1 A modulating circle reduces listening effort and improves spoken word recognition in older adults

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Abstract

Objectives. Perceiving spoken language in noise can be a cognitively demanding task, particularly for older adults and those with hearing impairment. The current research assessed whether an abstract visual stimulus—a circle that modulates with the acoustic amplitude envelope of the speech—can affect speech processing in older adults. We hypothesized that, in line with recent research on younger adults, the circle would reduce listening effort during a word identification task. Given that older adults have slower processing speeds and poorer auditory temporal sensitivity than young adults, we expected that the abstract visual stimulus may have additional benefits for older adults, as it provides another source of information to compensate for limitations in auditory processing. Thus, we further hypothesized that, in contrast to the results from research on young adults, the circle would also improve word identification in noise for older adults.

Design. Sixty-five older adults ages 65 to 83 ($M = 71.11$; $SD = 4.01$) with age-appropriate hearing completed four blocks of trials: two blocks (one with the modulating circle, one without) with a word identification task in two-talker babble, followed by two more word identification blocks that also included a simultaneous dual-task paradigm to assess listening effort.

Results. Relative to an audio-only condition, the presence of the modulating circle substantially reduced listening effort (as indicated by faster responses to the secondary task in the dual-task paradigm) and also moderately improved spoken word intelligibility.

Conclusions. Seeing the face of the talker substantially improves spoken word identification, but this is the first demonstration that another form of visual input—an abstract modulating circle—can also provide modest intelligibility benefits and substantial reductions in listening effort. These findings could have clinical or practical applications, as the modulating circle can be generated in real time to accompany speech in noisy situations, thereby improving speech intelligibility and reducing effort or fatigue for individuals who may have particular difficulty recognizing speech in background noise.

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2 Speech recognition is typically improved when the listener can see as well as hear the talker
3 (Erber, 1969; Sumbly & Pollack, 1954). This visual benefit is largely attributable to the complementary
4 nature of the phonetic information in the auditory and visual modalities; features that are easily lost in
5 noisy acoustic input (place of articulation) tend to be readily extracted from the visual modality, and
6 features that are difficult to lipread (voicing and manner of articulation) tend to be quite robust to acoustic
7 noise (Grant & Walden, 1996; Summerfield, 1987). A growing body of research also suggests that in
8 addition to fine phonetic detail, temporal features of the visual signal may also facilitate speech
9 recognition. For example, increasing the level of Gaussian blur in the visual modality substantially
10 reduces lipreading performance, but has little effect on audiovisual speech recognition (Tye-Murray,
11 Spehar, Myerson, Hale, & Sommers, 2016), and listeners obtain intelligibility benefits from visual speech
12 depicted by point-light displays (Rosenblum, Johnson, & Saldaña, 1996), which do not contain sufficient
13 detail to be lipread. Though neither of these stimuli contain fine phonetic detail, both contain temporal
14 cues to salient features in the acoustic input, suggesting that temporal features of the visual stimulus may
15 benefit speech recognition. However, the few studies that have sought to determine whether a
16 temporally-rich but otherwise phonetically-sparse visual signal can enhance intelligibility have failed to
17 find any evidence of visual benefit (Schwartz, Berthommier, & Savariaux, 2004; Strand, Brown, &
18 Barbour, 2018; Summerfield, 1979). Thus, it may be that gross phonetic detail such as that provided by a
19 video with a high level of Gaussian blur, in combination with temporal correspondence, may be necessary
20 to improve speech intelligibility.

21 Although there is no evidence to date that temporal features of the visual signal alone are
22 sufficient to improve speech intelligibility, they have been shown to reduce the cognitive load incurred by
23 processing speech (Strand, Brown, & Barbour, 2018). This concept, referred to as listening effort (i.e., the
24 mental effort required to complete a listening task; Pichora-Fuller et al., 2016), relies on the assumption of

1 a limited capacity system (Kahneman, 1973): as the listening task becomes more difficult, fewer resources
2 remain available to simultaneously complete other tasks. One of the most commonly used methods of
3 assessing listening effort is the dual-task paradigm, which quantifies the remaining resources after speech
4 recognition has occurred based on performance on a secondary task (see Gagné, Besser, & Lemke, 2017
5 for a review). Using a dual-task paradigm, Strand, Brown, and Barbour (2018) recently demonstrated that
6 an abstract, visually-presented circle that modulates with the amplitude of speech—and therefore contains
7 temporal information but no fine phonetic detail—reduces listening effort but has no effect on spoken
8 word recognition in two-talker babble. In addition, abstract visual stimuli that are tied to temporal
9 properties of the acoustic signal improve listeners' ability to detect speech in noise (Bernstein, Auer, &
10 Takayanagi, 2004; Tye-Murray et al., 2011), suggesting that the reduction in listening effort observed by
11 Strand et al. (2018) may be due to low-level attentional enhancement towards salient features in the
12 acoustic input.

13 Strand and colleagues (2018) noted that this research could inform clinical interventions intended
14 to reduce listening effort, such as the creation of an application or device that could generate abstract
15 visual stimuli to accompany auditory input in difficult listening situations. Although certainly a step in
16 that direction, that study was conducted on normal-hearing college students, who typically have little
17 difficulty recognizing speech even in adverse listening conditions. A population that would benefit more
18 from such a device is one for whom speech recognition requires considerable effort (e.g.,
19 hearing-impaired individuals or older adults). Thus, the goal of the present study was to attempt to extend
20 the findings of Strand et al. (2018) to a population of older adults to assess whether age-related cognitive
21 and perceptual differences affect the extent to which an abstract visual stimulus can reduce listening effort
22 and/or improve speech recognition accuracy.

23 Relative to young adults, older adults typically have impaired cognitive abilities (Wingfield, Tun,
24 & McCoy, 2005)—including diminished inhibitory control (Hasher & Zacks, 1988; Sommers &

1 Danielson, 1999; Stoltzfus, Hasher, & Zacks, 1996), working memory capacity (Salthouse, 1991;
2 Wingfield, Stine, Lahar, & Aberdeen, 1988), and processing speed (Salthouse, 1991, 1996). These
3 changes in cognitive abilities complicate the task of listening to speech, above and beyond peripheral
4 changes such as age-related hearing loss. As a result, not only does speech identification suffer in older
5 adulthood (e.g., Pichora-Fuller, Schneider, & Daneman, 1995; Tun, O’Kane, & Wingfield, 2002), but
6 more listening effort is required for older adults than young adults (Desjardins & Doherty, 2013; Gosselin
7 & Gagné, 2011; McCoy et al., 2005). Strand et al. (2018) demonstrated robust decreases in listening effort
8 in young adults with the addition of an abstract visual stimulus, but it is not clear whether older adults
9 would incur the same benefits. Age-related changes in processing speed (Salthouse, 1991, 1996) may
10 make it more difficult for older adults to take advantage of rapidly-changing visual information and
11 therefore limit the utility of the modulating circle. If this is the case, the modulating circle may have no
12 effect on listening effort in older adults or may even increase effort if they find it distracting.

13 Alternatively, the abstract visual stimulus may reduce listening effort for older adults, as it did for
14 young adults. The benefits older adults derive may even be larger than those observed in young adults
15 because the complementary information provided by the visual input may compensate for age-related
16 declines in auditory processing. Compared to young adults, older adults have poorer thresholds for
17 detecting gaps between acoustic events (Schneider, Pichora-Fuller, Kowalchuk, & Lamb, 1994), are
18 worse at judging the duration of an acoustic event relative to a reference stimulus (Fitzgibbons &
19 Gordon-Salant, 1995), and have greater difficulty determining the temporal order of two auditory tones
20 (Fitzgibbons & Gordon-Salant, 1998). If the visual information can compensate for limitations in auditory
21 temporal processing, it may provide substantial reductions in listening effort.

22 Given that high temporal sensitivity is necessary to process auditory-only speech (e.g., the
23 difference in the voice-onset-time between /da/ and /ta/ is approximately 65 ms; Lisker & Abramson,
24 1964), if older adults have impaired auditory temporal sensitivity, they may obtain benefit from the

additional temporal information provided by a visual modulating circle that contribute to speech intelligibility as well as effort. For example, the modulating circle would become larger more quickly for voiced relative to unvoiced consonants, so if this information was ambiguous in the auditory-only condition, the visual signal may clarify this distinction in the audiovisual condition and improve intelligibility. Thus, in addition to reductions in listening effort, the modulating circle may also afford intelligibility benefits for older adults.

In Strand et al. (2018), young adults did not show improved word identification when speech was accompanied by the visual stimulus, relative to listening alone. However, the speech task is not likely to have exhausted the resources young adults have at their disposal, so they could successfully complete the speech task and the secondary task simultaneously, even in the absence of visual input. As a result, adding the modulating circle may not have improved performance on the speech task because they were already performing that task to the best of their abilities; the circle simply allowed them to devote fewer resources to the speech task to attain the same level of performance, thereby leaving more available to perform the secondary task. In contrast, if the speech task exhausts older adults' cognitive resources, adding the modulating circle may free previously encumbered resources and actually improve their ability to identify words in background noise.

To our knowledge, only one study has examined whether older adults can benefit from an abstract visual stimulus (i.e., one containing only temporal information and no fine phonetic detail), and that study found that a natural talking face, but not an abstract Lissajous figure, can improve older adults' ability to detect speech in noise (Tye-Murray et al., 2011). This study, however, did not assess recognition benefits associated with the abstract visual stimulus, and only included nonsense syllables, which may not benefit from abstract visual stimuli to the extent that words do. Further, that study utilized a threshold-level detection task; the visual signal may be less effective at enhancing attention when the listening conditions

are extremely difficult. Thus, it is possible that an abstract visual signal will improve word identification accuracy for older adults.

The goal of the present study was to assess whether Strand and colleagues' (2018) results extend to a population of older adults. The methods we employed in this experiment were identical to those in Experiment 2 of Strand et al. (2018), except that the participants consisted of older adults rather than young adults, and the signal-to-noise (SNR) ratio was slightly easier to avoid floor-level performance on the word identification task. Participants first completed an audio-only and an audiovisual block with word identification only (i.e., single-task) to determine whether the modulating circle can improve spoken word intelligibility in older adults. Next, participants completed two more blocks while simultaneously performing a secondary task (i.e., dual-task) to assess listening effort. In dual-task paradigms, slowed responses to the secondary task are indicative of greater effort; when more resources are devoted to the primary (speech) task, fewer remain to complete the secondary task (Gagné et al., 2017). Thus, if the modulating circle reduces listening effort, response times should be faster in the audiovisual condition than the audio-only condition.

We hypothesized that we would replicate the finding that a modulating circle reduces listening effort and further expected that the magnitude of the reduction in listening effort would be even greater in older adults than in young adults. Older adults demonstrate poorer memory for speech presented in meaningful competing speech (i.e., the type of background noise we will employ) than young adults (Tun et al., 2002), suggesting that speech-on-speech masking may be particularly cognitively demanding for older adults. Given that the modulating circle facilitates stream segregation by drawing the listener's attention to salient features of the target speech (e.g., onset, offset, and high-amplitude points in time), this may reduce the cognitive burden imposed by intelligible background speech more for older adults than young adults, for whom speech-on-speech masking is easier to overcome. In addition, unlike Strand et al.

(2018), we expected that the modulating circle would improve spoken word identification accuracy in older adults as a result of their limited cognitive resources and impaired auditory temporal processing.

Materials & Method

All data and code are available at <https://osf.io/q8ngf/>. Stimuli, taken from Strand et al. (2018) are available at <https://osf.io/b94yx/>. This study was pre-registered via the Open Science Framework (see <https://osf.io/q8ngf/>).

Participants

Sixty-five older adults ages 65 to 83 ($M = 71.11$; $SD = 4.01$) were recruited from the Washington University in St. Louis community. This sample size was predetermined using power analysis; in order to reach this predetermined sample size, we collected data from 80 participants. Three participants were excluded due to technical difficulties (the computer crashed during the experiment), two were excluded for not completing the task correctly, six were excluded for having poor Montreal Cognitive Assessment (MoCA, a brief screening for mild dementia; Nasreddine et al., 2005) scores, five were excluded for having poor pure-tone averages (PTAs; two of these participants were also identified as outliers according to the MoCA criterion), and one additional participant was excluded for having poor accuracy on the word identification task.

We pre-registered that we would exclude individuals with PTAs worse than 25 dB in either ear, but this proved to be too conservative in the sample we tested, so we decided to loosen the criterion before analyzing the data to PTAs above 25 dB in both ears (averaged across 500, 1,000, and 2,000 Hz). To ensure that our findings were not affected by this decision, we conducted an additional set of analyses mirroring the primary analyses in which we did not exclude any participants for having poor hearing and included PTA as a covariate (see Results). We had also planned to exclude participants with MoCA scores below 26, but this clinical threshold also proved to be too conservative, so we loosened the criterion to scores below 24 before analyzing the data. Indeed, it has been shown that with this cutoff, the MoCA has

96% sensitivity and 95% specificity (see Carson, Leach, & Murphy, 2018; Luis, Keegan, & Mullan, 2009; McClannahan, Backer, & Tremblay, 2019). Given that speech stimuli were presented to both ears and all conditions were manipulated within-subjects, these minor deviations from our pre-registered exclusion criteria are not likely to affect the results. Participants were compensated \$15 for their time, and testing took approximately one hour. The Washington University in St. Louis Institutional Review Board approved all procedures.

Stimuli

The 400 words in this experiment were identical to those in Strand et al. (2018). Words were selected from a subset of the SUBTLEX-US database (Brysbaert, New, & Keuleers, 2012) such that all words were relatively high frequency (log-frequencies above 3), contained no more than five phonemes, and contained one or two syllables. Articles and conjunctions were omitted. 55% of words were classified predominantly as nouns according to the SUBTLEX-US part of speech dominance data (Brysbaert et al., 2012). The same four lists of 100 words (each maintaining the 55% noun composition) that were used in the previous experiment were used here, and each list appeared in each of the four conditions (counterbalanced across participants) so participants heard each word only once. Words were presented in the same two-talker babble from Strand et al. (2018), but we increased the SNR from -4 dB to 0 dB to avoid floor effects in identification accuracy. We also increased the inter-stimulus interval between words to allow older adults more time to respond.

Design and procedure

Before completing the primary task, participants completed a standard audiogram in an ETS-Lindgren Double-Wall Audiometric Examination Suite to determine their thresholds at 250, 500, 1,000, 2,000, 4,000, and 8,000 Hz (but note that PTA was calculated by averaging thresholds at 500, 1,000, and 2,000 Hz). Audiograms were conducted with a GSI Pello audiometer using GSI Grason-Stadler software (version 2.4.0 2016). Participants were then administered the MoCA, which

involves pen and paper tasks (e.g., copying a cube) and verbal tasks administered by the experimenter (e.g., recalling a list of words). MoCA scores were used for exclusion purposes only (see “Participants” section). Each of these tasks took under 10 minutes to complete.

Following the procedures of Strand et al. (2018), this experiment employed the semantic dual-task (see also Picou & Ricketts, 2014; Strand, Brown, Merchant, Brown, & Smith, 2018). In this task, participants listen to a stream of words presented one at a time and press a button on a button box (Cedrus RB-600) if the word can be classified as a noun. Response times to the noun judgment task are taken as a measure of listening effort with the rationale that more difficult listening conditions lead to increased cognitive load, leaving fewer resources available to rapidly make judgments about what was heard, resulting in slower response times on the noun judgement task. Indeed, participants are slower to complete the noun judgment task when the SNR is more challenging in audio-only settings (Picou & Ricketts, 2014; Strand, Brown, Merchant, et al., 2018).

Participants completed four blocks: single-task (identification only) in audio-only and audiovisual conditions and dual-task (speech + secondary task) in audio-only and audiovisual conditions. The two single-task blocks always appeared before the two dual-task blocks, but the order of the presentation of audio-only vs audiovisual conditions both the single- and dual-task blocks was counterbalanced across participants. In each block, participants were presented a stream of words with an inter-stimulus interval randomly selected from 2,500 ms, 3,000 ms, and 3,500 ms. In the single-task blocks, participants were simply asked to listen and repeat aloud what they perceived, and responses were recorded via Audacity (version 2.2.2) and scored offline.

In the two dual-task blocks, participants completed the same speech identification task while simultaneously completing the noun judgment task. Participants were instructed to press a button on a button box as quickly and accurately as possible if the word could be classified as a noun, and then repeat the word aloud. Response time to trials in which a participant classified the word as a noun were taken as

a measure of listening effort, meaning that words that participants did not respond to (non-nouns) were not included in the analysis. Following the procedures of previous experiments using this task (Picou & Ricketts, 2014; Strand, Brown, & Barbour, 2018; Strand, Brown, Merchant, et al., 2018), we did not score accuracy at the noun classification task because approximately 84% of nouns can be classified as other parts of speech (Picou & Ricketts, 2014). Thus, few words can strictly be classified as nouns, and individuals may differ in their tolerance for what counts as a noun. Participants completed four identification-only practice trials before each of the single-task blocks, and eight dual-task practice trials before each of the dual-task blocks. Unlike in Strand et al. (2018), we opted not to collect subjective ratings of effort. Together, the single-task and dual-task blocks took approximately 20–30 minutes to complete.

Results

MoCA scores for the 65 participants included in the main analyses ranged from 24 to 30 ($M = 27.35$; $SD = 1.85$), and PTAs (averaged across both ears) ranged from 1 to 29 ($M = 14.22$; $SD = 6.64$). Data were analyzed using linear mixed effects models via the lme4 package (version 1.1.21; Bates et al., 2014) in R (version 3.5.2; R Core Team, 2016). In all models, participants and items were entered as random effects. Following the recommendations of Barr and colleagues (2013), we attempted to use the maximal random effects structure justified by the design. In cases of non-convergence, we employed different optimizers and control parameters to facilitate convergence. In cases of singularity, we selectively removed random effects that contributed the least to the total variance, focusing on pairs of random effects that showed estimated correlations of 1.00 or -1.00 (which is indicative of overfitting; see project code for more details). Where appropriate, p-values from mixed effects models were obtained via the lmerTest package (version 3.1.0; Kuznetsova, Brockhoff, & Christensen, 2017).

Listening effort analysis

Before performing the listening effort analyses, we removed trials with response times that were more than three median absolute deviations (MADs) above or below a participant's median response time for that condition (317 trials). We had originally planned to additionally remove trials with response times slower than 2,000 ms, but opted to remove this criterion because if there are indeed response time differences between the audio-only and audiovisual conditions, this decision would selectively remove trials in the slower condition. The MAD criterion should remove trials with extreme response times relative to that particular condition, so including an additional criterion is unnecessary. We made this decision before analyzing the data. The final analysis contained 6,072 response time trials.

The dependent variable was response time (analyzed continuously) to “noun” responses on the noun judgment task in the dual-task blocks. To determine whether condition affected response times to the secondary task, we built a full model with condition (audio-only or audiovisual) as a fixed effect and participants and items as random effects, and a reduced model that omitted condition as a fixed effect. A likelihood ratio test indicated that the full model provided a better fit for the data ($\chi^2_1 = 97.87$; $p < .001$), suggesting that the effect of condition was significant. The summary output for this model indicated that participants were on average an estimated 222 ms faster in the audiovisual condition relative to the audio-only condition ($\beta = -222.39$, $SE = 14.88$, $t = -14.95$, $p < .001$; Figure 1). The overall effect size was $d = .52$, and the by-participants effect size was $d = .91$ (see project code for details about calculating effect sizes). As in Strand et al. (2018), the modulating circle improved performance on an individual level; all but two of the 65 participants had faster average response times in the audiovisual relative to the audio-only condition, and 83% (54 of the 65 participants) showed benefits of 100 ms or greater. Response time differences (audio-only minus audiovisual) ranged from -103 ms to 481 ms.

Figure 1. A. Violin plot showing distributions of response times to the noun judgment task in the audio-only (left) and audiovisual (right) conditions. **B.** Scatterplot showing average by-participant response times in the two conditions. The line $y = x$ indicates equivalent performance in the audio-only and audiovisual conditions; thus, only two of the 65 participants did not show the response time benefit in the audiovisual condition. **C.** Violin plot showing the distribution of response time differences between the audio-only and audiovisual conditions for each participant. RT = response time; ms = milliseconds; $N = 65$.

Word identification analysis

For the word identification analysis, we only included data from single-task (i.e., identification-only) trials because performing the secondary noun classification task may affect performance on the primary task. Correct responses were scored as 1 and incorrect responses were scored as 0. Given the binomial nature of the outcome variable, we employed generalized linear mixed effects models using a logit link function. The analysis consisted of 13,000 total trials.

To determine whether the modulating circle affected identification accuracy, we built two nested models—a full model with condition as a fixed effect, and a reduced model that lacked condition as a fixed effect but was identical to the full model in all other respects. Condition was dummy coded (audio-only = 0, audiovisual = 1). The full model with condition provided a better fit for the data than the model without ($\chi^2_1 = 9.59$; $p = .002$), and the summary output for the full model indicated that participants recognized more words in the audiovisual than the audio-only condition ($\beta = 0.16$, $SE = 0.05$,

$z = 3.29, p = .001$; Figure 2). Average word identification accuracy was 67.51% in the audiovisual condition and 64.55% in the audio-only condition. Thus, the modulating circle afforded listeners a small but significant intelligibility benefit of 2.95%.

Figure 2. Distribution of word identification accuracy by-participants. Note that this analysis only included data from the first two blocks, during which participants attempted to recognize words in two-talker babble without the noun judgement task.

Exploratory PTA analyses

Next, we assessed whether the visual benefits for both effort and intelligibility hold when controlling for PTA, because individuals with worse hearing may benefit more from the addition of a visual signal. This analysis mirrored those described above, but did not exclude participants with poor hearing and thus included 69 participants (note that the participant who had been excluded from the

analyses reported above for having poor word identification accuracy was not identified as an outlier here). Condition and PTA (averaged across both ears) were included as fixed effects, and a by-stimulus random slope for PTA was included in the random effects structure. This full model was compared to reduced models that lacked either condition or PTA as a fixed effect. Finally, we tested for a condition-by-PTA interaction in both the identification and effort analyses. MoCA scores for this set of analyses were comparable to those reported above ($M = 27.32$; $SD = 1.82$; range = 24–30), and PTAs were slightly higher ($M = 15.16$; $SD = 7.56$; range = 1.0–36.5), which is to be expected given that we included participants with poorer hearing.

Listening effort analysis. A likelihood ratio test indicated that a model that included PTA did not provide a better fit for the data than one without it ($\chi^2_1 = 0.09$; $p = .77$), but, as above, a model that included condition provided a better fit than one without it ($\chi^2_1 = 105.73$; $p < .001$). Examination of the summary output for the full model indicated that response times were on average an estimated 222 ms faster in the audiovisual than the audio-only condition ($\beta = -221.61$, $SE = 14.15$, $t = -15.66$, $p < .001$). Finally, a likelihood ratio test indicated that the interaction between PTA and condition was not significant ($\chi^2_1 = 0.08$; $p = .78$), indicating that reductions in listening effort associated with the modulating circle were not moderated by hearing ability.

Word identification analysis. A likelihood ratio test indicated that a model including PTA provided a better fit for the data than one without it ($\chi^2_1 = 17.48$; $p < .001$), and a model including condition also provided a better fit for the data than one without it ($\chi^2_1 = 9.95$; $p = .002$). Examination of the summary output for the full model indicated that, as would be expected, participants with poorer hearing thresholds had poorer word identification accuracy than those with better hearing thresholds ($\beta = -0.05$, $SE = 0.01$, $t = -4.45$, $p < .001$), and word identification accuracy was better in the audiovisual compared to the audio-only condition ($\beta = 0.16$, $SE = 0.05$, $z = 3.32$, $p < .001$), consistent with the results of the primary analysis. Finally, we built a model that included the interaction between condition and PTA

and compared it to the model lacking the interaction. A likelihood ratio test indicated that the interaction was not significant ($\chi^2_1 = 0.04$; $p = .84$), suggesting that the effect of the visual signal did not differ by PTA.

Together, the results of these analyses indicate that in this sample of older adults with age-appropriate hearing, PTA is a significant predictor of word identification accuracy but not effort. Further, including PTA as a covariate does not affect the conclusions of this experiment—word identification accuracy is improved and effort is reduced when older adults watch a temporally-informative modulating circle as they listen to speech in two-talker babble.

Discussion

Previous research has shown that a modulating circle that appears at the onset of speech, modulates with the acoustic amplitude envelope, and disappears at speech offset reduces listening effort in young adults (Strand, Brown, & Barbour, 2018). Here, we extended this finding to a population of older adults without diagnosed hearing impairment, and showed that the benefits obtained from the abstract visual stimulus, as measured by the effect size associated with adding the visual stimulus, was numerically larger for older than the young adult sample from Strand, Brown, & Barbour (2018). Crucially, though the circle did not affect speech intelligibility for young adults, we found that this abstract visual stimulus—which contains only temporal information about the acoustic speech—actually improved spoken word identification in older adults by a small (approximately 3%) but significant amount. Despite a significant relationship between PTA and performance on the word identification task, our conclusions were unaltered when PTA was included as a covariate.

Why might the abstract visual stimulus have improved intelligibility in the current study, but not in previous work (Schwartz et al., 2004; Strand, Brown, & Barbour, 2018; Summerfield, 1979)? The most likely explanation is that older adults have fewer cognitive resources at their disposal (e.g., Salthouse, 1991) and poorer auditory temporal processing (e.g., Schneider et al., 1994) compared to their younger

counterparts, so the cognitive benefits conferred by the modulating circle were sufficient to improve speech intelligibility. Each of the previous studies was conducted on young adults, and this population may be attaining their maximum performance for the level of the background noise even in audio-only conditions, so without the fine phonetic detail that a talking face would provide, visual benefit can only occur at the level of listening effort. It is also possible that the modulating circle only improves intelligibility in more difficult listening conditions. Indeed, overall accuracy in this study (~65%) was lower than in the study conducted by Strand and colleagues (2018) using the same materials (~82%). This explanation seems unlikely, however, because word identification accuracy on a similar task was approximately 23% in the audio-only condition in a study conducted by Summerfield (1979), yet no intelligibility benefits were observed from the addition of an abstract visual stimulus. Future research should assess whether intelligibility benefits emerge in young adults when the task is made more difficult, but regardless, age likely plays an role in the visual benefit observed here.

The finding that an abstract visual stimulus not only substantially reduces effort but also improves speech intelligibility for older adults has important practical applications. For example, the development of a device that generates a modulating circle to accompany audio-only speech—such as a telephone call, podcast, audiobook, or the radio—could improve the user’s ability to multitask or encode what was heard into memory. Such an intervention is promising for a clinical setting, given that a reduction in effort was observed in 63 of our 65 participants, the effect size was larger for older adults than young adults reported in Strand, Brown, & Barbour(2018; $d = .52$ versus $d = .42$), and we demonstrated intelligibility benefits along with reductions in listening effort. Thus, this modulating circle has been shown to decrease subjective ratings of effort in young adults (Strand, Brown, & Barbour, 2018), substantially decrease objectively measured effort in older and younger populations, and improve intelligibility in older adults.

These reductions in effort are akin to those of noise-reduction algorithms in hearing aids, which decrease effort and improve subjective ease of listening, even when they do not improve speech

intelligibility in background noise (Desjardins & Doherty, 2014; Ricketts & Hornsby, 2005; Sarampalis, Kalluri, Edwards, & Hafter, 2009; Walden, Surr, Cord, Edwards, & Olson, 2000). A device that offers large effort benefits and modest intelligibility benefits could greatly improve communication for individuals for whom recognizing speech in noisy environments can be difficult and often exhausting (Gosselin & Gagné, 2011; Tun, McCoy, & Wingfield, 2009; Wingfield et al., 2005). Because listening to speech in real-world settings rarely occurs in isolation, decreases in listening effort can have important consequences for listeners and may be expected to improve users' ability to multitask, recall what they heard (e.g., see Sommers & Phelps, 2016; Van Engen, Chandrasekaran, & Smiljanic, 2012), or reduce fatigue (Alhanbali, Dawes, Lloyd, & Munro, 2017; McGarrigle, Dawes, Stewart, Kuchinsky, & Munro, 2016; McGarrigle et al., 2014).

Given that the modulating circle provides temporal cues to salient moments in the acoustic signal, the benefits incurred by the visual stimulus are likely a function of low-level attentional enhancement and reduction of temporal uncertainty. It is important to note that though small, the intelligibility benefit emerged in this study despite the relatively predictable timing of the presentation of each word. To create some temporal uncertainty, we varied the inter-stimulus interval from 2,500 to 3,500 ms, but even with this variability participants knew with a maximum of one second of uncertainty when the word would be presented. Indeed, after completing the task several participants noted that recognizing the words became easier as they “got into the rhythm” of the task. Future research could present stimuli at more unpredictable intervals to determine whether the magnitude of the intelligibility benefit is dependent upon the degree of temporal uncertainty in the acoustic signal. This would also increase the external validity of the study—speech in everyday listening situations typically occurs in unpredictable intervals, and given that the modulating circle provides temporal cues to salient moments in the acoustic stream, this type of visual stimulus is likely to be particularly beneficial in these situations.

One clear limitation of the current study is its use of isolated words. We opted for words rather than sentences because we wanted to use the exact stimuli and task used in Strand et al. (2018). It would be advantageous to assess the extent to which these findings extend to more naturalistic listening situations. If the primary function of the modulating circle is alerting the listener to the onset of the speech stream, then this abstract visual stimulus may be less beneficial for continuous speech once the target speech stream has been segregated from the background noise. In contrast, if the amplitude modulation plays an important role (see Peelle & Sommers, 2015), then the circle may be beneficial even for continuous speech, as the circle can alert the listener to salient moments in the target speech stream, thereby improving their ability to maintain attention on the stream of interest. Thus, an informative next step for this line of research would be to assess which features of the visual signal (onset/offset or modulation) are driving the reductions in effort.

Another fruitful line of research would be to determine whether the modulating circle benefits speech recognition or effort in a more naturalistic setting, such as a simulated phone conversation with high levels of background noise. Indeed, this is exactly the type of situation in which the device mentioned above would likely be utilized—not only do telephone conversations rarely occur in quiet settings, but telephones also typically transmit only frequencies in the range of 300–3400 Hz (Brault, Gilbert, Lansing, McCarley, & Kramer, 2010), so the signal is necessarily degraded. The modulating circle may be most beneficial in this situation because telephone conversations contain both temporal uncertainty and continuity of speech—the onset information provided by the abstract visual stimulus could reduce temporal uncertainty (i.e., indicate to the listener when their interlocutor has begun speaking), and the modulatory information could help the listener maintain focus on the target stream. As mentioned above, this device would be particularly beneficial for older adults or individuals for whom communication over the telephone can be difficult. Indeed, the narrow bandwidth transmitted by telephones has been shown to impair intelligibility in older adults, and visual information in the form of a

talking face has been shown to offset this deficit (Braault et al., 2010). However, given that the talker's face is often not visible during telephone conversations, a modulating circle that is generated on-line from the acoustic signal may be a promising alternative in these situations.

Given that the effect size for the older adults reported here was numerically larger than that for the young adults in Strand, Brown, & Barbour (2018), follow-up research should evaluate whether the effect persists or is even stronger for other populations that may have difficulty recognizing speech in background noise. For instance, this research may be particularly beneficial for individuals with mild hearing loss, or for individuals who use cochlear implants. The preliminary analyses reported here suggest that though poorer hearing thresholds are associated with poorer performance on the word identification task, PTA is unrelated to effort, at least for older individuals with relatively good hearing ($N = 66$ participants with thresholds below 25 dB in at least one ear, $N = 3$ participants with thresholds above 25 dB in both ears). Other studies have shown that individuals with poorer hearing expend more listening effort when recognizing speech (e.g., McCoy et al., 2005), but it is likely that this effect did not emerge here because of the restricted range in this sample. Thus, future research should assess whether a visual signal that provides temporal cues to the acoustic speech alone is sufficient to reduce effort and improve intelligibility in hearing-impaired individuals.

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