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Research Article

Age-Related Differences in the Online Processing of Spoken Semantic Context and the Effect of Semantic Competition: Evidence From Eye Gaze

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Purpose: The study examined age-related differences in the use of semantic context and in the effect of semantic competition in spoken sentence processing. We used offline (response latency) and online (eye gaze) measures, using the "visual world" eye-tracking paradigm.
Method: Thirty younger and 30 older adults heard sentences related to one of four images presented on a computer monitor. They were asked to touch the image corresponding to the final word of the sentence (target word). Three conditions were used: a nonpredictive sentence, a predictive sentence suggesting one of the four images on the screen (semantic context), and a predictive sentence suggesting two possible images (semantic competition).
Results: Online eye gaze data showed no age-related differences with nonpredictive sentences, but revealed slowed processing for older adults when context was presented. With the addition of semantic competition to context, older adults were slower to look at the target word after it had been heard. In contrast, offline latency analysis did not show age-related differences in the effects of context and competition. As expected, older adults were generally slower to touch the image than younger adults.
Conclusions: Traditional offline measures were not able to reveal the complex effect of aging on spoken semantic context processing. Online eye gaze measures suggest that older adults were slower than younger adults to predict an indicated object based on semantic context. Semantic competition affected online processing for older adults more than for younger adults, with no accompanying age-related differences in latency. This supports an early age-related inhibition deficit, interfering with processing, and not necessarily with response execution.

Age-related sensory and cognitive changes and their relation to speech comprehension have been the focus of considerable research since the early publication of the report by the Committee on Hearing and Bioacoustics and Biomechanics (1988). Given the changes in the auditory and cognitive systems that often occur with aging, it is remarkable that comprehension of spoken language is one of the more preserved abilities in older age (Peelle & Wingfield, 2016).

This resilience has been attributed to older adults' ability to use age-related advantages, such as crystalized intelligence (Horn & Cattell, 1967) and experience with language (Ben-David et al., 2015; Kavé & Halamish, 2015), to overcome reduced cognitive resources and hearing acuity. For example, the consensus in the literature is that, unlike many other cognitive and speech measures, older adults are at least as able as younger adults to use a preceding linguistic context to aid recognition of spoken words degraded by noise or impaired hearing. Importantly, this consensus on context facilitation has been based on offline measures such as accuracy in recognizing words heard in noise (Benichov et al., 2012; Dubno et al., 2000; Pichora-Fuller et al., 1995) or recognizing words from just their acoustic onsets (Lash et al., 2013; Wingfield et al., 1991).

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Such offline measures provide evidence regarding the end point of recognition, but fail to afford information regarding the time course and underlying processes leading to the recognition response as the sentence unfolds in time. The "visual world" eye-tracking paradigm was specifically developed to examine the time course of speech understanding (Allopenna et al., 1998; Tanenhaus & Trueswell, 2006). In the classic version of this paradigm, four images, depicting different nouns (i.e., the visual world), are presented on a monitor. Participants are asked to select the image corresponding to the last word of a spoken sentence (verbally referenced target) as an eye-tracking camera records the location of their eye gaze. Tracking the location of eye gaze to the four images as the sentence unfolds in time provides a highly sensitive and continuous measure of the time course for differentiating the verbally referenced target from all other depicted alternatives.

The analysis of online eye gaze has uncovered effects that were previously not available from offline measures. For example, Nitsan et al. (2019) used the visual world paradigm to compare participants with higher and lower working memory spans on the time course of word recognition in noise. Group differences in span (higher vs. lower) did not affect offline accuracy, but eye gaze analysis revealed that participants with reduced working memory spans were slower to recognize the word by as much as 550 ms than participants with better spans.

Eye tracking provides a useful way to compare older and younger adults' processing of online speech that minimizes potential effects of age-related slowing in overt response execution. That is, offline measures of accuracy and response latencies reflect not only the processing of the word, but also motoric processes (key-pressing or articulation of the word; Ben-David & Icht, 2017, 2018) and memory span (e.g., holding the spoken word in memory until a response prompt). As a result, when offline measures are used, age-related slowing and changes in memory span may interact with the effect of age on speech processing per se. However, the time it takes to execute a saccade is minimally affected by aging (Pratt et al., 2006). As the spoken sentence unfolds in time, tracking eye gaze reflects processing of the item at approximately the same time for older and younger adults.

Research using the visual world paradigm has found little or no age-related differences in online processing of spoken words when no other competitor is presented, whereas these same studies have found age-related differences in accuracy and response latencies (Ayasse et al., 2017; Ben-David et al., 2011). For example, Ayasse et al. (2017) presented spoken sentences with predictive semantic context (e.g., "You cannot open the door with the wrong key") to older and younger listeners. Age-related slowing was found in overt response latencies (placing the computer cursor on the verbally referenced target), while eye gaze on the referenced target revealed no age-related difference, suggesting similar semantic context facilitation in online processing for both age groups (for similar results using morphosyntactic context, see Huettig & Janse, 2016).

In contrast to these relatively preserved abilities, older adults' recognition of words has generally been found to be more susceptible than younger adults' to interference from words that share similar sounds with a target word (Rogers & Wingfield, 2015; Sommers, 1996; Sommers & Danielson, 1999) or that might be suggested by the same semantic context as a target word (Lash et al., 2013). This interference was noted both in offline (reduced accuracy and increased latency) and online measures, using eye tracking (slower fixations on the target, e.g., Revill & Spieler, 2012). Furthermore, as this interference was evident independently of differences in hearing acuity, it suggests that effects are due to a more central, cognitive source (Rogers et al., 2012; Rogers & Wingfield, 2015).

The inhibition deficit hypothesis in aging (Hasher et al., 1991; Hasher & Zacks, 1988) has been suggested as an account for this age-related vulnerability to interference in word recognition from semantically or phonologically related words (e.g., Lash et al., 2013; Sommers & Danielson, 1999). This has been supported by a large body of research showing that older adults are less able than younger adults to ignore irrelevant information and inhibit activation of unselected stimuli in the visual (Ben-David et al., 2014; McDowd & Shaw, 2000; Troyer et al., 2006) and in the auditory domain (e.g., Lash et al., 2013; Rogers & Wingfield, 2015; Sommers & Danielson, 1999; Tun et al., 2002). Although the inhibition deficit hypothesis has retained a prominent position in the literature on cognitive aging, there has been a debate about its generalizability across different tasks, its relation to speed of processing (Cerella, 1990; Cerella & Hale, 1994; Verhaeghen, 2013), and the locus of the deficit (Burke, 1997; Burke & Osborne, 2007). In the domain of language processing, the question is whether the inhibition deficit involves interference in the early stage of lexical activation, a late-stage difficulty in inhibiting competing responses, or both.

A possible direction regarding the locus of interference comes from a recent study by Ayasse and Wingfield (2020). In a visual world paradigm, older and younger adults were asked to use a computer mouse to click on the written word corresponding to the final word of a spoken predictive context sentence. While no age-related differences in eye gaze were documented when the target word was flanked by a semantically unrelated written word, older adults were slower than younger adults to gaze at the target word in the presence of semantic competitor. The authors suggested this as evidence for interference operating early in the spoken word recognition process in older age. However, as no information on the overt response latency was obtained, it is possible that an age-related increase in late interference was also involved. Furthermore, because the authors presented two options rather than four on the monitor, it remains unclear whether the presence of a competitor interfered by increasing the rate of fixations on the competitor, or by decreasing fixations on the target.

The Current Study

The goal of this study was to compare the efficiency of older and younger adults on their use of predictive semantic context in speech processing, as viewed through the lens of both online and offline measures. Specifically, while offline studies suggest that older adults can use context on word recognition at least as efficiently as younger adults (e.g., Benichov et al., 2012; Pichora-Fuller et al., 1995; Wingfield et al., 1991), less is known on the separate effects of predictive context on offline versus online measures. Similarly, while age-related inhibition deficits have been widely documented in the literature, it is not clear whether the interference effect of a semantic competitor on word recognition occurs early-stage, during online word processing, late-stage at the end point of processing (as appears in response execution), or across both stages. The current study tests context processing with and without competition in online (eye gaze) and offline (response latency and accuracy) measures. With the availability of both measures in a single experiment, it will be possible to determine whether any age-related effects observed in contextual facilitation or in stimulus competition will yield parallel or dissociative effects in these two measures.

In order to address these questions, we used an adaptation of the visual world paradigm. Participants were presented with four images, and asked to touch the image on a computer screen representing the final word of a spoken sentence. We used sentences that either did or did not contain predictive information (e.g., *"In winter, better take an umbrella"* vs. *"On the display, there is an image of a book"*). Half of the predictive context trials were competition trials, in which two of the four images were as likely to serve as a target word (in the example above, the two images might be an *umbrella* and a *coat*) and the other half presented no such competition. Both offline measures (response accuracy and latency to touch response) and online measures (eye gaze on the target image) were recorded as the sentence unfolds in time.

Method

Participants

Participants were 30 younger adults (24 women, six men) with a mean age of 25 years (SD = 1.65 years) and 30 older adults (23 women, seven men) with a mean age of 71 years (SD = 5.76 years). The younger adults were undergraduate students at the Interdisciplinary Center Herzliya who received partial course credits for their participation. The older adults were community-dwelling volunteers who were paid 35 NIS (approximately $10) for their participation. All participants were native Hebrew speakers or had learned Hebrew before the age of 6 years, as indicated by a self-report (Ben-David & Icht, 2016). This was further confirmed by the Vocabulary subtest of the Hebrew version of Wechsler Adult Intelligence Scale–Third Edition (Goodman, 2001), with all participants scoring within the clinically normal range for their age groups (within 1 SD from the average for their ages, see Table A1 in Goodman, 2001) with no significant difference between groups (M = 41.2, SD = 3.9 and M = 43.6, SD = 7.46 for younger and older, respectively; $t(58) = 1.81$, $p = .075$). All participants had digit span scores within the clinically normal range for their age group (within 1 SD from the average for their ages, see Table A1 in Goodman, 2001) with no significant difference between groups (M = 16.5, SD = 3.1 and M = 15.4, SD = 3.2 for younger and older, respectively; $t(58) = 1.38$, $p = .171$). None of the participants had a self-reported history of stroke, Parkinson's disease, or other neurologic involvement that might compromise their ability to perform the experimental task.

Audiometric assessment was conducted using a MAICO MA-51 audiometer using standard audiometric procedures in a sound attenuating testing booth. Although as expected (Morrell et al., 1996), the younger adults had better hearing than the older adults, with the younger adults having a mean pure-tone threshold average (PTA) across 0.5, 1, and 2 kHz of 5.7 dB HL (SD = 3.5) and the older adults a mean PTA of 18.1 dB HL (SD = 4.6), both groups fell within the range considered to be clinically normal hearing for speech (PTA < 25 dB HL; Katz, 2002). None of the participants reported regular use of hearing aids and all testing was conducted unaided. All participants had normal or corrected-to-normal vision, as tested using Landolt C charts for near vision. When necessary, participants used their own corrective eyewear throughout the experiment. The study received ethics approval from the Interdisciplinary Center Ethics Committee and all participants signed a written informed consent.

An a priori power analysis in G*power (Faul et al., 2009) assuming a small effect size ($\eta_p^2 = .04$, $f = .20$, a conservative estimate targeting 10% of the minimal effect found in a parallel study by Ayasse & Wingfield 2020, $\eta_p^2 = .41$) and a medium correlation between repeated measures (.5) suggested 27 participants in each group to obtain .95 power; 30 participants in each group were recruited.

Stimuli

Auditory Stimuli

The speech stimuli consisted of 200 recorded sentences, with the last word of each sentence representing the name of a target object that would appear on a computer screen. Sentences were recorded onto computer sound files by a native Hebrew-speaking female in a professional radio studio (Interdisciplinary Center Radio) using a sampling rate of 48 kHz. The root-mean-square intensity was equated across all recorded sentences.

The recorded sentences either had a meaning that increased the likelihood of the sentence–final word (semantic context) or that did not contain any semantic cues to the final word (no context sentences). In both cases, the final word was a concrete noun that was the name of a picturable object. As illustrated in the example in the bottom panel of Figure 2, each context sentence had three components. The first contained the predictive cue (/kedaj baxoref/

– "In the winter"), the second was a filler phrase that carried no information (/lehistovev im/ – "better take"), and the third was the target noun, (/mitrija/ – "[an] umbrella"). In the no-context condition, the noun would be preceded by the noninformative phrase (/jeʃ batet͡suga tmuna ʃel sefer/ – "On the screen there is an image of a book"). A list of the context sentences can be found in Appendix A.

A preliminary study was conducted to confirm that the semantic context sentences were predictive of the sentence–final words. Twenty-five undergraduates who did not serve in the main experiment read each of the context sentences with the final word (target word) missing. For the *semantic context/no competition* condition, instructions were to indicate which of four images displayed on a computer screen was the best match to the likely missing final word of the sentence. For the *semantic context/semantic competition* condition, instructions were to indicate which two of four images on the screen might match the likely sentence–final word. Sentences were chosen for the experiment if at least 95% of the responses corresponded to the intended target word(s).

Visual Stimuli

On each trial participants saw four images displayed in the four corners of a 3 × 3 grid on a touch screen computer monitor (T 23" ATCO infrared 4096 × 4096). Object images were taken from the normed color image set of Rossion and Pourtois (2004), supplemented by images from commercial clip art databases selected to match the Rossion and Pourtois images in visual style. A pretest confirmed that all of the images were clearly identifiable, familiar, and had uniform name agreement.

For the semantic context/no competition, only one of the four images matched the sentence-final object name (*target image*). In the semantic context/semantic competition trials, two of the depicted four images matched the sentence-final object name (*target and competitor image*). The remaining three (no competition) or two (semantic competition) images (*filler images*) were always unrelated either to the context sentence or to the target image(s). Their Hebrew names were also dissimilar in phonology to the target image name. To control for unintended effects, such as word frequency predictability effects, the allocation of images as target, competitor, or filler was counterbalanced across participants. For that end, we created five versions of the experiment; in each version, 100 trials were displayed: 10 semantic context/no competition and 10 semantic context/semantic competition (out of a pool of 50 sentences), 30 no context sentences, and 50 filler sentences (out of a pool of 150). The relative positions of target(s) and fillers within the grid displays were counterbalanced across displays. An example of a stimulus array for a semantic context/semantic competition presentation is shown in Figure 3, in which either an umbrella or a coat could be implied by a sentence starting with "*In the winter….*"

Procedure

Participants were tested individually in an IAC sound attenuating booth, seated 60 cm from the computer screen with their head placed in a chin rest to stabilize head movements. Eye movements were recorded via a table-mounted SR EyeLink 1000 eye-tracking system (SR Research) that sampled eye gaze position every 2 ms.

The experiment began with a calibration procedure followed by three practice trials to familiarize participants with the task and instructions. This was followed by the main experiment consisting of 100 sentences: 10 semantic context/no competition sentences, 10 semantic context/semantic competition sentences, and 30 no context sentences, with 50 filler trials intermixed in presentation. Each trial began with a visual alerting cue consisting of a black dot centered on the computer screen, followed by the appearance of the 3 × 3 grid containing four images, one at each corner of the grid. Participants had 2 s to examine the images and their positions on the computer screen, after which a fixation cross appeared at the center of the grid. Participants were instructed to touch the fixation cross with the index finger of their dominant hand, at which point the fixation cross disappeared, and the recorded sentence was presented. Participants were instructed to listen carefully to the sentence and to touch the image that best matched the final word of the sentence as fast as possible, but without making careless errors. To encourage accuracy, a feedback signal appeared over the participant's selection; a green square if correct and a red square if incorrect. Stimulus sentences were presented binaurally via a MAICO MA-51 audiometer using TDH 39 supra-aural headphones at 45dB above each participant's worst ear PTA.

Data Collection

Data was collected via the Data Viewer software (SR Research). Interest areas were defined in rectangular regions around each image following the grid. The samples were then grouped and binned into 20 ms time bins, with 10 samples summed per bin. The proportions of fixation to each of the images on the screen were calculated over 20 ms time bins throughout each trial. Trials with incorrect response were not analyzed. Overt response accuracy was measured as percentage of trials in which the correct image was touched by the participant; latency was measured as the time in milliseconds from the onset of auditory stimuli (the beginning of the sentence) to the touch response.

Statistical Analyses

All of the following analyses used mixed-model, repeated-measures analyses of variance (ANOVAs; Generalized Linear Model) with planned comparisons. Partial eta squared (η_p^2) was used as the measure for power in all statistically significant tests, and p values set at .05 to indicate significance.

Results

Behavioral Responses

Participants were highly accurate in selecting object images that matched the sentence–final words. Younger adults performed the task with 100% accuracy, and older adults performed with 99.6% accuracy, with a total of 14 errors (out of 3,000 trials), six of them in nonfiller trials, and no more than one error per participant.

Figure 1 and Table 1 show mean latencies to correct responses as measured from onsets of the recorded sentences to the participants' touch on the referenced object. Data are shown for the younger and older adults for the no context, semantic context/semantic competition, and semantic context/no competition conditions.

The mean latency data shown in Figure 1 were submitted to a 2 (age group: younger, older) × 3 (trial type: coded as a dummy variable, no context, +1, semantic context/semantic competition, 0, semantic context/no competition, −1) mixed-model ANOVA, with trial type as a within-participants variable. Latency data from two participants, one older and one younger, could not be retrieved due to technical errors.

As might be expected, the older adults had generally longer latencies than the younger adults, which was confirmed by a significant effect of age, $F(1, 56) = 5.210$, $p = .026$, $\eta_p^2 = .085$. There was also a significant ordered trend for dummy variable of trial type (no context > semantic context/semantic competition > semantic context/no competition), $F(1, 56) = 254.388$, $p < .001$, $\eta_p^2 = .820$, with post hoc paired comparison testing confirming longer latencies in the no context condition than in the semantic context/semantic competition condition, $t(57) = 15.95$, $p < .001$, which in turn, was longer than in the semantic context/no competition condition, $t(57) = 7.38$, $p < .001$. The appearance of a similarity in the pattern of condition effects for the two age groups was in accord with the absence of a significant trial type × age group interaction, $F(1, 56) = 0.985$, $p = .325$. That is, in terms of the behavioral responses, both the younger and older adults' behavioral response latencies were slowed by the presence of a semantic competitor, but there was no evidence that the older adults were differentially slowed.

Patterns of Eye Gaze

A total of 5.3% of the trials collected from all participants were excluded from analysis, as no target fixations were recorded. These include eight semantic context trials (four for older and four for younger adults), 13 competition trials (eight and five for older and younger adults, respectively), and 140 no context trials (60 and 80 for older and younger adults, respectively) out of 3,000 analyzed trials.

For the analysis of semantic versus no context trials (Section 1 of the Results), removed trials exceeded 20% for three participants (two older and one younger adult). Appendix B presents this analysis conducted for 57 participants excluding these three participants. Note that all of the main trends were replicated. In the analysis of competition trials (Section 2 of the Results), none of the participants exceeded 20% removed trials; hence, no further analysis was called for.

For each 20-ms time bin, percentage of fixations to each one of the image types (target, unrelated, and semantic competitor if displayed) were averaged. Next, analyses were conducted separately in four consecutive time frames, taking into account that it takes about 200 ms to program and launch a saccadic eye movement (Hallett, 1986): (a) 1000–1680 ms, corresponding to the presentation of the semantic cue (if exists, e.g., "*In the winter*…"), or the no context sentence (e.g.,

Figure 1. Mean latencies to correct responses as measured from onsets of recorded sentences to the participants' touch on the referenced object. Data are shown for the younger and older adults for the no context, semantic context/semantic competition, and semantic context/no competition conditions. Error bars indicate 1 *SE*.

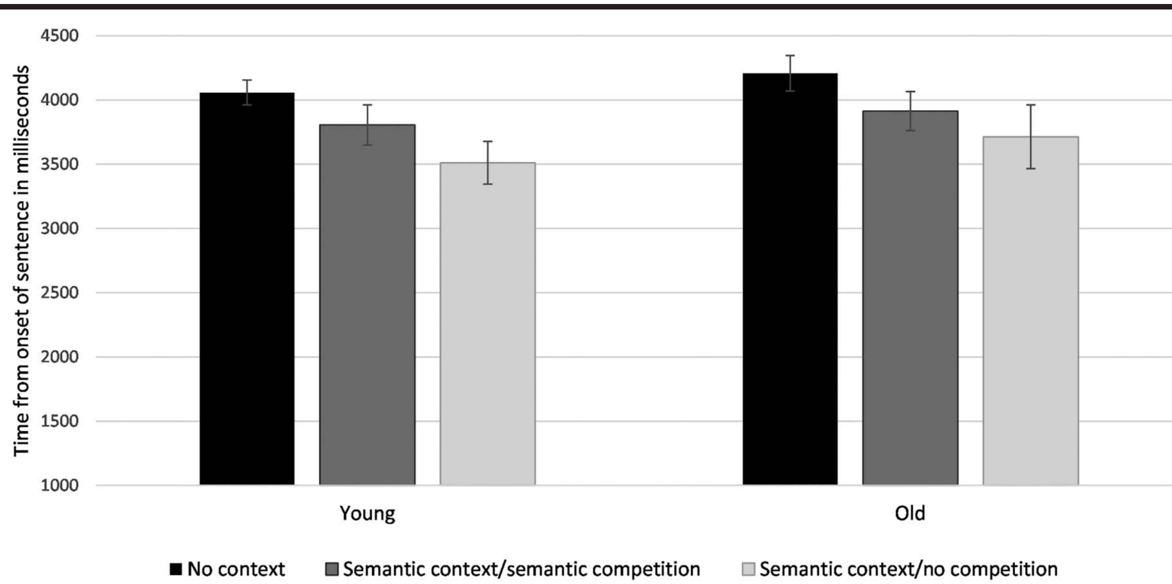


Table 1. Mean and standard deviation of latency (in milliseconds) for touch response on the target (measured from the onset of the sentences), as a function of the different trial types: no context, semantic context/semantic competition, and semantic context/no competition.

	No context	Semantic context/ semantic competition	Semantic context/ no competition
Younger adults	4,028 (261)	3,775 (297)	3,448 (475)
Older adults	4,209 (198)	3,897 (315)	3,697 (337)

"*On the display*…"); (b) 1700–2880 ms, cue-processing after the full semantic context has been heard but before target-word onset. A filler phrase was presented at that time (e.g., "…*where is*…"), (c) 2900–3180 ms, corresponding to the presentation of the onset of the target word; and (d) 3200–3500 ms, corresponding the processing of the complete target word.

Figures 2 and 3 provide a visual description of the averaged eye gaze data. The top panel of Figure 2 shows the proportion of fixations to the target image as the sentence unfolds in time for older (black lines) and younger (gray lines) adults in the following two conditions: no context (dashed lines) and semantic context/no competition (solid lines). The bottom panel of Figure 2 presents the acoustic waveform of two example sentences that represent the two conditions, with the different segments of the sentence marked as shaded rectangles. The four time frames described above are marked below the eye gaze graph. Recall that time frames begin 200 ms after each acoustic event. Figure 2 clearly shows that semantic context leads to earlier fixations on the target for both age groups. When no context is presented, older and younger adults' eye gaze appears to be highly similar. When semantic context is presented, younger adults appear to reap a larger early gain from context relative to older adults, as evident in the second time window. By the third time window, this younger adults' advantage disappears.

Figure 3 similarly presents eye gaze data for the semantic context/semantic competition condition. Here, an age-related difference appears only in the fourth time window, after the spoken word has been fully heard.

The Advantage Accrued by Semantic Context: Age-Related Differences

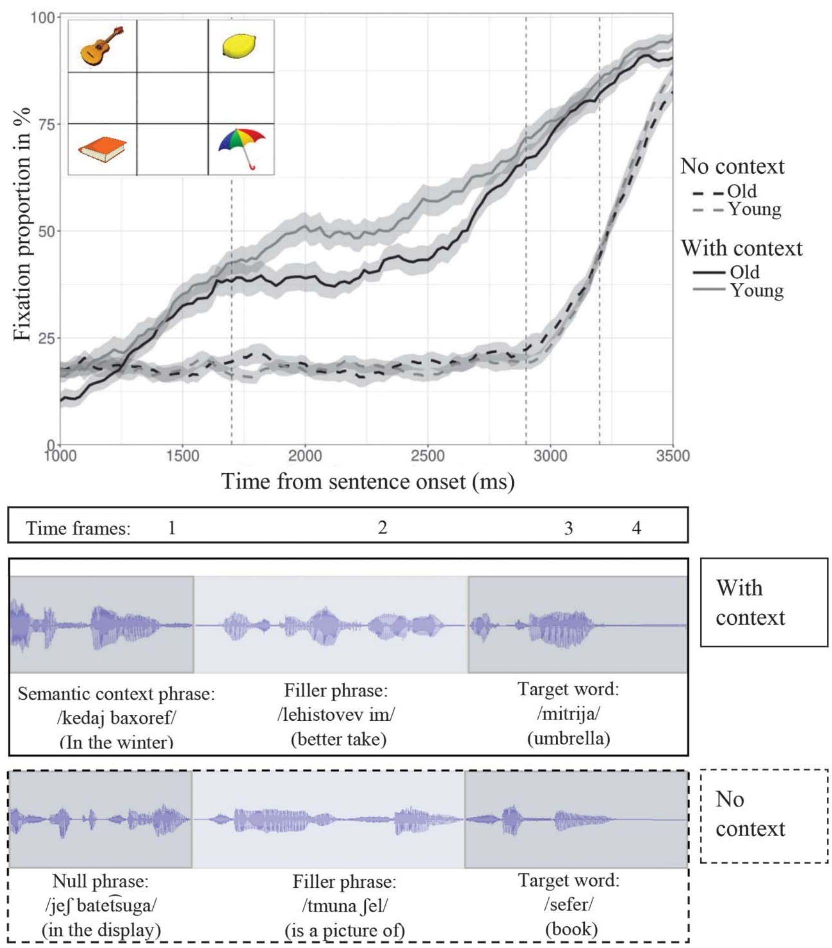
In the following analyses, separately for data in each time frame, we conducted a 2 (object: target, average of three unrelated images) × 2 (condition: no context, semantic context/no competition) × 2 (age group: older, younger) mixed-model, repeated-measures ANOVAs, with object and condition as within-participant variables and age group as between-participants variable.

Time Frame 1 – cue presentation. ANOVA indicated a main effect for object, $F(1, 58) = 30.235$, $p < .001$, $\eta_p^2 = .343$, with a larger proportion of fixations to the target than to the unrelated images, and a main effect for condition, $F(1, 58) = 20.193$, $p < .001$, $\eta_p^2 = .258$, with more fixations initiated when a semantic context was presented. The two effects interacted significantly, $F(1, 58) = 20.350$, $p < .001$, $\eta_p^2 = .260$. Planned contrasts indicated that the advantage of fixations to the target over the unrelated images was evident only when a semantic cue was present, $t(59) = 5.82$, $p < .001$, but not when it was absent, $t(59) = .76$, $p = .449$. Most importantly, age group membership did not yield a significant main effect, $F(1, 58) = 2.843$, $p = .097$; a significant interaction with condition, $F(1, 58) = 0.867$, $p = .356$; with object, $F(1, 58) = 0.006$, $p = .940$; or a triple interaction, $F(1, 58) = 1.547$, $p = .219$. In sum, when the semantic cue was presented, we found an early activation of the target over unrelated images, but age group did not lead to any change in this performance.

Time Frame 2 – cue processing. The two main effects and their interaction were replicated in this time frame: An advantage of fixations to the target over average unrelated images (main effect for object), $F(1, 58) = 285.570$, $p < .001$, $\eta_p^2 = .831$; increased fixations when a semantic cue was presented (a main effect for condition), $F(1, 58) = 252.738$, $p < .001$, $\eta_p^2 = .813$; and an interaction of the two effects, $F(1, 58) = 383.279$, $p < .001$, $\eta_p^2 = .869$. However, in the second time frame, we note a significant main effect for age group, $F(1, 58) = 4.765$, $p = .033$, $\eta_p^2 = .076$; a significant interaction of age group and condition, $F(1, 58) = 4.353$, $p = .041$, $\eta_p^2 = .070$; and a triple interaction of age group, condition, and object, $F(1, 58) = 12.217$, $p = .001$, $\eta_p^2 = .174$. As presented in Figure 2, this triple interaction is the result of a larger advantage of gaze to target over unrelated images accrued by the presence of the semantic cue for younger than for older adults in this time frame. Indeed, post hoc analyses (age group × condition interactions conducted separately for objects, using Bonferroni correction with p set at .006) revealed that the proportion of target fixations increased by the presence of a semantic cue for younger adults to a larger extent than for older adults, $F(1, 58) = 9.051$, $p = .004$, $\eta_p^2 = .135$, and the proportion of fixations to unrelated images decreased to a larger extent for younger than for older adults, $F(1, 58) = 10.224$, $p = .002$, $\eta_p^2 = .150$.

Time Frames 3 and 4 – hearing the target word. Once the word has been presented, in both time frames that represent the onset and the offset of the spoken word, analyses replicated the two main effects, for object (the advantage of fixations to the target over average unrelated images, $F(1, 58) = 719.636$, $p < .001$, $\eta_p^2 = .925$, and $F(1, 58) = 2942.636$, $p < .001$, $\eta_p^2 = .981$, for Time Frames 3 and 4 respectively), for condition (the advantage of trials that present the context over ones that do not, $F(1, 58) = 416.032$, $p < .001$, $\eta_p^2 = .878$, and $F(1, 58) = 204.814$, $p < .001$, $\eta_p^2 = .779$, respectively), and their interaction (with larger advantage of target over unrelated images when a semantic context was present, $F(1, 58) = 609.500$, $p < .001$, $\eta_p^2 = .913$, and $F(1, 58) = 271.598$, $p < .001$, $\eta_p^2 = .824$, respectively). However, age-group did not generate a main effect, $F(1, 58) = 1.630$, $p = .688$, and $F(1, 58) = 1.923$, $p = .171$, or any double or triple interaction, $F(1, 58) < 1.662$, $p > .202$.

Figure 2. Top panel: proportions of looks to the target image in the semantic context and no context conditions (ribbons represent standard error of the mean). Vertical lines represent the four time frames: (a) 1000–1680 ms (presentation of the semantic cue, if existed); (b) 1700–2880 ms, cue-processing after the semantic context has been heard but before target-word onset (a filler phrase is heard); (c) 2900–3180 ms, corresponding to the presentation of the onset of the target word; and (d) 3200–3500 ms, corresponding the processing of the complete target word. Bottom panel: representation of waveform for example sentences for both conditions; shaded rectangles represent the different segments of the sentence. Time frames begin 200 ms after each acoustic event. In the upper left panel, an example of visual stimuli fitting for both sentences.



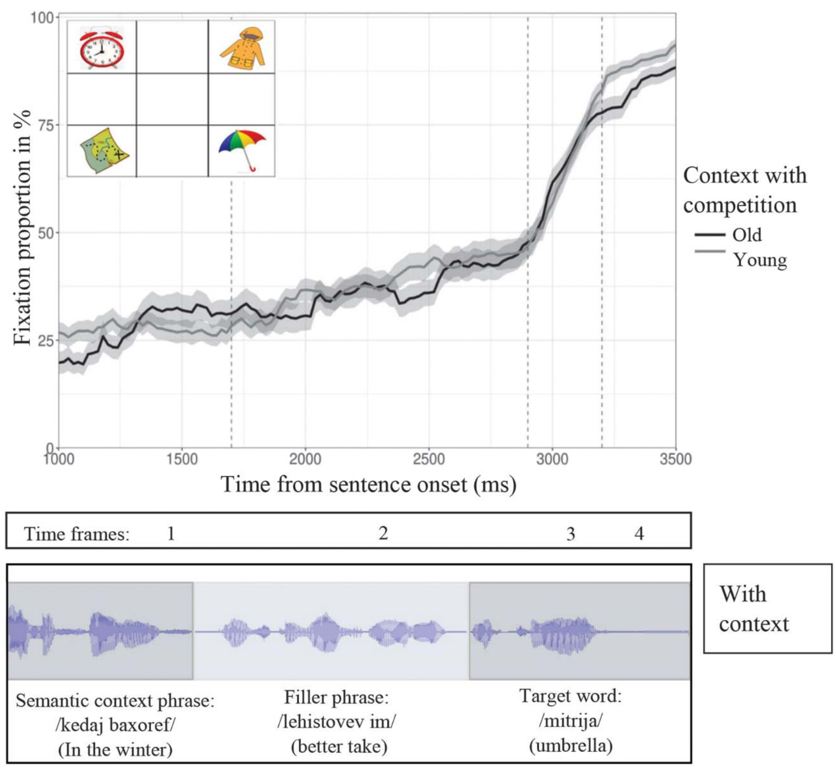
The Activation of a Semantic Competitor: Age-Related Differences

The previous analyses gauged age-related effects in the advantage of fixations on target over unrelated images in two conditions: no context and semantic context/no competition. Here, these effects are examined in the condition in which the semantic context leads to two alternative images. This is illustrated in Figure 3. The previous analyses were conducted separately for data in each time frame: a 2 (object: target, average of two unrelated images) × 2 (age group: older, younger) mixed-model, repeated-measures ANOVA, with object as a within participant variable and age group as a between participant variable.

In all four time frames, we found a significant main effect for object, with more fixations on the target than on the average of unrelated images, $F(1, 58) = 134.464$, $p < .001$, $\eta_p^2 = .699$; $F(1, 58) = 354.882$, $p < .001$, $\eta_p^2 = .860$; $F(1, 58) = 795.157$, $p < .001$, $\eta_p^2 = .932$; $F(1, 58) = 3637.029$, $p < .001$, $\eta_p^2 = .984$ (for Time Frames 1, 2, 3, and 4 respectively). Notably, in Time Frames 1, 2, and 3, no main effect for age group was observed, $F(1, 58) = 0.299$, $p = .587$; $F(1, 58) = 0.231$, $p = .632$; $F(1, 58) = 0.138$, $p = .711$, and the effect of object and age group did not lead to a significant interaction, $F(1, 58) = 0.029$, $p = .865$; $F(1, 58) = 0.452$, $p = .504$; $F(1, 58) = 0.045$, $p = .833$, for Time Frames 1, 2, and 3, respectively.

This was not the case in the fourth time window. Once the complete target word has been heard, we see no main effect for age group, $F(1, 58) = 2.808$, $p = .099$, but a significant interaction of object and age group, $F(1, 58) = 7.655$, $p = .008$, $\eta_p^2 = .117$. This interaction reflects the observation that the advantage of target over averaged unrelated images was smaller in the fourth time frame for older than for younger adults.

Figure 3. Top panel: proportions of looks to the target image in the semantic context/semantic competition condition as the sentence unfolds in time for both age groups (ribbons represent standard error of the mean). Vertical lines represent the four time frames: (a) 1000–1680 ms (presentation of the semantic cue); (b) 1700–2880 ms, cue-processing after the semantic context has been heard but before target-word onset (a filler phrase is heard); (c) 2900–3180 ms, corresponding to the presentation of the onset of the target word; and (d) 3200–3500 ms, corresponding the processing of the complete target word. Bottom panel: representation of waveform for an example sentence; shaded rectangles represent the different segments of the sentence. Time frames begin 200 ms after each acoustic event. In the upper left panel, an example of visual stimuli that consists of two viable options to end the sentence (umbrella and coat).



In a separate analysis, fixations on the competitor were compared between older and younger adults, in each time frame. No age-related difference was indicated in any of the time frames, $t(58) = 1.77$, $p = .080$; $t(58) = 1.16$, $p = .248$; $t(58) = 0.69$, $p = .487$; and $t(58) = 0.21$, $p = .831$, for Time Frames 1, 2, 3, and 4, respectively.

In sum, when the context led to two possible images, the younger adult advantage disappeared during context processing, only to reappear in the final time window, once the full word has been spoken. This late advantage was not the cause of increased fixations on the competitor for older relative to younger adults.

Discussion

The purpose of this study was to assess age-related differences in the processing of predictive semantic context, and the inhibition of semantic competitors, as a spoken sentence unfolds in time. Younger and older adults listened to sentences and were instructed to touch an image presented on the monitor representing the last word of the sentence. Three conditions were used: a nonpredictive sentence, a sentence predictive of the final word (semantic context), and a predictive sentence suggesting two possible images, the final word and a semantic competitor (semantic context with competition). Both offline measures (response accuracy and latency) and online measures (eye movements) were taken.

Offline measures did not reveal a differential age-related difference in the advantage accrued by a semantic context, or in the disadvantage resulting from semantic competitor (even if older adults produced generally slower screen-touch responses). On the other hand, online eye gaze measures revealed significant age-related differences in context processing with and without competition. When context was presented without competition, older adults were slower than younger adults to gaze on the target image after the semantic cue and before target presentation (noting that the effect size was not large). This age-related difference was diminished once the first phoneme of the word had been heard. When context was presented with competition, there were no age-related differences prior to the presentation of target word, but older adults were slower than younger adults to gaze at the target word after it was presented, suggesting greater interference by the presence of a competitor.

Studies using traditional offline measures, such as recognition thresholds for words presented in noise or recognition from word onsets, have yielded the common finding that hearing a word within a sentence context facilitates its recognition for both younger and older adults (Cohen & Faulkner, 1983; Dubno et al., 2000; Fischler & Bloom, 1979; Heinrich et al., 2015; Pichora-Fuller, 2008; Wingfield et al., 1991). Although the older adults in this study were generally slower in our offline touch response measure, they showed the same relative gain in response latencies as younger adults when a word was presented within a constraining sentence context.

The use of eye gaze as an online measure of processing time revealed several features not available from offline measures alone. One of these was the finding that eye gaze to a target in the no-context condition had a similar timeline for both age groups. This would suggest that older adults' slower offline touch responses were due to motoric slowing, rather than an effect of postulated generalized cognitive slowing (Cerella, 1990; Cerella & Hale, 1994; Salthouse, 1985, 1996). Ayasse et al. (2017), using the visual world paradigm, also found older adults to be slower than younger adults in giving an overt response (clicking on the target image using a computer mouse). However, their older adults' eye gaze toward the target image was not slower than younger adults' eye gaze. Taken together, these findings suggest task-dependent, age-related slowing, rather than general slowing of all central cognitive processes.

Our study is not the first to show that age-related differences, often found in offline measures of speech processing, are not apparent when online measures are implemented, and no context is available (hinting that different stages of processing are gauged). For example, when Ben-David et al. (2011) used eye tracking to examine online processing of a single spoken word in ideal listening conditions, no differences were found between younger and older listeners. Our current data extends this to a spoken sentence as long as no predictive context is present. In fact, one may consider the baseline sentences in our study that carry no semantic information (e.g., "*on the display there is an image of a book"*) as equivalent to carrier sentences often used in single-word processing studies (e.g., "*point at the..*"; Hadar et al., 2016; Nitsan et al., 2019).

When in the competition condition, the context led to two viable options, younger adults were faster than older adults to resolve the conflict between the spoken target word and its' semantic competitor. Once the word had been heard, we observed residual age-related slowing in spoken word processing. This delay may reflect difficulties older adults have in using the incoming acoustic information to inhibit the activation of the semantic competitor. The reduced ability of older adults to inhibit lexical competitors is consistent with an age-related inhibition deficit (Hasher & Zacks, 1988; Lustig et al., 2007) and coincides with existing literature showing that older adults are less able to suppress irrelevant competitors than younger adults, whether the competitors are phonological, or in this case, semantic (Ayasse & Wingfield, 2020; Lash et al., 2013; Sommers & Danielson, 1999).

It is notable that the age-related inhibitory deficit in this study was not evident in an analysis of the offline measure of response latency, but only in an analysis of online eye gaze. Although this is not the first study to use the visual world paradigm to compare online and offline measures of word recognition of words heard within a sentence context (see Ayasse et al., 2017), it is, to our knowledge, the first to compare the effects of semantic competition using both online and offline measures. In our data, once the target word has been presented, older adults were differentially slower than younger adults to gaze at the target word when the semantic context led to two viable alternatives. However, this interference appeared not to have had a residual effect on response activation and execution, as the differential effects of competition observed with eye gaze did not carry through to the response latencies. This appears to support an early-stage, age-related inhibition deficit, where the presence of a semantic competitor slows the activation of the target word as it unfolds in time, rather than a late-stage failure to inhibit an activated competitor slowing the response. That is, it appears that an age-related inhibition deficit that slowed activation of the target was resolved once a recognition decision had been made and the recognition response executed. These findings further support the importance of investigating speech processing in aging via the lens of online processes, rather than only examining overt offline responses.

Limitations and Future Studies

This study was conducted in a sound attenuated booth, in optimal listening conditions. Clearly this does not mimic real-life situations, where speech is often masked by background noise and listeners are actively involved in concurrent resource-demanding tasks. It is thus possible that the age-related effects and their absence in this study may not be replicated under more challenging listening conditions (see Ben-David et al., 2012; Tun et al., 2002). Future studies may wish to address this by testing the effects of predictive context and competition among younger and older adults while mimicking the challenges listeners face in daily communication such as adverse listening conditions (e.g., speech in noise, rapid speech) and dual-task protocols (e.g., hearing speech while engaging in another task), or both. Our current findings, however, form a necessary basis for such future studies.

Conclusions

In the current paper, we compared older and younger adults' processing of spoken semantic context with and without semantic competition, using both online and offline measures. While traditional offline measures were not able to reveal the complex effect of aging on spoken context use, online measures suggest that older adults process context differently than younger adults. In addition, age-related decrease in inhibition efficiency was noted in online measures, as older adults were slower than younger adults to gaze on the target image in the presence of a semantic competitor. However, offline latency measures did not reveal such age-related differences in inhibition. In sum, age-related effects on speech processing are complex, indicating different processing and target activation trends, often visible only when online measures are employed.

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Appendix A

Semantic Context Sentences Used in the Study, Translated From Hebrew to English

1. In winter, better take an umbrella.
2. My hair is wild, where is the brush?
3. Lets' start driving, where is the taxi?
4. We went to the garden and there we saw a seesaw.
5. Let's drive to the beach, there is a bus.
6. It's dark here, where is the flashlight?
7. I'm hungry, maybe we could order pizza.
8. I hear music, where is the piano?
9. Let's wash hands, where is the soap?
10. I want to sit down, there is a bench.
11. I want to eat, is there a salad?
12. In the furniture store, where is a couch?
13. Keep driving until you see a road sign.
14. Look to the skies, where is the sun?
15. In a furniture store, there is a desk.
16. In the clothing store, you can find a sweater.
17. At the electronic store, I buy an oven.
18. I'm in the electronic store, where is a TV?
19. My head hurts, where is a medicine?
20. I want something sweet, where is the cake?
21. I'm doing laundry, there is a t-shirt.
22. From the window at night, you can see the moon.
23. Yesterday at the grocery store, I bought some eggs.
24. Making a salad, where's the tomato?
25. In the bathroom, you can find a toilet.
26. She wants to drink, where is the bottle?
27. For fruit salad, I'm cutting a banana.
28. I came home, where is the door?
29. In the stationery store, you can find a pen.
30. On a desert trip, you can see a camel.
31. Yesterday on safari, everybody saw a giraffe.
32. I hear music, where is the guitar?
33. In the pencil box, you can find a pencil.
34. Early in the morning, I'm having coffee.
35. Let's start eating, where there's a spoon?
36. Let's wash hands, where there's a sink?
37. After the food, please order me a cola.
38. I want to drink, where is a glass?
39. I am hungry, I bought some bread.
40. In the classroom, there is a board.
41. I saw a doctor, holding a thermometer.
42. Close the door, where is the key?
43. Go take a shower, where is a towel?
44. Making a fruit salad, where's the mango?
45. For the trip, you have to take a map.
46. In the bathing bag, you can find a comb.
47. In the school bag, you can find a notebook.
48. Come and eat, where is the fork?
49. It's cold outside, don't forget the coat.
50. The room is dark, where there's a lamp?

Appendix B

Replication of Section 1 Analysis With Three Removed Participants

To ensure that removed trials did not change the results of the analysis, we describe the replication of analysis conducted in Section 1 after removing three participants (two old, one young) for whom 25% of the trials in this analysis were removed.

1.4. Time Frame 1 – cue presentation

Analysis indicates a main effect for object, $F(1, 55) = 26.524$, $p < .001$, $\eta_p^2 = .325$, with a larger proportion of fixations to the target than to the unrelated images, and a main effect for condition, $F(1, 55) = 19.207$, $p < .001$, $\eta_p^2 = .259$, with more fixations initiated when a semantic context was presented. The two effects interacted significantly, $F(1, 55) = 18.709$, $p < .001$, $\eta_p^2 = .254$, planned contrasts indicated that the advantage of fixations to the target over the unrelated images was evident only when a semantic cue was present, $t(56) = 5.588$, $p < .001$, but not when it was absent, $t(56) = .796$, $p = .429$. Most importantly, age group membership did not yield a significant main effect, $F(1, 55) = 0.672$, $p = .416$; a significant interaction with condition, $F(1, 55) = 0.200$, $p = .657$; with object, $F(1, 55) = 0.057$, $p = .813$; or a triple interaction, $F(1,55) = 0.669$, $p = .417$.

1.1. Time Frame 2 – cue processing

The two main effects, and their interaction, were replicated in this time frame: an advantage of fixations to the target over average unrelated images (main effect for object), $F(1, 55) = 271.549$, $p < .001$, $\eta_p^2 = .832$; increased fixations when a semantic cue was presented (a main effect for condition), $F(1, 55) = 232.804$, $p < .001$, $\eta_p^2 = .809$; and an interaction of the two effects, $F(1, 55) = 370.963$, $p < .001$, $\eta_p^2 = .871$. However, a triple interaction of age group, condition, and object, $F(1, 55) = 9.129$, $p = .004$, $\eta_p^2 = .142$.

Post hoc analyses (age group × condition interactions conducted separately for objects) revealed that the proportion of target fixations increased by the presence of a semantic cue for younger adults to a larger extent than for older adults, $F(1, 55) = 6.703$, $p = .012$, $\eta_p^2 = .109$, and the proportion of fixations to unrelated images decreased to a larger extent for younger than for older adults, $F(1, 55) = 8.077$, $p = .006$, $\eta_p^2 = .128$.

1.2. Time Frames 3 and 4 – hearing the target word

Once the word has been presented, in both time frames that represent the onset and the offset of the spoken word, analyses replicated the two main effects, for object (the advantage of fixations to the target over average unrelated images, $F(1, 55) = 824.750$, $p < .001$, $\eta_p^2 = .937$ and $F(1, 55) = 3084.641$, $p < .001$, $\eta_p^2 = .982$, for Time Frames 3 and 4, respectively), for condition (the advantage of trials that present the context over ones that do not, $F(1, 55) = 392.724$ $p < .001$, $\eta_p^2 = .877$ and $F(1, 55) = 199.161$, $p < .001$, $\eta_p^2 = .784$, respectively), and their interaction (with larger advantage of target over unrelated images when a semantic context was present, $F(1, 55) = 603.789$, $p < .001$, $\eta_p^2 = .917$, and $F(1, 55) = 252.661$, $p < .001$, $\eta_p^2 = .821$, respectively). However, age group did not generate a main effect, $F(1, 55) = 0.237$, $p = .628$, and $F(1, 55) = 0.489$, $p = .487$, or any double or triple interaction, $F(1, 55) < 1.150$, $p > .288$.