Efficiency of spoken word recognition slows across the adult lifespan

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Abstract

Spoken word recognition is a critical hub during language processing, linking hearing and perception to meaning and syntax. Words must be recognized quickly and efficiently as speech unfolds to be successfully integrated into conversation. This makes word recognition a computationally challenging process even for young, normal hearing adults. Older adults often experience declines in hearing and cognition, which could be linked by age-related declines in the cognitive processes specific to word recognition. However, changes in word recognition across the lifespan have not been well documented and it is unclear whether any such changes can be accounted for by hearing or domain-general cognition. Participants (N = 107) responded to spoken words in a Visual World Paradigm task while their eyes were tracked to assess the real-time dynamics of word recognition. We examined several indices of word recognition from early adolescence through older adulthood (ages 11 – 78). The timing and proportion of eye fixations to target and competitor images reveals that spoken word recognition became more efficient through age 25 and began to slow in middle age, accompanied by declines in the ability to resolve competition (e.g., suppressing *sandwich* to recognize *sandal*). This suggests a limited age range where listeners are peak performers. There was a unique effect of age even after accounting for differences in cognition and hearing thresholds. Word recognition may thus be an important marker for early changes to cognition in older adulthood and a mediator between hearing loss, quality of life, and cognitive decline.

Introduction

Typical (and atypical) aging is associated with two major changes that impact quality of life: hearing loss and cognitive decline. Both impact social functioning, which in turn predicts physical, mental and cognitive health (DuPertuis et al., 2001). A critical link between these is speech recognition. When older adults find it challenging to recognize speech, communication becomes difficult or tiring and they may withdraw from social situations. This isolation leads to psychosocial issues and potentially to cognitive decline in a downward spiral (Lin et al., 2011).

Hearing loss and cognitive decline are often studied individually, and we are only beginning to connect them (Griffiths et al., 2020; Lin et al., 2011). However, this work has neglected a critical potential mediator: the cognitive processes specifically involved in language. Even elderly adults with normal hearing often report difficulties with speech understanding in the real world (Pichora-Fuller, 2003; Pichora-Fuller & Souza, 2003). Thus, peripheral hearing loss—as measured through standard audiometry—does not account for all the language processing changes observed in aging. Beyond the ability to encode speech input, cognitive issues may prevent listeners from properly using even a well encoded input to access language.

Cognitive declines are well-documented phenomenon in aging. This work has typically focused on general cognitive skills like working memory, cognitive control, or decision making–classic measures in the neuropsychology of aging. These skills generally decline starting in middle age, and much of the variance is due to working memory and speed of processing (Salthouse, 1991). These declines have been linked to social outcomes (Béland et al., 2005; James et al., 2011; Small et al., 2012). Consistent social engagement can mitigate cognitive decline (suggesting that social support drives differences in cognition); however, there is also evidence that declining cognition may lead to less engagement (Small et al., 2012). This raises the need to investigate the types of cognitive abilities that support social engagement.

The ability to understand spoken language—speech perception—is likely a critical mediator between cognition and social engagement. Language comprehension lies at the intersection of auditory processing and cognition and could mediate auditory and cognitive declines. A normal hearing (NH) individual with poor language processing may function as if they had a hearing loss. Supporting this, older adults often report difficulty comprehending speech even when they can hear it (Pichora-Fuller, 2003). Conversely, stronger language skills could offer resilience to the effects of hearing loss, allowing people to benefit from a more socially enriched environment. Language processing is highly plastic and can adapt to novel circumstances (Clayards et al., 2008; Kapnoula & McMurray, 2016) even into older adulthood (Colby et al., 2018). This raises the possibility of interventions to improve the efficiency of language processing which in turn could improve psychosocial outcomes.

There are several known changes to language processing that accompany aging. Older adults are slower to process complex sentences (Payne et al., 2014) and exert more effort when processing speech (Ayasse et al., 2017; Tun et al., 2009), leading to fatigue. When processing speech, older adults also rely more on top-down information, showing larger effects of higher-level lexical knowledge (e.g., whether an item forms a word or a nonword, Mattys & Scharenborg, 2014) and sentential context (Pichora-Fuller, 2008). They also show greater reliance on working memory for complex sentences (Payne et al., 2014), suggesting an ability to recruit domain-general resources to offset peripheral declines. Despite clear differences in older adults' language processing, it remains unclear whether these differences are driven by domain-general age-related changes (e.g., memory systems), or language-specific changes.

Standard work on cognitive aging usually only measures language in the form of vocabulary. Since this crystallized ability is typically preserved across the lifespan, this has led to the common view that observed deficits in language *derive from* deficits in domain-general skills that do decline, like working memory. There has been some work—particularly in hearing impaired listeners—linking neuropsychological measures of domain-general cognition (Heinrich et al., 2016; Skidmore et al., 2020; Sonnet et al., 2017) to speech perception. However, it is unclear how such capacities are engaged in speech perception as few cognitive models of speech perception invoke such domain-general capacities. Further challenging the premise that decline in domain-general cognitive capacities underlies poor language, mounting work in the cognitive science of language suggests that functions like working memory are properties of the language system, not external modules (Acheson & MacDonald, 2009; Diachek et al., 2020; Fedorenko et al., 2006; MacDonald, 2016; Schwering & MacDonald, 2020). Thus, there is a need to investigate the cognitive mechanisms underpinning speech and language comprehension directly as potential factors in cognitive decline that are highly relevant to hearing loss.

One way to address this is by examining an aspect of language in which the role of domain-general cognition is likely to be minimal. To this end, the present study examines spoken word recognition across the adult lifespan. This is an ideal domain for capturing this problem for four reasons. First, word recognition bridges hearing to all areas of language (phonology, semantics, syntax). In fact, word recognition is a standard audiological assessment of hearing loss (Geller et al., 2021; Lehiste & Peterson, 1959; Owens & Schubert, 1977; Peterson & Lehiste, 1962).

Second, word recognition is cognitively challenging, tapping language-specific processes that are well understood in younger adults. Research with young NH listeners suggests lexical access – the process of recognizing a word and activating its meaning – starts by immediately activating an array of candidates as soon as any amount of input is heard. For example, after hearing *ro-* at the onset of *rocket*, listeners activate a range of words like *rocket*, *rocker*, *rock* and *robin*. As the input unfolds, a competition process plays out: candidates that best match the input remain active, and others are ruled out, until one remains (*rocket*). This is not entirely driven by bottom up match to the input: competition is observed for words that mismatch at different times (the bone in trombone; Luce & Cluff, 1998) or even words whose sounds are out of order (cat after hearing tack; Dufour & Grainger, 2019; Toscano et al., 2013). As lexical items compete, more active items inhibit less active competitors (Dahan et al., 2001;

Luce & Pisoni, 1998)—once *rocket* becomes more active than *rocker,* it actively suppresses *rocker*. This ultimately speeds the process, and helps competition resolve more completely. Thus, lexical competition is a cognitive process that balances speed, efficiency, and flexibility to achieve robust speech recognition (McMurray, Apfelbaum, & Tomblin, 2022). Importantly, these competition mechanisms have been invoked at every level of language comprehension, from individual phonemes to discourse (Altmann, 1998; Dell & O'Seaghdha, 1992; Lotto & Holt, 2011; Weber & Scharenborg, 2012). Thus, word recognition can serve as a model system for understanding the aging of language cognition more broadly.

Third, models of word recognition do not invoke general cognitive systems that are affected by age (i.e., working memory, cognitive control; Hannagan et al., 2013; McClelland & Elman, 1986). Moreover, studies of the nature of competition during word recognition in quiet show only small or no effects of domain-general cognition (Kapnoula & McMurray, 2021; Zhang & Samuel, 2018). Thus, word recognition can be used to investigate age-related changes specifically in language function that may be independent of domain-general cognition.

Finally, well-established methods can trace out the time course of word recognition on the order of milliseconds in a way that offers a close match to computational models (McMurray et al., 2010; Mirman et al., 2008). This allows us to identify age-related changes in not just how well listeners recognize words, but to characterize how the fundamental process changes with aging. In the Visual World Paradigm (VWP), participants hear a word and match it to one of four pictures. For example, participants might hear *rocket* with a display containing pictures of the target (*rocket*), an onset competitor (*rocker*, a cohort), a rhyme (*pocket*), and an unrelated word (*bubble*). Eye movements are recorded while they do this task. Participants must find the target to respond; this requires them to launch fixations while lexical access is unfolding. Fixations to each object over time capture how much that item is considered. For example, in Figure 1A, after hearing *rocket*, participants fixate both the *rocket* and the *rocker*, but by around 500 msec they suppress *rocker* (though they may briefly fixate *pocket*). By around one second, they have

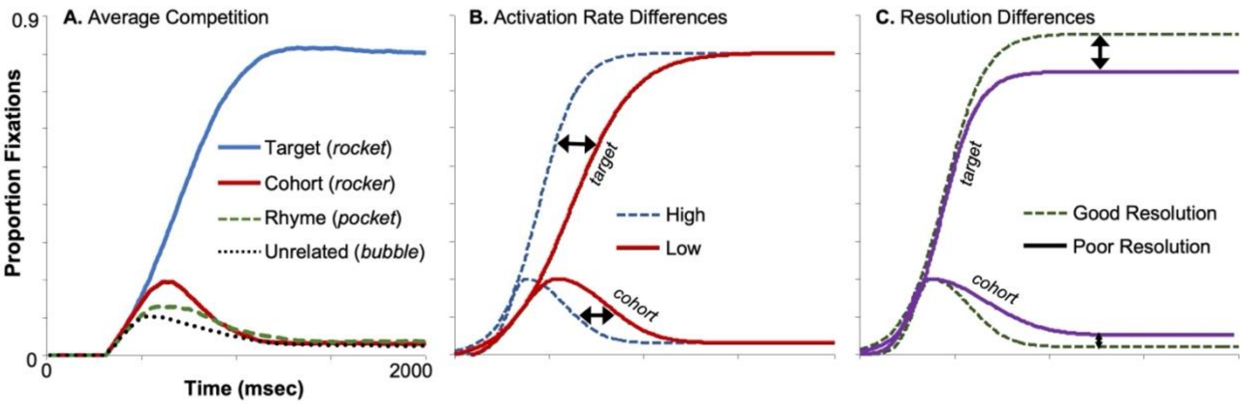

Figure 1. Average time course of fixations to different image types. A) Proportion fixations to target, cohort, rhyme, and unrelated images from the spoken word VWP experiment; B) Differences in the activation rate appear across multiple components of the curves and are associated with typical development; C) Differences in resolution affect the asymptotes and have been linked to disrupted language or challenging listening conditions.

fully committed to the target.

The VWP has been used to assess individual differences, development, disorders and challenging listening conditions (Brouwer & Bradlow, 2016; Farris-Trimble et al., 2014; McMurray et al., 2010; Rigler et al., 2015). These illustrate how word recognition is not unidimensional (McMurray, Apfelbaum, Colby, et al., 2022; McMurray, Apfelbaum, & Tomblin, 2022): typical development (through adolescence), for example, is linked to changes in the speed by which targets are activated and competitors are suppressed (Figure 1B; Rigler et al., 2015), while language disorders and challenging listening has its effects on the asymptotes as the ultimate degree of competitor suppression (Figure 1C; Brouwer & Bradlow, 2016; McMurray et al., 2010). This creates the opportunity to characterize aging in terms of both the efficiency and disruption of the underlying processes of spoken word recognition (among other dimensions).

Critically, there are also non-linguistic versions of the VWP that are closely matched to the word recognition task. These can be used to estimate the summed domain-general processes that may contribute to performance in the VWP (Farris-Trimble & McMurray, 2013), allowing us to pinpoint the contribution of aging on the dynamics of word recognition even after accounting for virtually all of the non-linguistic aspects of cognition relevant to the word recognition task. Together, this provides an unparalleled view of an aging language process.

To date, limited work has examined spoken word recognition in aging. Older adults have more difficulty managing competition: they are slower to recognize words with many competitors (Sommers & Danielson, 1999), and have difficulty suppressing competitors (Dey et al., 2017). Without sentence context, older adults require more information to recognize words (Lash et al., 2013; Wingfield et al., 1991). Most of this work, however, relies on accuracy, response time, and self-report measures that do not capture online processing, and none has examined the full lifespan nor controlled for domain-general cognitive abilities.

Several studies have used the VWP to characterize age-related changes in word recognition. Older adults are slower to fixate targets (Van Engen et al., 2020), experience more competition from high-frequency words (Revill & Spieler, 2012), and have more difficulty distinguishing targets from rhymes in noise (Ben-David et al., 2011). These effects are generally seen even after excluding trials where the participant clicks the incorrect image, suggesting differences in the process of word recognition, controlling for accuracy. This work supports the idea that they struggle to manage competition. However, these studies are limited in several regards. First, they only assess one type of competitor (either rhyme or cohort competitors; Ben-David et al., 2011; Revill & Spieler, 2012) or in the case of Van Engen et al. (2020), display no related competitors and only picture the target with unrelated distractors. In the latter case, no claims can be made about the nature of lexical competition, only about its speed. Also, the existing work has not examined the full lifespan (studies typically compare older and younger adults as discrete groups, with little to no sampling from middle age). Finally, and most importantly, these studies have not accounted for age-related changes in visual search and decision making that could also impact performance in the VWP.

We overcame these gaps with a comprehensive approach that incorporated a visual analogue of the VWP alongside the auditory spoken word VWP with a sample that spanned the lifespan. We present two different types of phonological competitors along with the target to get a more complete picture of the nature of lexical competition. Crucially, the visual VWP allowed us to control for any variance in performance that was the result of domain-general cognitive and motor performance in the VWP and leave the aspects explained exclusively by language unique to the spoken word VWP. Unlike standardized assessments of cognition or intelligence, the visual VWP is an identical task with the language modality removed, making it a better control task to factor out differences in domain-general cognition. We were thus able to isolate age-related changes to spoken word recognition from changes to processing speed and domain-general cognition, towards the goal of understanding how age impacts language-specific cognition.

Methods

Participants

Participants were recruited from the University of Iowa and surrounding communities. 111 participants between the ages of 11 – 78 participated in the study. Participants were evenly distributed across this age range, with at least 10 participants per decade of age. All participants were monolingual speakers of English and had no history of neurological or cognitive impairment. We excluded any participants who did not have a pure-tone average (PTA) of less than 30 dB HL in at least one ear (n = 4). PTA was calculated as the average hearing threshold at 0.25, 0.5, 1, 2, 4, and 6 kHz. We did not include 8 kHz in our PTA calculation to allow for some variability in high-frequency hearing loss, which is typical of age-related hearing loss (see Supplemental Figure S1 for average audiograms by age group). This left 107 individuals in our analyses of age effects (M_{age} = 47.8 years, SD_{age} = 19.5, range = 11.2 – 78.1 years). Due to missing data on subsets of tasks, the full multiple linear regressions contain data from 89 individuals. All recruitment and experimental protocols were approved by the University of Iowa Institutional Review Board.

Procedure

All tasks were completed in one visit to the lab that lasted approximately 1.5 hours. Participants were seated in front of a 19” computer screen in a sound-attenuated booth. Auditory stimuli were presented over loudspeakers placed approximately 1 meter in front of the participant. The experimental tasks were always completed in the following fixed order, following the consent process and hearing screening: the spoken word VWP was completed first, followed by the spatial Stroop task and visual VWP. For both VWP tasks, eye movements were recorded using an Eyelink 1000 desktop-mounted eye tracker with chinrest (SR Research; Ontario, Canada) sampling at 500 Hz. Before each VWP task, the eye-tracker was calibrated using a 9-point calibration and during the tasks, drift corrects were performed every 30 trials.

Spoken word VWP

Items. Stimuli sets were comprised of a target, onset (cohort) competitor, rhyme competitor, and unrelated item (e.g., *rocket, rocker, pocket, bubble*). There were 30 monosyllabic sets and 30 bisyllabic sets. These sets were developed over the course of a series of pilot studies intended to build a canonical VWP task. We started with 120 sets which were developed and piloted with 68 NH young adults. We then selected the 60 items with the most prototypical pattern of competition. The final 60 item sets were then tested for test-retest reliability in 29 young adults who completed the spoken word VWP task twice with a week delay. Test-retest correlations between our indices of interest were moderate to strong (Target activation rate: $r = 0.75$; Competitor resolution: $r = 0.62$; Peak Cohort Activation: $r = 0.54$).

Stimuli. Auditory stimuli were recorded by a female monolingual speaker of English in a sound-attenuated room sampled at 44.1 kHz. Auditory tokens were edited to reduce noise, remove clicks, and were amplitude normalized to 70 dB SPL. Visual stimuli were images from a commercial clipart database that were edited to have a cohesive style. Images were all scaled to 300 x 300 pixels.

Design and Procedure. Items from each set were used as the auditory target word once each, and then one item from each set was randomly selected to serve as the target word an additional time for a total of 300 trials (60 sets x 5 targets/set). This discourages participants from predicting the upcoming target word once the items in the display are visible (e.g., they cannot assume that once they have already heard *rocket, rocker* must be the target). Image placement was pseudo-randomized across trials and participants, such that each image type was equally likely to appear in any quadrant.

On every trial, participants saw a blue circle in the middle of the computer screen with the four images corresponding to an item set in each of the corners. After 500 msec, the circle turned red, and they clicked on it to play the auditory stimulus. Participants are instructed to click on the image that best represents the auditory target. Their eye movements are recorded while they complete this task.

Data Processing. Eye movements (fixations, saccades, and blinks) were processed using EyeLink Analysis 4.12 (McMurray, 2019). Saccades and the subsequent fixations were combined into a single unit, a look, which started at the onset of the saccade and ended at the end of the following fixation. Looks were assigned to one of four regions of interest, which were the regions that the images were displayed extended by 100 pixels. Looks were then identified as directed to one of the four image types (target, cohort, rhyme, unrelated) or to nothing. Any fixations launched before the onset of the target word (accounting for a 200 msec oculomotor delay) were ignored. Only trials where the correct target image was selected were included in further analyses as the logic of the analyses sought to identify differences in processing (given accurate word recognition), not differences in accuracy. Accuracy was high for all ages. For participants younger than 32.4, mean accuracy was 99.3%. For participants between the ages of 32.4-53.7, it was 99.4%. For participants between the ages of 53.7-66.1, it was 99.5%, and for the oldest participants (66.1 +), accuracy was 99.1%. Note that these age groups were created for descriptive purposes by dividing the participant sample into equally sized groups. All statistical analyses treat age as a continuous variable.

For each participant, average fixations to each item type at each sampling point was calculated (every four msec). Nonlinear curves were then fit to each participant's data (Farris-Trimble & McMurray, 2013) using a constrained gradient descent that minimized the least squared error between the function and the data (McMurray, 2020). Target looks were fit with four-parameter logistic curves which include: the upper and lower asymptotes, the crossover (the point in time where the function switches) and the slope (the derivative at the crossover). Cohort, rhyme and unrelated competitor curves were fit with an asymmetric Gaussian with six parameters: the initial and final asymptotes, the location and height of the peak, and the onset and offset slopes. We used the parameters from these functions to derive theoretically-meaningful indices that capture characteristics of each participant's looks. *Activation rate* captures the speed of target activation and was indexed by *target timing*. Slope and crossover values were log-transformed and z-scored for standardization. Crossover was multiplied by -1 and then the two values were averaged into a composite score of timing (where higher = faster). *Competitor resolution* was the difference between the asymptote of target looks and the average of the baselines of competitor and unrelated looks. This was calculated separately for both cohort and rhyme competitors (i.e., average of cohort and unrelated baselines, average of rhyme and unrelated baselines). *Peak competitor activation* is the maximum of fixations at the inflection point of the cohort (or rhyme) looks.

Visual VWP

Stimuli. Stimuli were 16 uncommon shapes (e.g., chevron, hourglass, trefoil) in 8 colors that were chosen to be color-blind friendly. Shapes were chosen that would not be easily named immediately. Final images were 300 x 300 pixels.

Design and Procedure. Sixteen sets were constructed such that each comprised four shapes in two contrastive colors (e.g., lavender chevron, lavender teardrop, yellow trefoil, yellow cross). Each shape and color appeared in four different sets. The same shape did not always appear as the same color, nor were the same two colors always paired in a set. Each item was used as the target 3 times for a total of 192 trials. Image placement was pseudo-randomized across trials and participants, such that the image type (target, competitor, unrelated) was equally likely to appear in any one quadrant.

Trials proceeded in a similar manner to the spoken word VWP. Instead of hearing an auditory target, the target shape appeared for 100 msec in the center of the screen. The participant was instructed to click on the shape in the display that identically matched the target.

Data Processing. Eye movements were processed in the same way as for the spoken word VWP task described above. The same curve fitting procedure was also used for target and competitor looks.

Other tasks

Pure tone audiometry. Hearing thresholds were established using a standard audiometric procedure. Starting at 25 dB HL, participants were instructed to raise their hand when they could hear a tone played to one ear over headphones. If the participant could hear the tone, amplitude was decreased by 10 dB. If they could not hear the tone, amplitude was increased by 5 dB. The lowest amplitude that participants consistently responded to was recorded as the threshold for that frequency. Both ears were tested at .25, .5, 1, 2, 4, 6, and 8 kHz. PTA was calculated as the average at .25 – 6 kHz (excluding 8 kHz). PTA from the better ear (i.e., the lower PTA of the two ears) was used as a predictor in analyses.

Spatial Stroop. Participants responded to the direction of an arrow on a computer screen as quickly and accurately as possible using the left and right arrow keys on a keyboard. On each trial, a fixation cross appeared for 200 msec before the arrow appeared. The arrows could appear on either the left or right side of the screen to create congruency or incongruency between the direction and the side of presentation. On congruent trials, the arrow pointed in the same direction as it was presented on the screen (e.g., the arrow pointed left and was presented on the left half of the screen). On incongruent trials, the arrow pointed in the opposite direction as its presentation side (e.g., pointed left and presented on the right side). The incongruent information slows response time, as participants must inhibit the congruent response. The arrow remained on the screen until the participant responded. There was an inter-trial interval of 1 second. There were 32 incongruent trials and 64 congruent trials (96 trials).

Accuracy was high in this task (congruent trials M = 99.0%, incongruent trials M = 93.9%). We calculated an effect of congruency for each participant by fitting a mixed effects linear regression and extracting the random effect of trial type (congruent vs. incongruent). First, we excluded incorrect trials, trials where the previous answer was incorrect, and any trials where the response time was slower than 2000 msec or faster than 200 msec. We then ran a mixed effects linear regression with trial type, prior trial type, z-scored response time on the previous trial, and an interaction between trial type and prior trial type predicting response time. Random effects of trial type and prior trial response time were included by participant. We used each individual's random effect of trial type as our metric of Stroop congruency. This score represents an individual's variability around the fixed effect of congruency, and thus represents how large of a congruency effect an individual showed relative to the group. That is, if a participant has a high, positive random effect, they have a larger effect of congruency on their response time.

Statistical Analyses

Our main analyses were multiple linear regressions predicting target timing (activation rate), competitor resolution, and peak competitor activation. Our initial models included age as a linear factor, and which was z-scored and squared to also include the quadratic effect of age. To account for additional factors that might influence our indices of word recognition, we ran larger models that included the corresponding index from the visual analogue of the VWP (e.g., visual target timing was included for spoken word target timing), each participant's PTA from their better ear, and their random effect of Stroop congruency as predictors, alongside age and age^2. In all models, all predictors were z-scored to obtain standardized regression coefficients, which allows for easier comparisons of effect size. Because the analysis of the rhyme competitors was similar to the cohort competitor analysis, it is presented in full in Online Supplement 1. All processed data, analysis scripts, and supplementary analyses are available at https://osf.io/zthbw/.

Results

The time course of fixations to each image type is presented in Figure 1A averaged across all participants. The typical pattern of competition between lexical candidates is apparent: fixations to the target and cohort competitors begin around 300 msec. This is as early as could be expected given that it takes approximately 200 msec to launch an eye movement, and there was 100 msec of silence before each word. Shortly after that, looks to the target continue to increase, while looks to the cohort and rhyme competitors peak early and are suppressed as more information supporting the target word unfolds.

Figure 2 presents the time course of looks to the target (Figure 2A), cohort (Figure 2B), and rhyme (Figure 2C) split by age group. Note that cohorts and rhymes are plotted after subtracting looks to the unrelated image to isolate competition from general fixations. Younger adults were faster to activate targets (slope of the target fixations) and had higher peak competitor fixations (Figure 2B & 2C). There were also differences at the asymptotes of the function at the end of the time course (higher target asymptote and lower baseline competitor looks), suggesting that younger adults are better able to resolve competition.

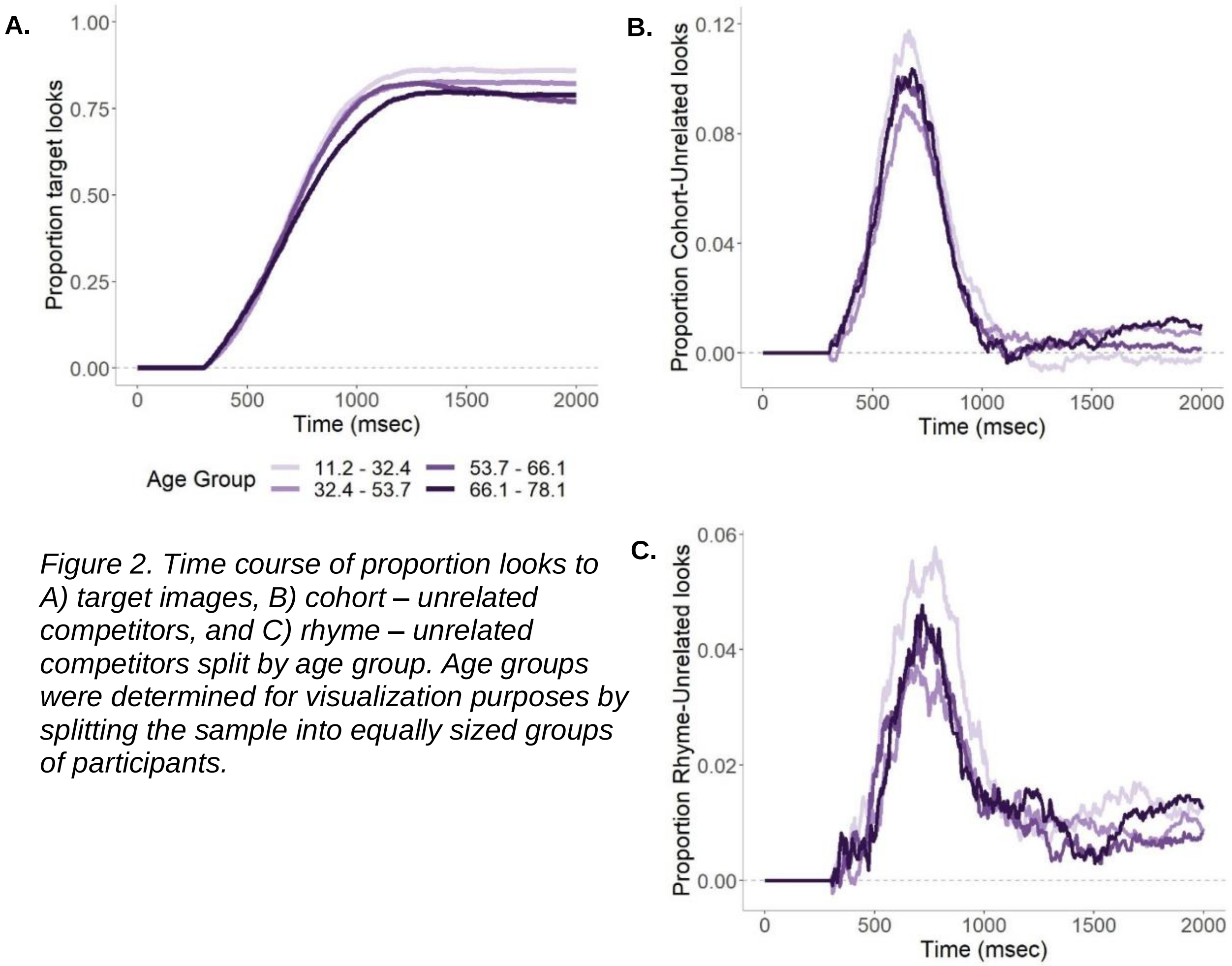

Figure 2. Time course of proportion looks to A) target images, B) cohort – unrelated competitors, and C) rhyme – unrelated competitors split by age group. Age groups were determined for visualization purposes by splitting the sample into equally sized groups of participants.

To better examine the effect of age, we characterized the time course of fixations in terms of three key indices motivated by prior work: *activation rate*, *competition resolution*, and *peak activation* (McMurray, Apfelbaum, & Tomblin, 2022; McMurray et al., 2010; Rigler et al., 2015). These were computed by first fitting non-linear functions to the time course of looking to each object (Farris-Trimble & McMurray, 2013), and forming theory-driven composites of their parameters (see Methods/Data Processing for details). Figure 3 presents these indices as a function of age. These were analyzed in a series of multiple regressions predicting each index from age, as well as the quadratic effect of age. There was a linear and quadratic effect of age on *activation rate* (age: β = -0.44, t(104) = -2.72, p = .007; age^2: β = -0.43, t(104) = -2.64, p = .009), suggesting that lexical activation becomes more efficient (speeds up) from childhood into middle age, when it begins to slow down. For *cohort competitor resolution*, there was a linear

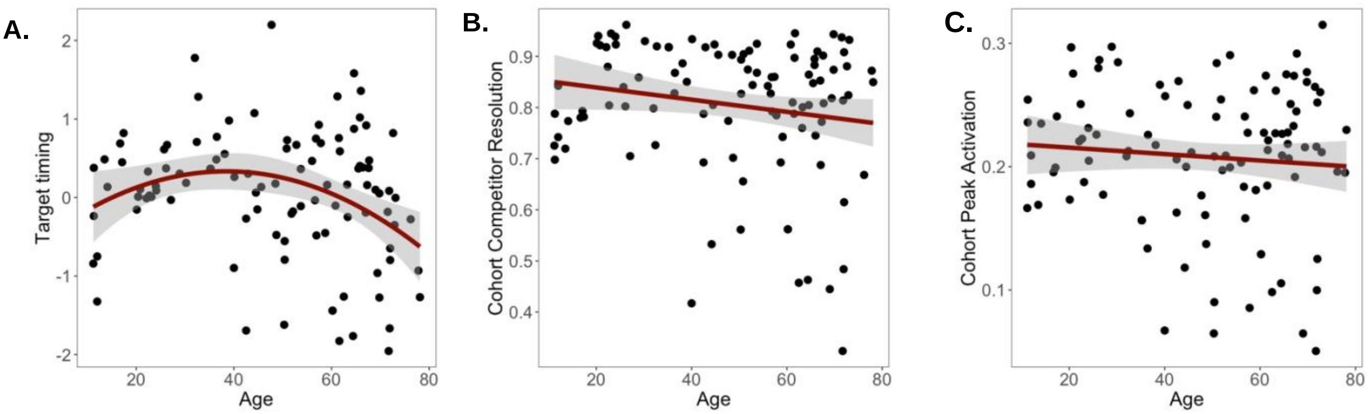

Figure 3. Indices of spoken word recognition presented by age. A) Composite target timing, B) Cohort competitor resolution, and C) Peak cohort activation by age.

effect of age (β = -0.06, t(104) = -2.07, p = .04; Age^2: β = -0.02, t(104) = -0.98, p = .32). As age increases, competitors are not as fully suppressed during word recognition. There was no effect of age on *peak cohort activation* (Age: β = -0.004, t(104) = -0.32, p = .75; Age^2: β = 0.02, t(104) = 1.30, p = .19). The analysis of the rhyme competitors largely mirrored that of the cohort competitors and is thus presented in full in an online supplement.

These initial analyses document robust age effects on real-time spoken word processing. However, these effects could be the result of different underlying changes. For instance, poorer hearing could slow older adults' processing as the incoming signal is more degraded compared to a younger adult. Similarly, domain-general processes like processing speed or inhibitory control are also likely declining with age, and thus could be driving differences in word recognition. To account for this, we ran additional linear regressions with factors to assess hearing ability (PTA), domain-general visual cognition and processing speed (the visual VWP), and domain-general inhibitory control (spatial Stroop). We included these factors along with age and age^2 in separate regressions for activation rate, resolution, and peak competitor activation.

Table 1 presents the results of a linear regression predicting activation rate from these factors. Hearing and inhibitory control were not significant. However, the activation rate index

Table 1. Summary of a linear regression predicting spoken word activation rate by age, PTA, visual target timing, and Stroop congruency.

	Estimate	**Std. Error**	**t (83)**	**p**
Age	-0.11	0.27	-0.41	0.68
Age^2	-0.52	0.19	-2.80	0.006
Better Ear PTA	-0.08	0.25	-0.32	0.75
Visual target timing	0.81	0.17	4.72	< 0.001
Stroop congruency	-0.2	0.18	-1.08	0.28

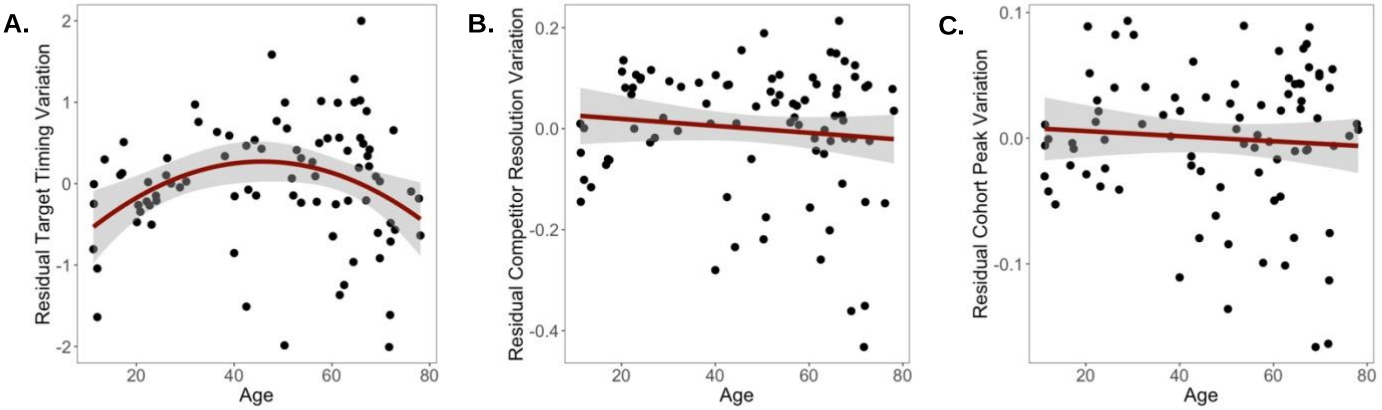

Figure 4. Residual variation from multiple linear regressions with PTA, visual cognition, and inhibitory control as predictors. A) Residual target timing variation, B) Cohort competitor variation, and C) Cohort peak variation by age. Notably, this is residual, unexplained variance from models that did not contain age or age^2 as predictors.

from the visual task significantly predicted activation rate in the spoken task ($\beta = 0.81$, t(83) = 4.72, p < .001): participants who were faster to fixate on targets images in the visual-only VWP were also faster to fixate in the auditory VWP. Nonetheless, even after accounting for this, we still found a significant quadratic effect of age ($\beta = -0.52$, t(83) = -2.80, p = .006), and age and age^2 accounted for 7% of the variance over and above an equivalent model without these factors (F(2) = 4.43, p = .01; see Figure 4 for visualization of the residuals from the model containing all factors except Age and Age^2). This supports the unique contribution of age to changes in the efficiency of target word recognition, as the effect of age is not fully explained by additional factors.

We next ran the same analysis with the index of cohort competitor resolution (Table 2). Like the prior analysis, domain-general cognitive control and hearing were not significant. We

Table 2. Summary of a linear regression predicting spoken word competitor resolution by age, PTA, visual competitor resolution, and Stroop congruency.

	Estimate	**Std. Error**	**t (83)**	**p**
Age	-0.11	0.05	-2.29	0.02
Age^2	-0.06	0.03	-1.92	0.06
Better Ear PTA	0.06	0.04	1.44	0.15
Visual competitor resolution	0.12	0.03	4.04	< 0.001
Stroop congruency	-0.01	0.03	-0.45	0.65

again found a significant effect of resolution in the visual VWP task ($\beta = 0.12$, t(83) = 4.04, p < .001), suggesting that individuals who can better resolve competition in the visual VWP also do so in the spoken word VWP. Nonetheless, even controlling for this, we found a small, but significant linear effect of age (linear: $\beta = -0.11$, t(83) = -2.29, p = .02; quadratic: $\beta = -0.14$, t(83) = -1.92, p = .06), uniquely accounting for 5% of the variance (F(2) = 3.06, p = .05). As age increases, individuals are worse at resolving competition. While this is a small effect, there is also a high amount of variability in this index in middle- and older-aged adults (Figure 3B). This suggests there may be some other factor driving this increased variability in older adulthood.

Finally, we ran the same regression predicting peak cohort activation (Table 3). Peak competitor activation in the visual analogue was the only significant predictor ($\beta = 0.04$, t(83) = 2.69, p = .008). Age did not have an effect on peak activation of spoken word competitors.

Table 3. Summary of a linear regression predicting peak spoken word competitor activation by age, PTA, visual competitor peak, and Stroop congruency.

	Estimate	**Std. Error**	**t (83)**	**p**
Age	-0.02	0.02	-1.01	0.32
Age^2	-0.003	0.01	-0.21	0.83
Better Ear PTA	0.01	0.02	0.64	0.52
Peak visual competition	0.04	0.01	2.69	0.008
Stroop congruency	0.0003	0.01	0.02	0.98

Discussion

Across the adult lifespan, spoken word recognition increased in efficiency until middle age, when it then began to slow down. This held even when accounting for differences in hearing acuity, domain-general visual cognition, processing speed, and inhibitory control. These non-linguistic factors thus do not explain the robust changes in the process of spoken word recognition across the lifespan. However, not all dimensions of lexical competition declined– there was no unique age-related effects on peak competitor activation.

While our study focused on aging, it also offers clear evidence that language-specific cognitive processes related to the speed of target activation continue to increase in efficiency (speed up) well into adulthood, from 11 to about 25. Previous work has found developmental changes to spoken word recognition into adolescence (Rigler et al., 2015); our study extends this developmental window into early adulthood (up through the mid 20’s). Consistent with previous work (McMurray, Apfelbaum, & Tomblin, 2022; Rigler et al., 2015), we find that developmental changes largely affect activation rate and not competitor resolution.

Conversely, we found surprisingly early age-related declines to both activation rate and competitor resolution. For activation rate, speed of target activation begins to slow down in middle age (around the mid 40’s). The nature this change is similar to Van Engen et al. (2020), who found that older adults were slower to fixate on targets compared to a group of younger adults. However, our evidence extends this by providing a clear picture of when word recognition begins to slow down across the lifespan.

In addition, starting around middle age, we also observed that increasing age leads to poorer resolution overall (though this was not accompanied by any changes early in life). Previous work has identified poor competitor resolution as a hallmark of Developmental Language Disorder (McMurray et al., 2010), and it has also been observed in recent second language learners (Sarrett et al., 2021), suggesting it is a marker of less stable lexical competition. Here we see it with typical aging, potentially providing a mechanism for prior results suggesting that older adults struggle with lexical competition (Dey et al., 2017; Sommers & Danielson, 1999). Alternatively, poor resolution has also been observed with moderately degraded speech and in good performing cochlear implant users (Farris-Trimble et al., 2014). In these domains, it has been proposed as a way to maintain flexibility – if an initial word is incorrectly perceived, it may be easier to reactivate words if competition has not fully committed. Future work should ask whether what appears to be poorer resolution is a sign of poorer language skills or is compensatory by relating this to real-world outcomes. In addition to differences in the mean competitor resolution, we also observed large increases in the variability of competitor resolution in older adults. This could reflect a mix of causes (e.g., less stable lexical representations *and* more flexibility) across listeners. However, future work should investigate whether cognitive outcomes relate to this index, as perhaps these competition dynamics can serve as early indicators of future cognitive health.

We found little evidence that domain-general cognitive control plays a role in spoken word recognition across the lifespan—traditional measures of control (the spatial Stroop) showed no correlation. While the absence of a relationship has been suggested by others (Kapnoula & McMurray, 2021; Zhang & Samuel, 2018), we provide evidence that this is true across the lifespan. Even as older adults begin to show declines to spoken word recognition, there is no evidence that they recruit domain-general resources to compensate. In contrast, we did observe a relationship between our visual analogue of the VWP. This likely reflects some high-level aspects of cognition (e.g., decision making, cognitive control), but may also capture a large range of lower-level individual differences such as visual search or eye-movement control. This remains an important avenue for future work. Importantly, however, even after accounting for this variation, we saw clear age-related changes to both the activation rate of targets and competitor resolution.

It is possible that poorer auditory encoding is driving the age-related declines to spoken word recognition. While we found no influence of hearing thresholds, it is possible that other aspects of auditory processing are linked to the changes we observe. For instance, the encoding fidelity of spectral or temporal cues is known to change with age (Bidelman et al., 2014; Humes et al., 2009), even at audible levels. Indeed, so-called “hidden hearing loss” has been identified in middle-aged and older adults who have typical hearing thresholds, but struggle with speech-related tasks (Bharadwaj et al., 2015). More work is needed to examine the Influence of peripheral auditory function on spoken word recognition.

The present work highlights the relatively short developmental window where individuals are at their most efficient when processing spoken words. The implications for this are twofold. First, it calls into question what psycholinguists consider ‘normal’ or ‘ideal’ in terms of language processing (McMurray, Apfelbaum, Colby, et al., 2022). As word recognition clearly continues to develop into early adulthood and begins to slow down again in middle age, this leaves perhaps a 20-year window where individuals are ‘peak’ performers. Second, it is likely that word recognition ability impacts a broad variety of skills. Even if the only language deficit is poorer word recognition, this would still slow down sentence recognition and thus cascade to other aspects of language processing. However, given that competition processes are broadly used, this could be a marker of global competition deficits throughout the language system. In turn, difficulty with language negatively impacts social outcomes, with individuals withdrawing from social situations when conversing becomes difficult. Thus, these indices of spoken word recognition have the potential to serve as important indicators of social and cognitive well-being, particularly in older adulthood.

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Efficiency of Spoken Word Recognition Slows Across the Adult Lifespan

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ONLINE SUPPLEMENT

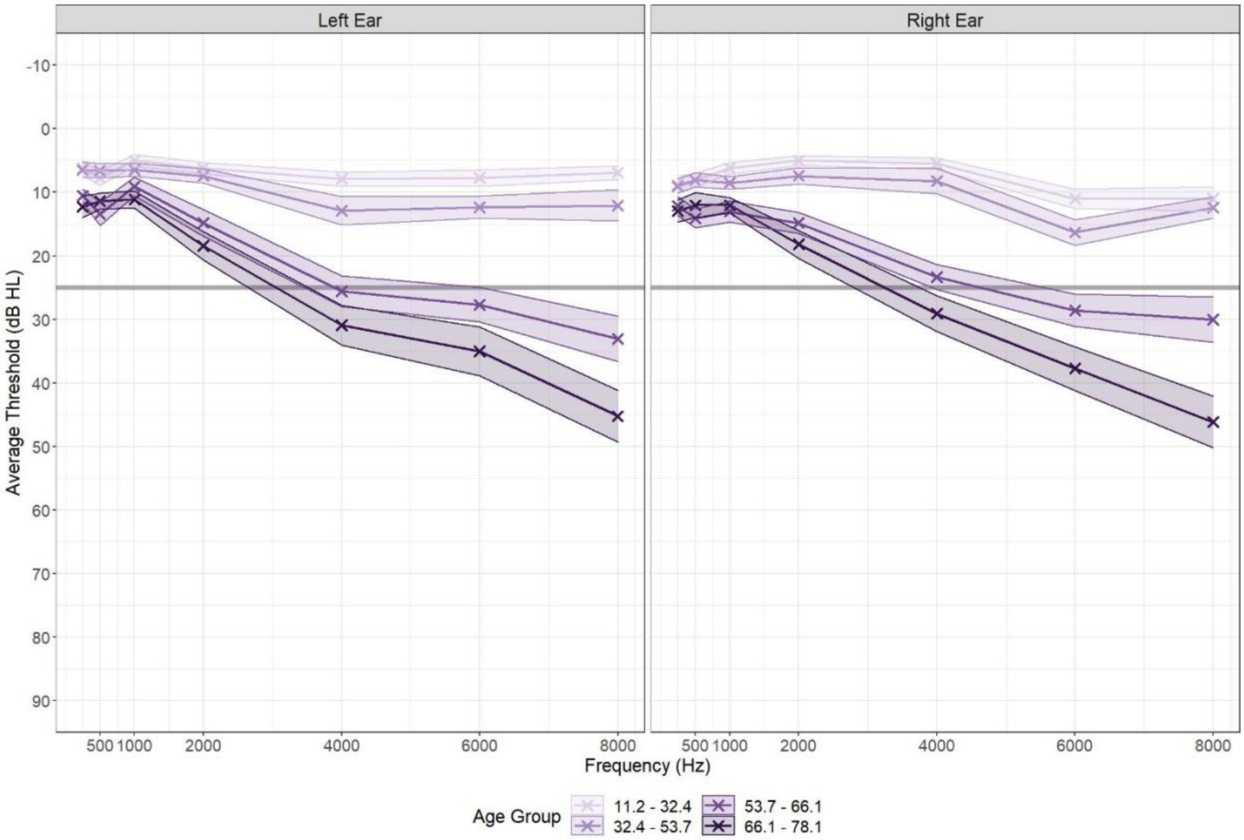

Figure S1. Average pure-tone thresholds (in dB HL) from each ear for each age group. Ribbon width represents standard error. Age group was determined for visualization by splitting the sample into groups with an equal number of participants. Horizontal line at 25 dB HL indicates the standard cut-off for 'normal' hearing.

Supplemental Analysis of Rhyme Competitors.

The analysis of looks to rhyme competitors strongly parallels that of cohort competitors and is presented for completeness here. Indices were calculated as described in the Data Processing section in the main text.

Figure S2 presents rhyme competitor resolution and peak activation as a function of age. These were analyzed in two multiple linear regressions predicting each index from age and the quadratic effect of age. There was a linear effect of age on ***rhyme competitor resolution*** (Age: $\beta = -0.05$, $t(104) = -1.92$, $p = .05$; Age^2: $\beta = -0.03$, $t(104) = -1.07$, $p = 0.28$), suggesting that as age increases, resolution becomes poorer. This is consistent with the analysis of the cohort competitors. For ***peak rhyme activation***, there was a significant quadratic effect of age (Age: $\beta = -0.0008$, $t(104) = -0.10$, $p = .91$; Age^2: $\beta = 0.03$, $t(104) = 3.97$, $p < .001$). This is in contrast to our analysis of cohort competitors, where there was no significant effect of age. However, we must account for changes to domain-general cognition and hearing to better explain these effects.

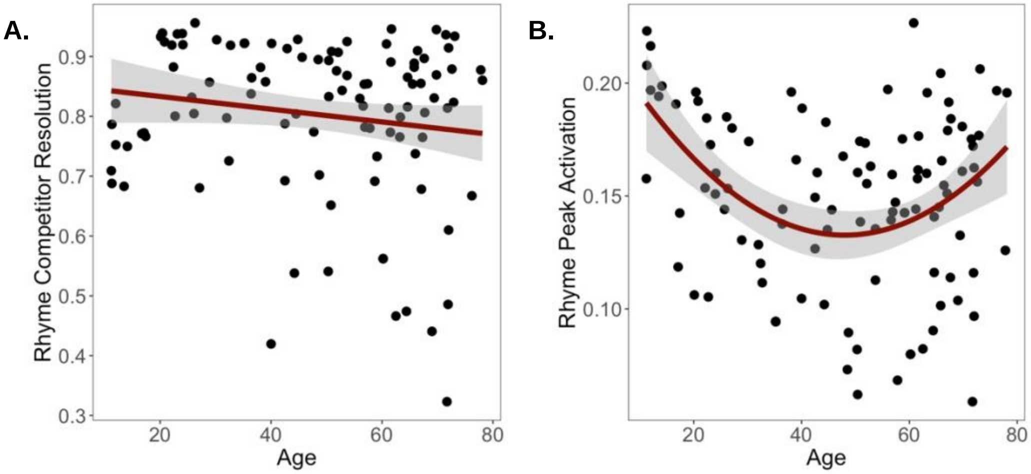

Figure S2. A) Rhyme competitor resolution and B) Peak rhyme activation by age.

Thus, we next conducted a multiple linear regression that predicted ***rhyme resolution*** from age, PTA, visual cognition, and inhibitory control (Table S1). Hearing and inhibitory control were not significant. Competitor resolution from the visual-only analogue of the VWP significantly predicted rhyme resolution ($\beta = 0.12$, $t(83) = 4.06$, $p < .001$), suggesting that individuals who are better able to resolve competition do so in both modalities. When controlling for this, we still found a significant effect of age on rhyme resolution (Age: $\beta = -0.10$, $t(83) = -2.19$, $p = .03$; Age^2: $\beta = -0.06$, $t(83) = -1.96$, $p = .05$). The addition of Age and Age^2 to a model containing the other factors was significant ($F(2) = 2.94$, $p = .05$). This is consistent with our analysis of cohort competitors, suggesting that as age increases, individuals become worse at resolving competition, regardless of competitor type.

Table S1. Summary of a linear regression predicting rhyme competitor resolution by age, PTA, visual competitor resolution, and Stroop congruency.

	Estimate	Std. Error	t value	p
Age	-0.10	0.05	-2.19	0.03
Age^2	-0.06	0.03	-1.96	0.05
Better Ear PTA	0.06	0.04	1.46	0.15
Visual competitor resolution	0.12	0.03	4.06	< 0.001
Stroop congruency	-0.02	0.03	-0.48	0.63

Table S2 presents the results of a multiple linear regression predicting ***peak rhyme activation*** by age, PTA, visual cognition, and inhibitory control. Only peak competitor activation from the visual VWP task significantly predicted peak rhyme activation ($\beta = 0.03$, $t(83) = 4.33$, $p < .001$). Despite an earlier indication of an effect of age, this is no longer significant once accounting for other factors. This is also consistent with our analysis of cohort competitors.

Table S2. Summary of a linear regression predicting peak rhyme competitor activation by age, PTA, visual competitor peak, and Stroop congruency.

	Estimate	Std. Error	t value	p
Age	-0.004	0.01	-0.32	0.75
Age^2	0.02	0.008	1.72	0.08
Better Ear PTA	-0.003	0.01	-0.26	0.79
Peak visual competitor activation	0.03	0.008	4.33	< 0.001
Stroop congruency	0.002	0.008	0.24	0.81