (Buchan et al., 2007, 2008; Lansing & McConkie, 2003) and noise-vocoded speech (Banks et al., 2020). Notably, fixations on the mouth increase for poorer signal-to-noise ratios (Vatikiotis-Bateson et al., 1998). These findings suggest that cues from a speaker's mouth are more important than other potential cues from a speaker's face – for example, movements from the eyebrows or forehead. In addition, it may also be the case that directing visual attention specifically to the speaker's mouth can benefit adaptation. Indeed, Banks et al. (2020) observed a relationship between the duration of fixations on a speaker's mouth and speech perception accuracy for noise-vocoded sentences, whereby longer fixations were related to more accurate perception, but the evidence for this relationship was relatively weak. Furthermore, when a listener directs their foveal vision towards (i.e., fixates or looks directly at) a speaker's mouth, other cues from the speaker's face are still accessible in peripheral vision and may contribute to overall improvements in speech perception. Although foveal vision provides the greatest visual acuity, (K. G. Munhall et al., 2004) have shown that high spatial frequency is unnecessary for visual speech cues to benefit perception of speech in noise. Similarly, Paré, Richler, ten Hove & Munhall (2003) demonstrated that direct fixation of a speaker's mouth is neither required nor related to the presence of a McGurk effect. Thus, the importance of specifically viewing a speaker's mouth in difficult listening conditions is still not fully clear. Listeners may benefit from viewing a speaker's face as a whole, as they can integrate multiple visual cues from a speaker's face with auditory cues. Conversely, it might be more beneficial if observers can *only* look at the speaker's mouth during adaptation to noise-vocoded speech, as their visual attention would be fully directed to the most salient visual speech cues. That is, listeners might be able to benefit more from focusing solely on the mouth if the eyes region is inaccessible to them.

A recent study tested to what extent listeners relied on information from the mouth region while listening to noise-vocoded sentences (Drijvers & Özyürek, 2017). Drijvers and Özyürek's primary aim was to establish how co-speech gestures contribute to information from visible speech to enhance noise-vocoded speech perception, but their design also included conditions in which the speaker's mouth region was obscured. They presented 20 normal hearing native speakers of Dutch with videos of a female speaker producing an action verb in a free-recall task. Specifically, there were three audio-only conditions created by blurring the speaker's mouth (clear (undegraded), 6-band noise-vocoded speech, and 2-band noise-vocoded). The design also included three speech plus visual speech conditions with clear, 6-band and 2-band degraded speech. Moreover, there were three conditions pairing clear, 6-band and 2-band degraded speech with visual speech and an iconic gesture. Finally, two visual-only control conditions were created by removing the audio in the visual and visual plus iconic gesture conditions, see Figure 1 in Drijvers and Özyürek for a visual representation of all conditions). Participants were tested in a within-group design and completed all conditions, however we will focus on the results relevant to the present study, omitting the effects of the presence of the iconic gesture. Compared to the conditions in which the mouth region was blurred, participants performed on average 10-20% better for the two vocoding conditions when full audiovisual information was available. However, as Drijvers and Özyürek did not test whether and how availability of visual speech information displayed by the mouth affected adaptation to noise-vocoded speech, this question remains unaddressed.

The current study aimed to establish to what extent the audiovisual benefit during perception of and adaptation to audiovisual noise-vocoded sentences relies on viewing visual cues from different parts of the face. Although movements from the speaker's mouth provide the greatest and most informative cues, movements in extra-oral areas (for example the upper and outer face and eye region) may also contribute to speech perception, albeit to a lesser extent, especially as not all acoustic elements of speech have equivalent mouth movements. For example, Scheinberg (1980) found that cheek puffiness could help observers identify consonants that are not discriminable based on mouth movements, while Preminger et al. (1998) found that certain consonants can be identified when viewing the upper part of the face only (i.e., with the mouth region masked). Lansing & McConkie (1999) also found that the upper face region can provide observers with information for sentence intonation. Accordingly, facial and head movements have been found to be closely related to, and predictive of, the acoustics features of speech (Munhall & Vatikiotis-Bateson, 1998; Yehia et al., 1998). Thomas & Jordan (2004) tested perception of congruent and incongruent words in noise while manipulating movements in different areas of the speaker's face (namely the mouth and outer face), while also manipulating the visibility of the mouth and eye region. They found that mouth movements were the most important for perception, but that information from extra-oral movements (from the outer face and upper eye region) also contributed to observers' perception. The present study did not aim to identify the exact extra-oral facial regions that may contribute to perception of noise-vocoded speech; nevertheless, based on the above findings, we predicted that some information may be gained by observers from our speaker's upper facial region when only this region was visible (i.e., when the mouth was obscured), compared to when the upper eye region was not visible (Hypothesis 3).

We tested our three hypotheses using five conditions in an experiment in which we tested perception of 4-band audiovisual noise-vocoded sentences also used in Banks et al. (2020) for five groups of participants in a between-group design. In condition AV Full, participants who were exposed to audiovisual stimuli with the whole face of the speaker visible. The next three conditions were included to establish the relative relevance of different parts of the face for adaptation to and perception of audiovisual noise-vocoded sentences, so we tested a group of participants who could not see the eye region, (AV Mouth) but who could see the mouth region, and a group had access to the eye region, but not the mouth region (AV Eyes). Another group of participants was exposed to a video of the speaker with the mouth and eyes obscured from view (AV Blocked), and a final group was shown a still image of the speaker while being tested (AV Still), so it contained no useful visual cues at all, per Banks et al. (2020).

We predicted a main effect of condition and a two-way interaction between condition and trial which would indicate differences in perception and adaptation between conditions. Specifically, hypothesis 1 is supported if conditions where the mouth is visible (AV Full and AV Mouth) show better perception and greater adaptation than conditions where the mouth is not visible (AV Eyes, AV Blocked and AV Still). Support for hypothesis 2 would require significant differences between the AV Full and AV Mouth conditions, with better perception and greater adaptation in the AV Mouth condition. Hypothesis 3 would be supported if we find significantly better perception and adaptation in the AV Eyes condition (i.e., when only the eye region was visible), than in the AV Still, and AV Blocked conditions (when the eye region was not visible).

In addition, we aimed to replicate the behavioural results reported in Banks et al. (2020) in an online experimental paradigm to demonstrate that participants were able to adapt outside the lab. Finally, we also asked participants to give us an indication of their perceived effort as different circumstances in which people process distorted speech have been shown to affect performance in similar ways yet be associated with different levels of perceived effort (McGarrigle et al., 2014, 2017; Pichora-Fuller et al., 2016). Finally, to ensure participants attended to the speaker's face, we queried them afterwards about how much attention they paid to the speaker's face and how much they thought being able to see the speaker's face helped them during the task.

Method

Participants

We tested 150 participants (18-30 years of age (Y), 125F and 25M), who all declared to be native monolingual speakers of British English and be resident in the UK at the time of the experiment. All declared to have good hearing and vision, and to not have any neurological or psychiatric disorders (including dyslexia). All participants were recruited through the online platform Prolific.co, and the experiment was hosted on Gorilla.sc. We tested 30 participants per condition. Participants were randomly allocated to each condition and were restricted from participating to more than one condition/group in the experiment. Our minimal sample size, per group as well as the ratio of female and male participants was based on Banks et al. (2020), and we tested 30 participants with a ratio of 25F:5M participants (see the Analysis section for further justification of the selected sample size). We replaced one male participant in condition AV Blocked and one male participant in condition Eyes, both for not engaging with the task (i.e., not giving a single response). The demographics were as follows across the five conditions: AV Full 25F|5M, mean 24.6Y, standard deviation (SD) 3.8SY, AV Mouth 25F|5M, mean 23.9Y, SD 3.6Y, AV Blocked 25F|5M, mean 22.8Y, SD 3.2Y, AV Still 25F|5M, mean 24.5Y, SD 3.8Y, AV Eyes 25F|5M, mean 24.3Y, SD 4.0Y. Participants and the speaker all consented to take part and were paid upon completion of the experiment at a rate corresponding to

£7.50 per hour (participants). The speaker consented to having her image published and was not paid. The experiment was approved by UCL's Research Ethics Committee (UREC, #0599.001).

Materials

We used the same materials as in Banks et al. (2020) and adapted them to create the stimuli for the specific conditions in the present study. Banks et al. originally used 91 randomly selected Institute of Electrical and Electronics Engineers Harvard sentences (IEEE, 1969). Stimuli were recorded in a soundproofed laboratory using a Shure SM58 microphone and a High-Definition Canon HV30 camera. A 26-year-old female native British English speaker recited the sentences, and was asked to look directly at the camera, to remain still and to maintain a neutral facial expression throughout the recordings to minimise head movement (see Figure 1). Video recordings were subsequently imported into iMovie 11, running on an Apple MacBook Pro, as large (960 x 540) high-definition digital video (.dv) files. Video recordings were then edited to create a video clip per sentence. The audio tracks for each clip were extracted as audio (.wav) files, then normalised by equating the root mean square amplitude. Next, they were resampled at 22kHz in stereo, cropped at the nearest zero crossings at voice onset and offset, and vocoded using Praat speech processing software (Boersma & Weenink, 2012) and custom scripts. Speech recordings were noise-vocoded (Shannon et al., 1995) using four frequency bands (cut-offs: 50Hz → 369Hz → 1160Hz → 3124Hz → 8000Hz), selected to represent equal spacing along the basilar membrane (Greenwood, 1990). Of the 91 sentences that were originally recorded, we randomly selected a subset of 60 for inclusion in the online experiment. To ensure that timing of the audio and video was synchronous, we attached the noise-vocoded audio stimuli as an audio track to the video stimuli using Final Cut Pro as a mono track to be played over both channels of a participant's headphones. We repeated the same procedure for an additional single sentence in quiet, to be used in the practice trial presented prior to the main experiment. Audiovisual stimuli were saved as MPeg-4 movie (MP4) files with a resolution of 1920x1080. We also created white rectangular shapes that were used to cover (parts of) the speaker's face in four conditions. The rectangle used to cover the eyes or the mouth in the conditions AV Mouth, AV Eyes, and AV Blocked was a width of 1920 pixels and a height of 720 pixels and a resolution of 300 pixels per inch. For the condition AV Still, we used a screenshot of the speaker’s face in PNG format with a width of 1907 pixels and a height of 1074 pixels and a resolution of 300 pixels per inch.

Procedure

The experiment was conducted online, via the Gorilla Experiment Builder (Gorilla.sc) (Anwyl-Irvine et al., 2020) and participants were recruited via Prolific (Prolific.co). Upon receiving an email invitation via Prolific, participants entered the online study and were linked through to the experiment hosted in Gorilla. They were then given information on the study, before providing consent. Participants who did not provide consent were rejected from the study. Next, they were asked to enable auto play of video and audio on their internet browser, maximise their screen, and plug in their headphones (Bluetooth headphones were excluded per participant report). The mean display resolution across participants was (SD = 234) * 856 (SD = 125), and the mean resolution of the experiment display (viewport) was 1466 (SD = 226) * 770 (SD = 123). They were subsequently routed to a page where they could check their sound levels where they were played a short sound consisting of one second of white noise. They were asked to replay this sound over their headphones and adjust their volume to a comfortable level before progressing to the headphone check.

The next check was previously developed to allow for more control over sound presentation in online experiments by providing a test to establish whether participants are wearing headphones (Woods et al., 2017). This test was designed to be difficult to complete if the participant is not wearing headphones, through the manipulation of anti-phase attenuation rather than differences in intensity between the tones. The headphone check is designed as a 3AFC task in which six sets of three sine wave tone stimuli are played. After participants clicked at the start button, a new page appeared where three 200Hz tones were played with a duration of 1000ms, with 100ms on- and off-ramps, two at -14dB (in-phase) and one at -20dB (180° out of phase). The stimulus duration per triad of tones was four seconds (tone duration: 900ms, interstimulus interval: 600ms, time before first stimulus onset: 100ms, time after the last stimulus offset: 100ms). Participants listened to six trials in total. The participants were to decide which tone they perceived as having the lowest intensity by selecting one of three buttons labelled “FIRST sound is SOFTEST”, “SECOND sound is SOFTEST”, and “THIRD sound is SOFTEST”. They had to select the correct stimulus for five of the six trials (accuracy level of 83.3%), or they were rejected from the study.

Participants who successfully completed the headphone check were subsequently routed through to the instructions and a single undistorted and visually unobstructed practice sentence. For the conditions AV Full, AV Mouth, AV Eyes, and AV Blocked, all groups saw the same MP4 video and heard the corresponding undistorted sentence. For the condition AV Still, participants were presented with the same still PNG image as used in the main experiment. Participants were asked attend to the video and spoken sentence and to type into a response text box any words they thought they had heard. After the single practice trial, they were shown a screen explaining what they should have typed in the response box. Subsequently, they were told that the main experiment would start next and that all trials would progress to the next trial automatically, so they would not be able to take a break until the main task finished.

In the main task, participants transcribed 60 noise-vocoded sentences. Participants triggered the start of the experiment and each subsequent trial by pressing the “Next” Button at the bottom of each screen. In each trial, the audiovisual noise-vocoded sentence and corresponding visual stimulus was presented. The noise-vocoded sentence was played only once per trial. The visual part of this stimulus was different for the five conditions (see Figure 1). Participants in the Full condition saw the unobstructed video. Participants in the AV Mouth and AV Eyes conditions were shown the video with a white rectangle covering the eyes or mouth of the speaker, respectively. As can be seen in Figure 1, the block covered either the upper or lower part of the face. The tip of the nose and chin were mostly visible in the AV Eyes and AV Mouth videos, but sometimes not visible due to the speaker moving while speaking. Participants in the AV Blocked condition were shown the video with a white block covering the mouth, nose, and eyes of the speaker Here, the chin and forehead of the speaker were visible, but the space in between was covered, so that only small head movements were visible.

Finally, participants in the AV Still condition were shown a still image of the speaker, where the entire face vas visible, but no movement.

After the main task, the programme moved to a final response screen, where participants typed in their response. They were asked to type in "/" if they could not decipher any words in the sentence. After finishing typing, they could move to the next stimulus by pressing the "Next" button. If they did not press this button, the experiment moved to the next trial automatically after 23 seconds. After the main task was completed, participants were shown a screen with three response sliders and a response text box. Participants were asked to provide ratings of their perceived effort as follows: "*Question 1: Please indicate using the slider below how effortful you found it to understand the sentences (0 = Not effortful, 100 very effortful):*". They were also asked to rate what proportion of the time the video was presented they looked at the speaker's face as follows: "*Question 2: Please indicate using the slider below what proportion of the time you spent looking at the speaker's face when the video was presented (0% of the time - 100% of the time):*". A final question queried whether being able to see the speaker's face helped their speech performance: "*Question 3: How much do you think looking at the speaker's face helped you understand the sentences? (0 Not at all - 100 Very much):*". At the bottom of the page was a response box where they were invited to type in any comments. After they clicked next, they were returned to Prolific for payment.

All data were collected in a single session lasting approximately 20 minutes. However, as the experiment was in part self-paced, durations differed across participants, although the main transcription part of the study lasted maximally 30min if participants did not manually progress each trial. A single participant (in the condition AV Blocked) took 30min for the main task, but as their responses were within the ranges specified for accuracy in their group, we included their data in the final analysis. Average durations for the entire session was 21min and 4s across all 150 participants (SD 7min and 14s). The session timed out automatically after 90 minutes. The average duration for the main transcription part of the session task was 12min and 30s (SD 3min and 18s) and as follows for individual conditions: AV Full 13min and 18s (SD 4min and 19s), AV Mouth 13mins and 27s (SD

2min and 18s), AV Blocked 13min and 31s (SD 2min and 18s), AV Still 10min and 28s (SD 3min and 19s), and AV Eyes took 13 minutes and 31 seconds (SD 2 minutes and 18 seconds). Data from all participants in the Condition AV full was collected first, followed by the AV Mouth condition, the AV Blocked condition, the AV Still condition, and the AV Eyes condition. Online testing took place in May-June 2020.

---Include Figure 1 about here ---

Design and Analysis

The experiment measured speech perception performance as the by-trial percentage of words accurately entered as the dependent variable. The independent variables were Trial and Condition. Trial was the stimulus number ranging from 1-60. The use of trial as an index of exposure contrasts with the proposed analysis in the pre-registration. Upon reflection, we opted to use trial as it would give a more fine-grained and accurate analysis of adaptation patterns. To support this choice we calculated the BF_{10} for models utilising blocks and trials for both the AV Full (Blocks BF_{10} =8.659 x 10^{+16}, Trials BF_{10} = 4.256 x 10^{+20}) and all conditions (Blocks BF_{10} = 2.515 x 10^{+30}, Trials BF_{10} = 1.112 x 10^{+36}) analysis, both of which supported the by-trials analysis. As such, we will hitherto present the by-trials analyses. The pre-registered by-blocks analysis is presented in the supplementary materials (https://osf.io/2w6j4/). The factor Condition had five levels: AV Full, AV Mouth, AV Eyes, AV Blocked, AV Still to test our three hypotheses outlined in the introduction. Hypothesis 1 predicted that being able to see the moving mouth improves adaptation and perception compared to when it is not visible. Hypothesis 2 predicted that having to focus on the mouth region (i.e., when only the mouth region is visible) improves adaptation and perception compared to when the full face is visible. Hypothesis 3 predicted that being able to see only the eye region improves perception and adaptation compared to when it is not visible. The AV Mouth condition was included to establish to what extent forcing participants to focus on the speaker's mouth affects perception of and adaptation to noise-vocoded sentences. The AV Eyes condition was included to test if and how being able to see only the eye region supports perception of and adaptation to noise-vocoded speech. The AV Blocked condition was included to determine if and how removing information conveyed by the speaker's mouth and eyes affected perception/adaptation. The AV Still condition was included to test if the presence of moving visual information affected perception/adaptation and to test if results for this condition show the same effects as reported in Banks et al. (2020), who included this condition as a control. If Hypothesis 1 is correct, then participants in condition AV mouth and AV Full should show better speech perception performance and greater adaptation, than participants in conditions AV Blocked, AV Eyes, and AV Still. If Hypothesis 2 is correct, then participants in condition AV Mouth should show better perception/adaptation, than participants in condition AV Full. Finally, if Hypothesis 3 is correct, then participants in condition AV Eyes should show better perception/adaptation than participants in conditions AV Blocked and AV Still.

We retrospectively scored participants' responses according to how many key words (content or function words) they correctly repeated out of a maximum of four following Banks et al. (2020). Banks et al. chose four keywords as the sentences they were all of varying duration, and therefore using four keywords made perception accuracy comparable across all sentences. We included/excluded (typed) responses as follows. Responses were scored as correct despite incorrect suffixes (such as -s, -ed, -ing) or verb endings; however, if only part of a word (including compound words) was repeated, this response was scored as incorrect following Banks et al. (2015, 2020). It should be noted that Banks et al. audio-recorded participants' verbal responses, and these responses were subsequently judged by an experimenter. In contrast, as we asked participants to type in their responses, we also included homonyms (e.g., "weak" instead of "week"), compound words separated by a space (e.g., "door knob" instead of "doorknob", as well obvious typos (e.g., "whire" instead of "wire"). Moreover, we excluded participants as follows: participants who had an average % error rate greater than three standard deviations (3SD) away from the group mean were excluded from further analysis and replaced. Participants were excluded if they failed to provide responses to a number of trials >2SD from the group mean.

As condition AV Full was intended to closely replicate the design of the audiovisual condition in Banks et al. (2020), we initially decided to collect 30 participants as a minimum sample and then used sequential hypothesis testing with Bayes Factors to determine our final sample size (Schönbrodt et al., 2017). After collecting the initial 30 participants, we calculated BF_{10} to assess whether we reached a pre-defined level of evidence ($BF_{10} > 3$ in favour of the alternative hypothesis, and $BF_{10} < 0.2$ in favour of the null hypotheses). BF_{10} indicates how likely the data are to occur under the alternative hypothesis. If $BF_{10} > 0.2$ and < 3.0, we aimed to collect additional participants. After collecting an additional participant for each group, we would calculate BF_{10} until we met the conditions noted above. In the case more participants were required, we planned to minimise the risk of type 1 and type 2 errors by graphing BF_{10} after running each additional participant to assess whether any changes in the BF were stable. When the BF was stable for four consecutive participants, we planned to cease data collection. However, the BF_{10} exceeded the criterion value of 3.0 after collecting 30 participants for each condition. As such, additional data collection was not necessary.

To calculate BF_{10}, we utilised Bayes Information Criterion (BIC) values obtained during model comparison of linear mixed effects (LME). The *step* function of *lmerTest* utilises a backward model-selection strategy to find the best fitting model. *Step* takes as input an *lmer* model. First, the random effects structure is subjected to backwards elimination, where random effects are either reduced or removed utilising log-likelihood tests. Random effects are removed from the model where it significantly improves model fit ($p < .05$). Next, this procedure is repeated for main effects, however, in this stage χ^2 tests of model fit are used after the removal of each model term, starting with the most complex interactions. Next, we performed a hierarchical comparison of the best fitting model (H1, e.g. accuracy ~ (1|participant) + trial) with a model excluding the effect of interest (H0, e.g. accuracy ~ (1|participant)) using the *anova* function to obtain BIC values for each. We used the difference in BIC to compute the Bayes Factor (BF_{10}) using the following equation (Jarosz & Wiley, 2014):

$$BF_{01} = e^{\Delta BIC/2}$$

$$BF_{01} = e^{BICH0-BICH1/2}$$

$$BF_{10} = 1/BF_{01}$$

We initially collected and analysed the data from condition AV Full only, as all hypotheses relied on whether it is possible to measure perceptual adaptation to distorted speech in an online paradigm. In this first stage, we tested whether accuracy increases over the course of the experiment, as measured over the course of the 60 trials. In this case, the H1 BIC value corresponded to a model predicting accuracy including main effect of trial, whilst H0 BIC was for a model only including random by-participants and by-items slopes. In the second stage, we analysed data for all five conditions and tested main effects of trial (as a linear and polynomial) and condition, and their interaction using LMEs as described above. The H1 BIC therefore modelled the critical two-way interaction between trial (see section 3.1.2) and condition, while the H0 BIC included the main effects only.

We also analysed the data collected in the questionnaire presented to participants in the online study after the main task. However, as this dataset was comprised of only one observation per question per participant, we utilised simple linear models to analyse the effort questionnaire data.

The design of conditions AV Full, AV Mouth, and AV Blocked was preregistered on www.AsPredicted.org under number #41527 *"Transcribing distorted audiovisual speech."* The inclusion and design of conditions AV Still and AV Eyes was preregistered on www.AsPredicted.org under number #42910 *"Transcribing distorted audiovisual speech, a follow-up study."* In all analyses we discuss results for the five conditions in the order they were collected. All raw data plus analysis scripts can be found on the Open Science Framework: https://osf.io/2w6j4/.

Results

Accuracy

For 12 trials (0.13%), stimulus materials could not be loaded by Gorilla across all 150 participants. In seven cases for the Full condition, two for the Mouth condition, two for the Eyes condition, the video mp4 file could not be loaded (which occurred to a different sentence every time and seemed to be due to a random occurrence or glitch in Gorilla). In a single case for the Still condition, the audio file could not be loaded. These 12 cases were therefore removed from the data set.

Accuracy: AV Full

Participants in the AV Full condition reported a mean of 1.7 (SD = 1.4) key words correct across the 60 sentences. We first examined the effect Trial to test our hypothesis that participants could adapt to noise-vocoded sentences. In this analysis, inclusion of the by-participants (p = .296) and by-items (p = .767) slopes did not significantly improve model fit. The best fitting model therefore included only by-participants and by-items random intercepts, and the main effect of trial (see Table I in the supplementary materials). In this case, the alternative hypothesis states that participant performance would increase over trials. Therefore, we compared the best fitting model (BIC = 17197) against a model including only the random effects (BIC = 17275). BF_{10} was > 150, indicating that the evidence in favour of the alterative hypothesis – that adaptation will occur across trials – was very strong (Raftery, 1995). The model outcomes for the linear effect of trial was significant (t = 10.387, p < .0001), indicating that participants in the AV Full condition adapted to the masked speech over trials. Whilst the quadratic effect of trial also reached significance (t = -2.329, p = .02), the smaller t- and p-values indicate that the effect of trial was better modelled as a linear effect. This effect is illustrated in Figure 2 below - generated using the *effects* package (Fox et al., 2019) to extract model estimates at five moments of the distribution for the linear function - which displays the model estimates of performance by Trial. To conclude, participants showed an increase in performance across the trials for the AV Full condition. Following these results, we decided to collect and analyse data for the four follow-up conditions.

--- Include Figure 2 about here ---

Accuracy for all five conditions

Mean accuracy was 43.069 (SD = 36.03) in the AV Full condition, 43.806 (SD = 36.13) in the AV Mouth condition, 5.486 (SD =13.625) in the AV Eyes condition, 5.333 (SD = 14.122) in the AV Blocked condition, and 3.861 (SD = 11.323) in the AV still condition. Figure 3 displays a locally estimated smoothed scatterplot (LOESS) of accuracy over the 60 trials. The LOESS function from *ggplot2* (Wickham, 2016) fits simple linear models to local subsets of the data to describe its variance, point by point. Taken together, the descriptive statistics suggest that performance was almost identical when participants were able to see the speaker's mouth movements (i.e., in the AV Full and AV Mouth conditions).

--- *Include Figure 3 about here* ---

To analyse all five conditions, we followed the same procedure as the analysis for the AV Full condition, while including testing condition (factor-coded) as an additional main effect, and the two-way interaction between condition and trial. The maximal model upon which we conducted the backwards stepwise model comparison therefore included by-item and by-participant random intercepts, a random intercept for participant nested within condition, the main effects of trial and condition, and the two-way interactions between trial and condition. Random slopes were excluded from the analysis, as their inclusion resulted in issues of singular model fit. The backwards stepwise model selection indicated that the inclusion of the main effect of block (*p* = .183), the interaction between block and condition (*p* = .766) and the simple by-participants random effect did not improve model fit (*p* = 1). As a result, the final model included a by-items random intercept, a random-intercept for participant nested within condition, the main effects of trial and condition, and the two-way interaction between condition and trial (see supplementary Table II for full model syntax and model summary). The analysis including the effect of block can also be found in the supplementary materials on the Open Science Framework: https://osf.io/2w6j4/.

To assess the likelihood of the alternative hypothesis – that different conditions would elicit different levels of adaptation – we compared a model including the interaction (H_1, BIC = 80876) against a null model only including the main effects (H_0, BIC = 80976). BF10 was therefore 5.185 x 10^{+21}, vastly exceeding Raftery's (1995) threshold for strong evidence (> 150) in favour of the alternative hypothesis. This reflects the floor performance seen in the AV Blocked, AV Eyes, and AV Still conditions relative to the AV Full, and AV Mouth conditions.

The outcomes of the linear model indicated that perception differed between conditions. Here, perception is reflected by the main effect of condition; the model tests whether mean performance differed significantly from zero. The results indicated that accuracy in AV Full (t = 18.739, p < .0001), AV Mouth (t = 20.077, p < .0001), AV Blocked (t = 2.444, p = .015), and the AV Eyes (t = 2.514, p = .012) conditions differed from zero. In contrast, accuracy did not differ from zero in the AV Still condition (t = 1.77, p = .078). Critically, performance did not significantly differ between the AV Full and AV Mouth conditions (t = 0.289, p = .77), indicating similar levels of accuracy. Both the AV Full (t = - 14.737, p < .0001) and AV Mouth (t = -15.026, p < .0001) conditions differed significantly from the AV Eyes condition, and both differed significantly from the AV Blocked and AV Still conditions (all t-values > 2, all p-values < .05). The AV Blocked, AV Still and AV Eyes conditions failed to differ from one another (all t-values < 2, all p-values > .05), indicating similar performance at floor in these conditions.

Adaptation is measured by the two-way interaction between trial and condition. The interaction term was significant for the AV Full (t = 12.659, p < .0001), AV Mouth (t = 12.657, p < .0001), and AV Eyes conditions (t = 2.092, p = .037). However, participants in the AV Blocked (t = 0.876, p = .381), and AV Still (t = 0.664, p = .507) conditions did not show adaptation with increased exposure. The two-way interaction between trial and condition did not differ significantly between the AV Full and AV Mouth conditions (t = -0.008, p = .994), indicating similar adaptation in these conditions. Both AV Full and AV Mouth differed significantly from the AV Blocked and AV Still conditions (all t-values > 2, all p-values < .05). Adaptation in the AV Block, AV Still and AV Eyes conditions did not significantly differ (all t-values < 2, all p-values > .05). This suggests that while a small amount of adaptation did occur in the AV Eyes condition, it remained indistinguishable from AV Blocked and AV Still conditions, suggesting the adaptation was minimal. For each condition, the data was better described by a linear function of trial (see figure 4 below). Two of the quadratic estimates (between trials 0 to 20, and 50 to 60) for the AV Mouth condition differ from the linear estimates, suggesting that the largest increase in performance occurred in the first twenty trials, and tailed off slightly in the last ten trials. However, the model estimates demonstrate the fit was better for the linear (*t* = 12.657, *p* < .0001) relative to the quadratic (*t* = -5.104, *p* < .0001) term. This demonstrates that adaptation largely proceeded linearly across trials, with only minor deviations from this trend over training.

--- Include Figure 4 about here ---

In summary, participants in the AV Full and AV Mouth condition showed increased speech perception performance and demonstrated adaptation (i.e., better accuracy for later trials). In contrast, when participants were unable to see the speaker's mouth (AV Block, AV Still, AV Eyes) speech perception was impaired, and participants were unable to adapt to the vocoded speech. Whilst participants in the AV Eyes condition showed adaptation, it was significantly smaller than that seen in the AV Full and AV Mouth conditions, and failed to significantly differ from AV Blocked and AV Still conditions, indicating that the effect was minimal. In comparison to the AV Mouth condition, in the AV Full condition, participants were able to see the speaker's eyes and upper face/head. As perception and adaptation did not differ statistically between these conditions, the results suggest that focusing specifically on the speaker's mouth does not benefit perception or adaptation any more than being able to see the speaker's full face. Taken together, the results support Hypothesis 1 - being able to see the moving mouth improves adaptation and perception - as adaptation and perception did not differ in conditions where participants were able to see the speaker's moving mouth. Hypothesis 2 - that having to focus on the mouth region improves adaptation and perception - did not receive support, however, as participant performance in the AV Mouth and AV Full conditions did not differ, despite being able to see the eyes in the latter. Hypothesis 3 - being able to see the speaker's eyes while the moving mouth is not visible improves adaptation and perception - was also not supported; there were no statistical differences in adaptation or perception between the AV Eyes, AV Still, or AV Blocked conditions.

Effort questionnaire

Ratings from two participants in the AV Mouth condition, and from one in the AV Blocked condition were removed as they were >3SD separated from the average for that respective condition. Participants in the condition AV Full provided on average an effort score of 91.2% (SD = 9.7%) and estimated that they had looked at the speaker's face 91.7% (SD = 14%) of the time, and 65% (SD = 28.7%) stated that being able to see the speaker's face helped speech perception**.** Participants in the condition AV Mouth provided on average an effort score of 85.6% (SD = 10.3%), rated they looked at the face 94.6% (SD = 8.8%) of the time, and 61.3% (SD = 31.9%) stated that seeing the speaker's face helped speech perception. Participants in the condition AV Blocked gave an average effort score of 97.2% (SD = 11.2%), rated they looked at the face 66.2% (SD = 28.8%) of the time, and 17.2% (SD = 22.2%) stated that seeing the speaker's face helped speech perception. Participants in the condition AV Still gave an average effort score of 98.8% (SD = 4.2%), rated they looked at the face 41.9% (SD = 30.6%) of the time and 2.1% (SD = 4.7%) stated that seeing the speaker's face helped speech perception**.** Participants in the condition AV Eyes gave an average effort score of 97.9% (SD = 5.1%), rated they looked at the face 69.4% (SD = 26.3%) of the time and 26.1% (SD = 22.7%) stated that seeing the speaker's face helped speech perception.

Three separate models were conducted of the dependent variables Effort (perceived effort score), Face (estimated proportion of time spent looking at the face), and Face (estimation of how much being able to see the face was helpful) with condition (AV Full, AV Mouth, AV Blocked, AV Still, AV Eyes) as a factor. In each case, AV Full was taken as the reference level for the condition factor. The Effort model revealed that participants reported significantly lower effort in the AV Mouth compared to the AV Full condition (t = -2.490, p = .014), whilst the AV Blocked (t = 2.716, p = .007), AV Eyes (t = 3.481, p = .003) and AV Still (t = 3.481, p = .0007) conditions reported significantly higher effort, suggesting that participants found the AV Mouth condition the least effortful (see figure 4). The Face model indicated that participants spent a similar amount of time looking at the speaker's face in the AV Full and AV Mouth conditions (t = 0.471, p = .638), however participants in the AV Blocked (t = -4.159, p < .0001), AV Eyes (t = -3.679, p = .0003), and AV Still (t = -7.941, p < .0001) conditions spent significantly less time looking at the face. The Face Helped model suggested that participants in the AV Full and AV Mouth condition found a similar benefit from seeing the face (t = -0.561, p = .575), while participants found the face helped significantly less in the AV Blocked (t = -7.678, p < .0001), AV Eyes (t = -6.292, p < .0001) and AV Still conditions (t = -10.211, p < .0001).

Overall, the participant ratings on these three factors align well with the experimental results; participants who could see the speaker's mouth reported lower required effort. Participants reported lower effort for the AV Mouth relative to the AV Full condition. This pattern offers some degree of support for Hypothesis 2 (being forced to focus on the speaker's mouth should improve perception and adaptation); removing the information provided by the eyes in the AV Mouth condition was associated with reduced perceived effort. This effect was not reflected in the accuracy data. When participants could not see the speaker's mouth, effort was increased. Participants who were able to see the speaker's mouth (AV Full, AV Mouth) reported the highest benefit from being able to see the face, and that seeing the face assisted, in contrast to participants who could not (AV Block, AV Eyes, AV Still). As a result, it appeared that in this online testing environment, being able to see the speaker's moving mouth improved both objective (adaptation and perception) and subjective measures of performance (perceived effort).

--- Include Figure 5 about here ---

Discussion

This study aimed to establish if viewing the mouth or eyes (i.e. the upper or lower part) of the speaker's face affected perception of and adaptation to noise-vocoded sentences when compared to viewing their whole face. We ran an online experiment with five listener groups, who could either see the full moving face of the speaker (AV Full), see the moving face with the eyes blocked (AV Mouth), see the moving face with the mouth blocked (AV Eyes), see the face with the eyes and mouth blocked (AV Blocked), or were presented with a still image of the speaker's face (AV Still). We tested three hypotheses: Hypothesis 1 predicted that being able to see the moving mouth improves adaptation and perception, Hypothesis 2 predicted that having to focus on the mouth region improves adaptation and perception, and Hypothesis 3 predicted that being able to see only the eye region would improve perception and adaptation compared to when the eye region was not visible. All groups transcribed 60 4-band noise-vocoded sentences. The results showed clear differences between the five conditions, with participants in the conditions AV Full and AV Mouth showing considerably better overall accuracy scores than the participants in the other three groups, where performance was effectively at floor level. There was no difference in overall accuracy between conditions AV Full and AV Mouth, and no differences were found between AV Eyes, AV Block, and AV Still. Second, the results showed an interaction between condition and trial, indicating that participants in the conditions AV Full and AV mouth improved their accuracy scores over the course of the experiment, while no such pattern was found for the other three conditions. Therefore, perceptual adaptation to noise-vocoded speech was only found when the moving mouth area of the speaker's face was visible.

AV Full and AV Still conditions

The results for the AV Full condition in part replicate the results from the audiovisual condition in Banks et al. (2020) as participants adapted to the noise-vocoded sentences over the four blocks. However, participants performed overall worse than in Banks et al.'s audiovisual condition, as our participants showed an average overall accuracy of 43% correct, and accuracy improved from 33.7% to 50% when comparing how performance improved over the 60 sentences when split into four blocks of 15 sentences, in analogy with Banks et al. Participants in Banks et al.'s audiovisual condition repeated an average of 54% of key words correctly, and this accuracy percentage improved from 42% to 61% over their six testing blocks (participants improved between 42% to 59% over the first four blocks, i.e., over the first 60 sentences). In contrast, the results for the condition AV Still, which replicates the audio-only condition in Banks et al., show a very different picture. Banks et al. report an average performance of 35% of key words correctly repeated, with performance increasing from 24% to 43% over their six blocks (participants improved to 37% over the first four blocks, i.e., over the first 60 sentences). We found that average performance was 4% for our AV Still condition on average, with performance remaining largely stable. Therefore, while we mostly replicated the (patterns in) the results for the AV Full condition, such replication was clearly not found for the AV Still condition. Furthermore, baseline and overall accuracy was lower in the AV Full condition in the present study compared to the audiovisual condition in Banks et al.

It is not clear what factors can account for the differences in results between our and Banks et al.'s results for the AV Full and AV Still conditions. It seems plausible that this difference might be accounted for by differences across both studies, the most prominent of which is the difference in testing platform. Banks et al. tested their participants in a sound-proofed, light-controlled lab, and participants were tested using the same stimulus delivery parameters (e.g., headphones, intensity and sound card, screen size and resolution) and in the absence of any other distractions. In contrast, participants in the current study were tested online. They all wore headphones, but these headphones varied in quality, and by our estimation only a very small number (two out of 150 participants) of headphones listed by our participants could match the audio quality delivered by the headphones used in Banks et al. (Sennheiser HD 25-SP II). In Banks et al. participants were tested in a more controlled environment in terms of focusing their attention on the task, while in our experiment, we could not control their testing environment and whether they were refraining from engaging in other distractions (e.g., looking at their phone). Also, Banks et al. recorded participants' eye gaze using eye-tracking while participants adapted and could therefore closely monitor whether and where participants looked at the speaker while listening to the audiovisual sentences.

As participants were tested in their own environment and eye gaze was not monitored, we cannot be certain that participants attention was focused on the task alone or that they always looked at the video in the audiovisual conditions. However, all participants were asked in a final questionnaire whether and how much they looked at the speaker's face after the main task ended. On average, participants in the condition AV Full estimated that they had looked at the speaker's face 91.7% of the time and 65% stated that being able to see the speaker's face helped speech perception. For the condition AV Still, participants on average looked at the face 98.8% (even though it displayed no movement) of the time even though only 2% stated that being able to see the speaker's face helped speech perception. Second, we presented participants with 30 fewer stimuli than Banks et al., who exposed them to 90 sentences in total. However, it does to seem likely that this issue can explain the observed difference in the results for the AV Full and AV Still conditions, as baseline accuracy between the two studies was vastly different. A final reason might be due to differences in participant sample, particularly given that participants in Banks et al were recruited from a University (and were therefore mostly undergraduate students), whereas the sample in the present study was drawn from the general population, or as far as participants on Prolific represent this population. However, as we included two conditions where both the mouth and eyes were blocked (and participants could only take part in one condition/group), using slightly different visual stimuli, i.e., a still image compared to the video of the speaker with eyes and mouth obscured, both of which had similarly poor overall accuracy, this explanation also seems unlikely. It is thus plausible that differences between our results for condition AV Full and AV Still and Banks et al.’s were mostly related to the differences in testing conditions: online versus lab-based.

AV Mouth, Eyes, and Block conditions

We included the AV Mouth, Eyes, and Blocked conditions to test the three hypotheses of this study. Hypothesis 1 stated that being able to see the moving mouth region (AV Full and AV Mouth) will show better speech perception performance, and greater adaptation, than when the mouth region is not visible (AV Eyes, AV Still and AV Blocked). AV Mouth was also included to test whether participants would perform better and adapt more if their attention was focused on the mouth region per Hypothesis 2. The condition AV Eyes and AV Blocked were included to establish whether information from the eyes was useful per hypothesis 3. The results from AV Mouth, in which participants could see the mouth moving but the eyes were blocked, were nearly identical to those reported for the AV Full condition, and therefore also replicate in part the results for the audiovisual condition in Banks et al. Better speech perception performance in AV Full and AV Mouth compared to the other three conditions (AV Eyes, AV Still and AV Blocked), and an interaction between condition and trial, confirm Hypothesis 1. Next, we predicted that participants in the AV Mouth condition might show better overall speech perception performance, and greater adaptation than the AV Full condition, as their attention would be focused specifically on the speaker's articulatory mouth movements. This prediction was not supported by speech accuracy results, as performance did not differ between the AV Mouth and the AV Full group, and there was also no difference in the rate and amount of perceptual adaptation. Thus, the results refute Hypothesis 2 with respect to objective task performance. However, we found that being able to see the speaker's moving mouth without the eyes improved a subjective measure of performance (perceived effort) compared to the AV Full condition. Banks et al (2020) found a relationship between longer fixations on a speaker's mouth and better perception of noise-vocoded speech, although evidence for this was weak. However, as we did not specifically account for subjective performance when we designed the experiment (and it was not included in the preregistration), the present results do not confirm Hypothesis 2. Yet, we are planning to explore the subjective performance differences between distortion conditions further in future online studies. Nevertheless, we cannot exclude the possibility that in the AV full and the AV mouth conditions participants focused only on the mouth region, and that this is the reason for the similar performance in the two conditions. Future studies could elucidate this issue by combining online perceptual adaptation to noise-vocoded speech with eye-tracking using the participant's webcam. A recent study has shown that it is feasible to collect eye gaze data online and establish whether participants look more at the mouth or the eyes of a moving face (Semmelmann & Weigelt, 2018). Using a setup similar to the one used in Semmelman & Weigelt could further clarify whether participants looked at the mouth equally in the conditions tested in the present study.

Finally, it can be concluded that not being able to see the speaker's eyes and the upper part of the speaker's face, did not benefit speech perception or adaptation as we predicted for Hypothesis 3. It was found to be unhelpful for participants to be only able to see the speaker's eyes and upper face during perception of noise-vocoded audiovisual speech, i.e., any movements from the speaker's eye region offered no benefit to perception of the noise-vocoded speech. Furthermore, overall accuracy and adaptation were almost identical in the AV Full and AV mouth conditions, indicating that viewing the speaker's entire face offered no additional benefits over and above viewing only their mouth. Thus, our results do not support Hypothesis 3 that information from the speaker's eye region may contribute to perception of degraded speech.

The results for the conditions AV Eyes and AV Blocked mirrored those for AV Still. For all three conditions a floor effect was found, with participants on average reporting 4.9% of key words correctly. In addition, participants did not improve their performance over the course of the experiment, although there was a small improvement over trials in the AV Eyes condition. These results were unexpected as they do not replicate findings reported by other studies using noise-vocoded sentences. The majority of studies examining adaptation to noise-vocoded speech were conducted using audio-only stimuli, yet still manage to find evidence that participants adapt after short-term exposure to a low number of sentences or words (Davis et al., 2005; Huyck & Johnsrude, 2012; Kennedy-Higgins et al., 2020; Paulus et al., 2020). Studies using audiovisual stimuli report adaptation for their audio-only conditions. For instance, Pilling & Thomas (2011) presented two groups of participants with noise-vocoded sentences in audiovisual and audio-only training conditions. Participants in both groups adapted readily to the noise-vocoded sentences, although participants in the audiovisual group adapted more than those in the auditory-only condition (participants were exposed to three blocks of 76 sentences (pre-training, training, post-training) and reported key words). Nevertheless, Pilling & Thomas used an 8-band noise-vocoder with a pitch-shift that aimed to approximate a cochlear implant with a 6 mm place mismatch, while we used 4-band noise-vocoded speech without a pitch shift. The degradations are therefore different, and it is likely that the degradation used in Pilling & Thomas resulted in overall more intelligible speech.

Our results for the AV Blocked, AV Still, and AV Eyes conditions are instead similar to those reported in (Drijvers & Özyürek, 2017), as they report close to floor-level performance for their conditions with 2- and 6-band noise-vocoded speech where the mouth area was not clearly visible. Our results are also in line with those reported by Rosen et al. (1999), who examined perception of and adaptation to 4-band spectrally shifted noise-vocoded speech in a live setup. Participants were trained to the distorted speech with a connected discourse tracking task. In this task they were to repeat words when communicating with a live speaker who could be seen though a glass partition and whose speech was vocoded and pitch-shifted in real-time. Participants were exposed to eight blocks of five minutes of speech and reported back what they could understand. After the first block, they could only understand around 1% of the key words, but after the training had finished, they could understand over 40%, showing a clear adaptation effect. It therefore appears that our participants' performance was comparable to that of the participants in Rosen et al. after the first training block. However, we do not know if our participants would subsequently also improve, as our experiment ended after the presentation of 60 sentences. It would be interesting to repeat our study with a more longitudinal design, e.g., like Rosen et al.'s study, to enable establishing the extent to which learning continues and to also gain insights into individual patterns of learning.

Limitations

Despite similarities with previous studies of noise-vocoded speech perception, it is unclear why participants were unable to understand or adapt to the noise-vocoded sentences in the AV Blocked, AV Still, and AV Eyes conditions. It seems likely that participants simply 'gave up' as they were not able to understand most of the sentence when they first heard them. It could be that participants in fact need to be able to understand at least part of the sentence upon the first encounter for perception to improve over time. However, this explanation cannot fully explain our results, as participants in Rosen et al. and Pilling & Thomas also started out at a similarly low performance level of <5% correct, and participants all improved over the course of both studies. It should be noted that their participants were provided with a significantly larger number of sentences/utterances than was the case in our study: Pilling & Thomas exposed participants to 228 noise-vocoded sentences, and participants in Rosen et al. listened to a speaker whose speech was noise-vocoded and spectrally shifted for a total of 40 minutes in eight five-minute blocks. In follow-up studies, it could be considered to provide participants with substantially more training sentences and to present these to them in separate sessions to further facilitate learning and avoid potential fatigue effects. In addition, it might be useful to examine if participants would show better performance and adaptation in similar online conditions to AV Block, AV Still, and AV Eyes for 6, 9, or 10-channel noise-vocoded sentences; the online (and anonymous) setting may have particularly affected participants' motivation to understand the speech compared to a laboratory setting where an experimenter is present. Moreover, a final possibility could be that participants in the online conditions simply did not adapt because they were not made aware that they actually *could* adapt to this type of distortion. We did not mention in the instructions that we expected them to adapt and the title of the study on Prolific was "Transcribing distorted audiovisual speech". Perhaps participants would adapt more if they were 'primed' to learn in the instructions or if learning or adaptation was mentioned in the name of the experiment. We asked participants to provide comments after the main task ended, and most comments could be summarised as they all found the task very difficult and the speech near-impossible to understand. Second, it seems possible that participants may not have attended the stimulus materials sufficiently to correctly perceive them. Huyck & Johnsrude (2012) showed that perceptual adaption to noise-vocoded speech only occurred when attention was selectively directed to the speech task, rather than concurring auditory and visual distractors in their task. Therefore, it seems likely that the current result may in part be explained by participants not paying their full attention to the stimuli. It is not straightforward to control for this issue in an online design. However, or suggestion to combine our online design with eye-tracking to monitor the extent to which participants fixated on the face would likely provide more insights into this issue.

Third, we stress that our results may be modest in scope due to the specific manipulation used, which involved occluding of parts of the face using superimposed white blocks. While this manipulation was very effective in establishing the intended aim of preventing the participants from viewing specific parts of the face, it was somewhat lacking in ecological validity. A more ecologically valid manipulation would be to record stimuli while the speaker was actually wearing a face mask to cover the mouth and/or eyes. Yet, when using a face mask to obscure parts of the speaker's face, care should be taken to avoid a potential confound between speech production and occlusion site (mouth or eyes). Wearing a face mask over the mouth might alter speech production. For instance, the face mask could impede speech articulation, making speech intrinsically less understandable, e.g., due to the speaker articulating less clearly (although there is some evidence that the effect of wearing a face covering is relatively minor (Llamas et al., 2009). Alternatively, the speaker could aim to compensate for the face mask's presence by articulating more clearly (Smiljanić & Bradlow, 2009). Thus, any future study aiming to use a more ecologically valid approach than the current study should therefore ensure to control for possible confounds.

Fourth, even though noise vocoded-speech is a useful model to study adaptation to degradations of the speech signal in normal-hearing listeners, noise-vocoded speech is not a perfect approximation of the type of speech signal experienced by someone with a cochlear implant. For instance, due to the way the electrodes are placed on the auditory nerve, the transformed speech signal will also be pitch-shifted (Rosen et al., 1999). In addition, as the number of frequency bands decrease, the amount of fine-grained spectral information decreases accordingly (Shannon et al., 1995). In addition, noise-vocoding the speech signal does not adequately simulate the representation of phonetic-acoustic cues in a real cochlear implant. For example, depending on the specific configuration of the vocoder (e.g., carrier filter widths), normal hearing people listening to vocoded speech may rely more on formant transitions for differentiating pairs of syllables, whereas cochlear implant users are more inclined to benefit from spectral tilt when performing the same task (Winn & Litovsky, 2015). Moreover, speech perception in normal hearing (vocoded) and cochlear implant listeners differs when the spectral degradation is convolved with additional degradation in the input signal, e.g., when the speech is accented. While the speech recognition performance is better in CI over NH (vocoded) listeners when listening to unaccented speech, this pattern of performance reverses when speech is accented (Tinnemore et al., 2020). Future studies could therefore aim to address some of these issues by combining noise-vocoding with pitch shifting, to establish how listeners perceive and adapt to a more direct representation of the percept likely experienced by people with a cochlear implant.

Conclusion

The results from our study demonstrate that it is essential to be able to see a speaker's moving mouth while trying to understand noise-vocoded sentences in an online setup. When the mouth was not visible, participants could not understand the noise-vocoded sentences at all. Our prediction that being able to see the speaker's mouth movements would benefit observers when listening to noise-vocoded speech, compared to situations when these movements were not visible was confirmed. However, our prediction that participants who were forced to focus more on the mouth rather than the whole face would perform better, was not confirmed as participants in both AV Full and AV Mouth conditions performed equally well. In addition, it also appears that being able to see the eyes region, but not the mouth region, does not support speech perception or adaptation. Moreover, from our results it can also be concluded that, while we partially replicate the lab-based results from Banks et al., it should not be assumed that lab-based tasks will necessarily replicate in online designs, especially when these tasks are particularly difficult. Finally, even though this study was conducted with normal-hearing listeners, we expect that our results may have implications for those with hearing loss, especially when communicating in adverse listening conditions. Our work has demonstrated the key role of the availability of the mouth region when background noise is present or the speech signal is degraded. We recommend to always ensure that listeners are able to observe the speaker's moving mouth to optimise intelligibility and reduce perceived listening effort.

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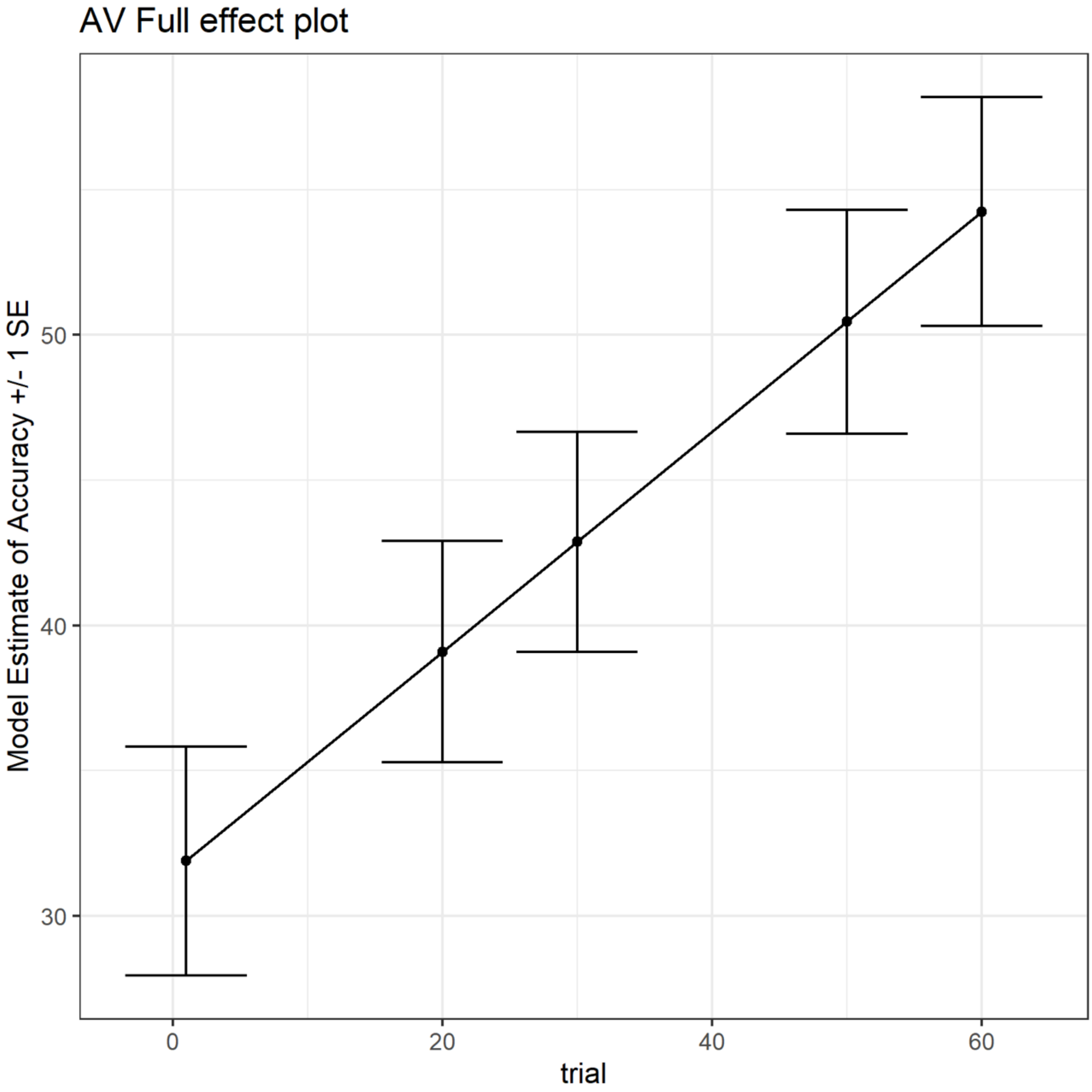
Figures

AV Full AV Mouth AV Blocked AV Still AV Eyes

Figure 1. Still images from conditions AV Full, AV Mouth, AV Eyes, AV Blocked, and AV Still.

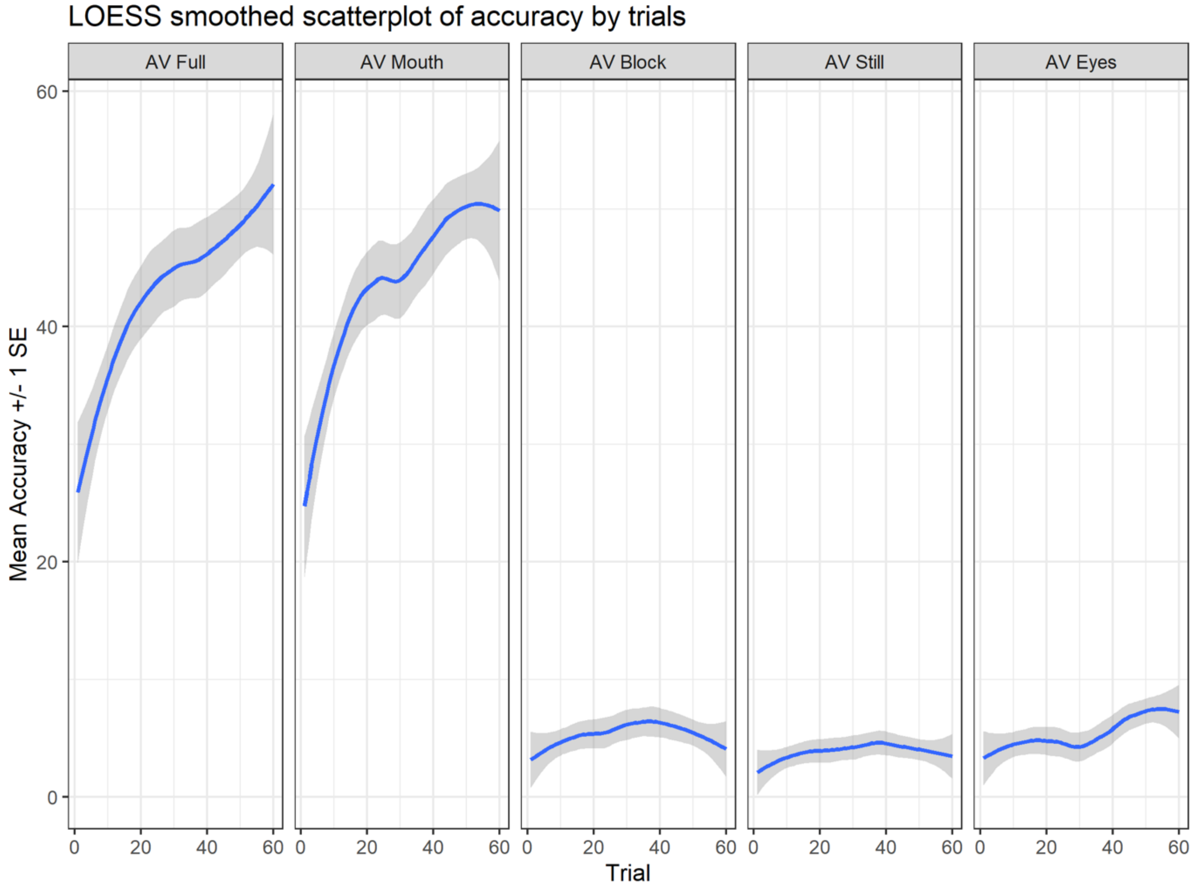


941

942 *Figure 2. Model estimates of percentage correctly reported key words across trials in condition AV Full,*

943 *error bars represent one standard error.*

944



945

946 *Figure 3. Locally Estimated Scatterplot Smoothing (LOESS) plot showing mean accuracy across*

947 *individual trials all five conditions, borders represent one standard error.*

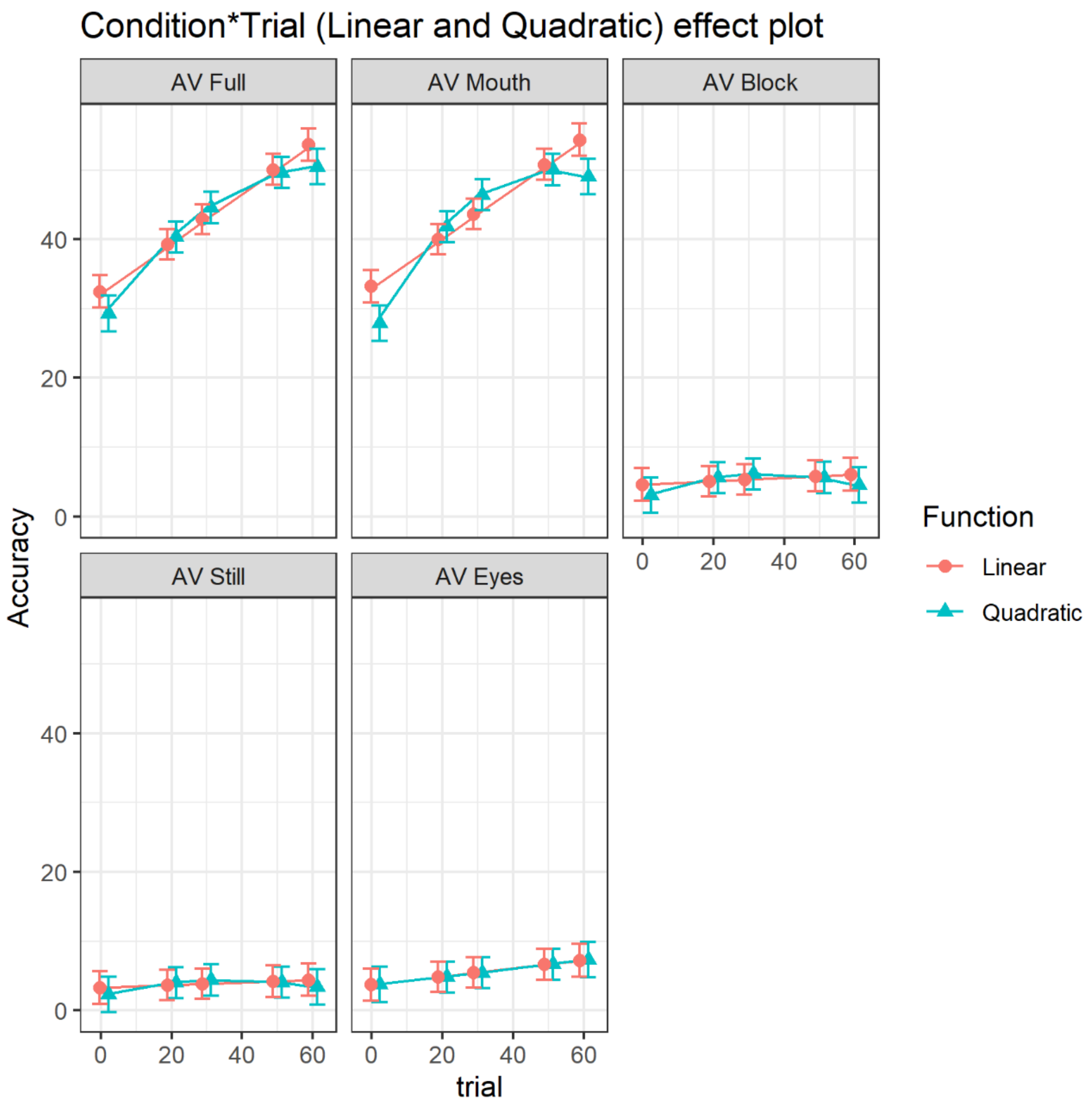


Figure 4. Model estimates of percentage correctly reported key words across trials – modelled as a linear and quadratic relationship - in all conditions, error bars represent one standard error.

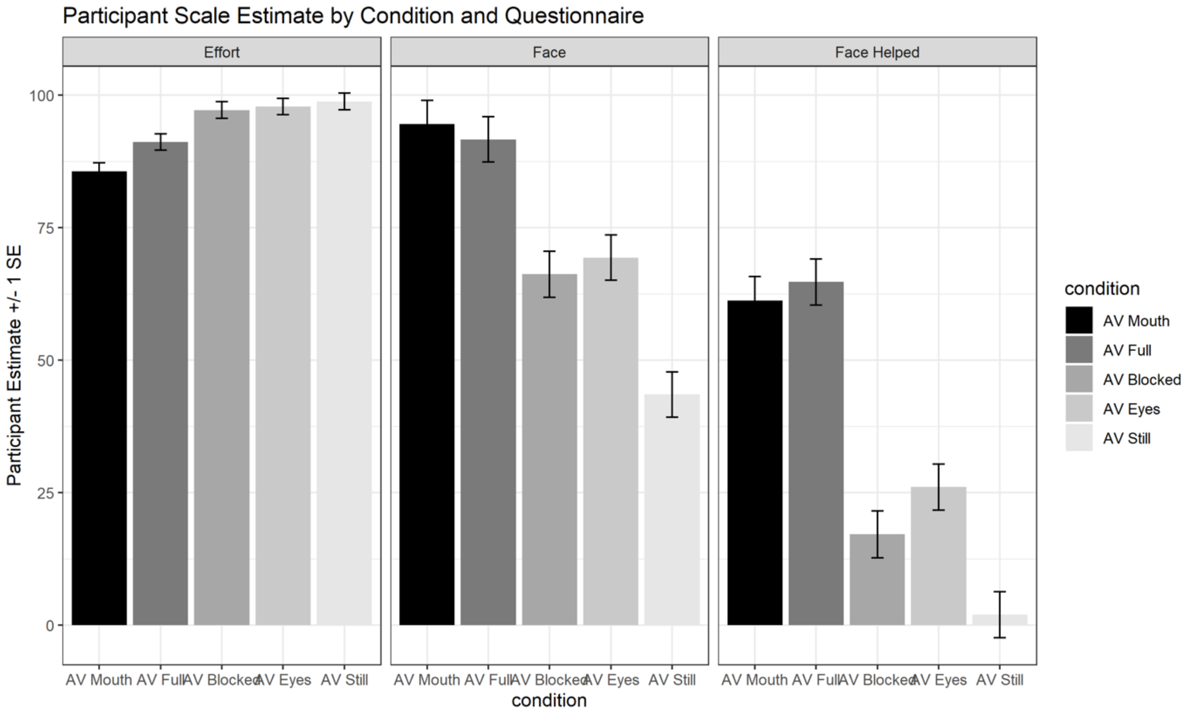


Figure 5. Participant estimates of perceived effort, time spent looking at the speaker's face (Face), and whether the face being visible helped participants during the task (Face Helped). Error bars indicate one standard error.