Adult age effects in auditory statistical learning

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ABSTRACT

Statistical learning plays a key role in language processing, e.g., for speech segmentation. Older adults have been reported to show less statistical learning on the basis of visual input than younger adults. Given age-related changes in perception and cognition, we investigated whether statistical learning is also impaired in the auditory modality in older compared to younger adults and whether individual learning ability is associated with measures of perceptual (i.e., hearing sensitivity) and cognitive functioning in both age groups.

Thirty younger and thirty older adults performed an auditory artificial-grammar-learning task to assess their statistical learning ability. In younger adults, perceptual effort came at the cost of processing resources required for learning. Inhibitory control (as indexed by Stroop color-naming performance) did not predict auditory learning. Overall, younger and older adults showed the same amount of auditory learning, indicating that statistical learning ability is preserved over the adult life span.

Keywords: statistical learning, auditory learning, aging, inhibitory control, hearing sensitivity

1. INTRODUCTION

Language has been argued to be probabilistic in nature [1]. In line with this idea, frequencies with which units co-occur have been shown to play an important role in perception at various linguistic levels. At the word level, for example, sequences of phonological elements are not equally probable. Consider the phonological sequences /kæ/ as in *cat* and /hæ/ as in *hat*. Both sequences are legal word beginnings in English. However, /æ/ is more likely to follow /k/ than /h/. By the age of eight months, infants are already sensitive to these phonotactic probabilities and they, like as adults [12], make use of these statistical properties to segment fluent speech into words [13]. At the sentence level, transitional probabilities between words have been found to facilitate speech segmentation into phrases, thereby enabling syntax acquisition [16].

The ability to implicitly extract such statistical regularities from input is called statistical learning [8]. As sensitivity to statistical regularities appears to be essential in online speech processing, language users with better statistical learning ability are expected to show better speech processing performance. Indeed, statistical learning ability has been shown to predict sentence processing performance in younger adults [11]. In older adults, however, deficits have been reported in the ability to learn probabilistic associations from visual input [11, 14]. This has been taken as evidence for a more general decrease in pattern sensitivity in older age [10]. If older adults indeed have generally poorer pattern sensitivity than younger adults, then older adults' statistical learning performance should also be affected in a different (i.e., non-visual) modality. Given the importance of statistical learning for language and speech processing, the present study investigated whether younger and older adults also differ in auditory statistical learning.

Importantly, age-related declines in perceptual and cognitive abilities may be expected to lead to an age group difference in auditory statistical learning. Many older adults suffer from high-frequency hearing loss [6]. That is, older adults' ability to extract acoustic information from the speech signal is not only poorer, but auditory processing also becomes more effortful, which may take resources that would otherwise be available for encoding the information in memory [7]. Reduced hearing sensitivity may therefore limit auditory learning. Moreover, the ability to inhibit irrelevant information is often reported to decline with age [5]. As older adults may be less able to ignore extraneous information, they may be less sensitive to relevant regularities. Therefore, the current study also investigated whether individual statistical learning ability is related to an individual's hearing sensitivity and inhibitory control.

2. METHODS

2.1. Participants

Thirty younger adults aged between 18 and 30 years (M = 21.6 years, SD = 2.9) and 30 older adults aged between 61 and 77 years (M = 67.9 years, SD = 4.7) participated in the current study. Participants were recruited via the participant pool of the Max Planck Institute for Psycholinguistics and were paid €8 per hour for their participation.

2.2. Hearing sensitivity

To assess participants' auditory functioning, we measured air-conduction pure-tone thresholds with an Oscilla USB-300 screening audiometer. The pure-tone average [PTA] was calculated over 1, 2 and 4 kHz to account for age-related high-frequency hearing loss. As auditory stimuli were presented binaurally, the PTA of the better ear served as index of hearing sensitivity, with higher values indicating poorer hearing. Younger adults had a mean PTA of 3.78 dB HL (SD = 6.15) and older adults of 18.22 dB HL (SD = 6.81). Pure-tone average thresholds differed significantly between age groups ($t(58) = 8.56$, $p < .05$).

2.3. Inhibitory control

Participants' performance on the Stroop color word test [4] was taken as a measure of inhibitory control. The Stroop test consisted of three subtasks (I-III). Each subtask consisted of 100 stimuli regarding the colors blue, green, red and yellow: (I) color words printed in black ink, (II) colored patches and (III) color words printed in a conflicting color. Stimuli for each subtask were printed on a white A4 sheet (landscape orientation) and arranged in a 10x10 array. Participants were asked to read the color words printed in black (subtask I), name the color of the patches (subtask II) and name the ink color of the color words (subtask III) as quickly and accurately as possible. Participants' time to complete each task was measured (in seconds). An interference score was calculated for each individual by subtracting the time for completing subtask II from that of subtask III. The higher the score, the more difficult it was for participants to ignore the distracting incongruent information (i.e., color words) during color-naming.

On average, younger adults took 20.3 s (SD = 6.62) longer to name the 100 ink colors in the presence of distracting information. Older adults needed an additional 35.1 s (SD = 12.92). The difference in inhibitory control between age groups was significant (*Welch's* $t(1, 57.49) = 5.58$, $p < .05$).

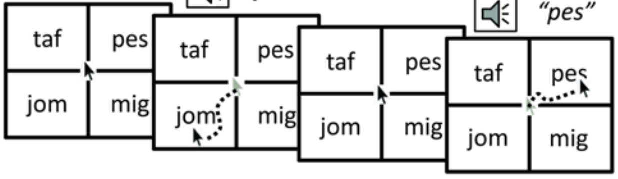
2.4. Auditory statistical learning

We adopted the artificial grammar learning - serial reaction time paradigm [14] as it was built to resemble statistical learning in online language processing. Materials contained eight monosyllabic Dutch CVC-nonwords (i.e., *lin, jom, taf, bur, zol, pes, mig, vun,*) used in previous studies on statistical learning [17]. Stimuli were recorded by a 65 year old male native speaker of Dutch. Mean stimulus duration was 442 ms (SD = 60).

On each trial, participants were presented with a visual display with four quadrants, and one printed nonword in each of the four quadrants. Participants were instructed to click as quickly as possible on two target nonwords that would be presented auditorily one after the other (cf., Figure 1). The second target was only presented once the participant had clicked the correct first target. The first target was always located left (i.e., in the upper left or lower left quadrant) and the second target was always located right (i.e., in the upper right or lower right quadrant) but the specific target positions were randomly assigned. As such, within each column, one nonword served as target and one as distractor. Participants had no possibility to anticipate the first target. Crucially, which of the two nonwords from the right column was going to be presented was dependent on the first target nonword. That is, nonwords were grouped into two grammatical sets. Within each set, two nonwords were selected as 'leaders' (Set 1: *jom*, *lin*; Set 2: *taf*, *bur*) which served as first targets only. The remaining two nonwords of a set were 'followers' (Set 1: *pes*, *vun*; Set 2: *mig, zol*), as they only appeared as second targets, following a leader nonword of the same set. Thus, four combinations of nonwords were legal within a set, resulting in a total of eight grammatical combinations (i.e., Set 1: *jom-pes*, *jom-vun*, *lin-pes*, *lin-vun;* Set 2: *taf-mig*, *taf-zol*, *bur-mig*, *bur-zol).* Given that a target could only follow a nonword from the same set, the transitional probability from the first to the second target was 1.0 within a trial. Within the grammar, however, the transitional probability between leaders and followers was 0.5 as a leader could precede two possible followers (cf., Figure 1, '*jom*' can be followed by '*pes*' or '*vun*' (the latter is not in the display), but never by '*mig*').

In total, the statistical learning task consisted of 20 blocks of eight trials each. The blocks were subdivided into three phases. The exposure phase spanned 16 blocks. Each grammatical combination

Figure 1: Procedure of a grammatical trial during the exposure phase of the statistical learning task.



was presented once in each block, such that participants were repeatedly exposed to the different grammatical combinations. Once participants start to implicitly detect the regularities in the input, they should become faster in clicking on the second target compared to the first target. This facilitation was measured by dividing participants' response time to the first *unpredictable* target by their response time to the second *predictable* target per trial. However, as participants may also speed up their click responses over trials, improvement during the exposure phase may partly reflect task learning.

To control for task learning effects, we implemented a test phase. In the test phase, which consisted of two blocks, the grammar was reversed. That is, leaders from one subset were now followed by followers from the other subset (e.g., *jom-mig*). If participants had detected the underlying patterns during exposure, they should show a drop in facilitation scores as they would need to correct their initial expectations. Thus, participants' statistical learning ability was operationalized as their drop in performance from the end of the exposure phase (i.e., blocks 13-16) to the test phase (blocks 17-18).

The last two blocks constituted the recovery phase and served as a control. In this phase, the grammatical combinations were re-introduced. By re-introducing the original grammar, participants' performance should not decrease any further.

3. RESULTS

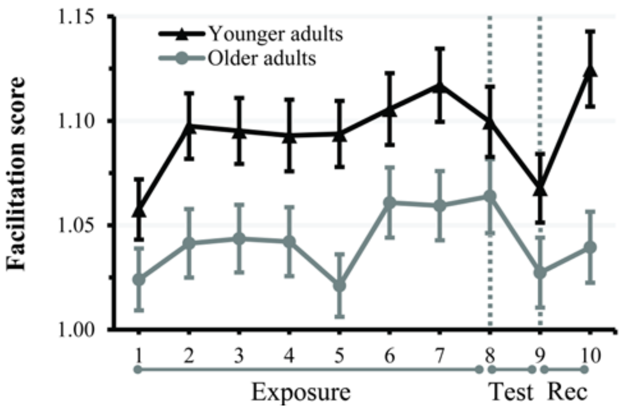
3.1. Age effects in auditory statistical learning

Participants' facilitation scores were analyzed by means of linear mixed-effect models using the lmer function from the lme4 package [2] in R. Facilitation scores were restricted to those within 2.5 standard deviations from the age group's mean. Mean facilitation scores per age group and block are displayed in Figure 2.

To explore age group differences in statistical learning, we tested the influence of two predictors and their interaction on facilitation scores. These predictors of interest were the fixed categorical variables of age group (i.e., younger or older adults) and phase, which indicated whether a participant was exposed to grammatical trials at the end of the exposure phase (blocks 13-16) or to ungrammatical trials during the test phase. The position of the first target (i.e., upper left or lower left), the alignment of targets within a trial (i.e., horizontal or diagonal) and the interaction between target position and alignment were entered as fixed control variables.

In the random effect structure, participants were assumed to differ in their facilitation scores (random effect of participant) as well as in their amount of statistical learning (random slope of phase on participant). Moreover, it was tested whether individuals varied in their sensitivity to target position and target alignment (random slopes of position and alignment on participant). In a stepwise selection procedure, interactions were removed before predictors if they did not attain significance at the 5% level.

Figure 2: Statistical learning performance per age group and block (of 16 trials). Error bars indicate one standard error from the mean. The area between the dotted lines represents where the effect of removing the regularities is observed.



The ensuing most parsimonious model explained facilitation scores as a function of phase, age group, target position and target alignment. Participants' facilitation scores were lower if the first target appeared upper left compared to lower left. This suggests that participants anticipated targets to appear in this position, probably due to influences of the Western writing system. Moreover, participants' facilitation scores were higher if targets were aligned diagonally. This implies that participants were biased towards a diagonal mouse movement. These effects of control predictors also emerged from all subsequent analyses. Going from the end of the exposure phase to the test phase resulted in a drop in facilitation scores (β = -0.044, *SE* = 0.016, *t* = -2.76, *p* = .007), thereby indicating statistical learning. Older adults showed overall lower facilitation scores than younger adults (β = -0.05, *SE* = 0.021, *t* = -2.32, *p* = .021). However, age group did not interact with phase, suggesting that the amount of statistical learning did not differ between younger and older adults.

Note that we also tested whether younger and older adults differed in their improvement over the course of the exposure blocks and in response to re-introducing the grammatical regularities in the recovery phase. This was not the case.

3.2. Individual predictors of auditory learning

Individual predictors of auditory statistical learning were identified within the separate age groups. We used the same approach as described in section 3.1, but instead of age group, hearing sensitivity, inhibitory control and their respective interactions with phase were included in the fixed-effect structure of the model. In the younger adults, the best-fitting model showed effects of target position, target alignment and phase (β = -0.048, *SE* = 0.022, *t* = -2.18, *p* = .030), the latter indicating statistical learning. Importantly, this effect of phase was modified by hearing sensitivity (β = 0.008, *SE* = 0.004, *t* = 2.16, *p* = .032): the poorer younger adults' hearing sensitivity, the less they were affected by removing the underlying regularities in the test phase and, hence, the less they learned.

In older adults, facilitation scores were explained by target position and alignment. Facilitation scores indicated a trend to drop in the test phase (β = -0.042, *SE* = 0.022, *t* = -1.95, *p* = .055). Though this effect just missed significance, the more powerful age group comparison showed learning in both younger and older adults. Overall, older adults with poorer hearing showed higher facilitation scores (β = 0.005, *SE* = 0.002, *t* = 2.91, *p* = .005). However, none of the participant characteristics interacted with phase and, thus, none were associated with older adults' amount of auditory statistical learning.

4. DISCUSSION

Based on findings from visual statistical learning [10], older adults have been argued to be generally less sensitive to co-variation in the environment than younger adults. The current study investigated whether a reduced sensitivity to statistical properties can also be observed for *auditory* input, given the importance of statistical learning for speech processing. Our results showed the same amount of auditory statistical learning for both age groups. This result thus challenges the notion of a general age-related decline in pattern sensitivity. Even though hearing loss may impact on auditory statistical learning (as is evident from the younger adult data), the ability to implicitly detect regularities in an input is not affected by age per se. However, older adults apparently experience difficulties in deriving sequential patterns from the visual modality. This is in line with previous studies indicating that auditory learning is superior to visual learning in sequence learning tasks [3].

Our age group comparison also showed that the relation between the first and second click response differed between younger and older adults. Overall, older adults showed lower facilitation scores than younger adults. As we implemented a speeded computer mouse task, this was probably due to age effects on motor speed [15].

A second aim of this study was to investigate the association between individual perceptual and cognitive abilities and auditory statistical learning performance. The results show that in both younger and older adults the amount of auditory learning was not predicted by individual inhibitory control. However, as we adopted a rather simple grammar in the current study, little task-irrelevant information was present. Under more natural conditions of auditory statistical learning, e.g., in speech processing, the input is less controlled and contains more distracting information. Therefore, inhibitory control might play a role in more demanding situations of auditory statistical learning.

In younger adults, those with poorer hearing (within a normal hearing range) showed smaller amounts of statistical learning. This suggests that perceptual effort comes at the cost of processing resources required for auditory learning. Although older adults' hearing was generally poorer (within a normal to near-normal range) than that of younger adults, this hearing effect on learning was not observed in the group of older adults. Possibly, this was due to the availability of supportive visual information throughout the task. Older adults may have implicitly compensated for the loss of acoustic detail by attending more to the visual information present. Learners have been shown to successfully integrate multimodal input during statistical learning [9]. Therefore, we may speculate that increased attention of older adults to the written presentations of the nonwords and, thus, a better integration of the information from both modalities may have compensated for hearing loss effects on processing effort in the auditory modality. Better integration of the information from both modalities may also account for the finding that older adults with poorer hearing showed overall higher facilitation scores than older adults with better hearing. By paying more attention to the printed nonwords, participants may remember their positions better and are, hence, faster in locating the correct target.

Our results add to a growing body of studies on possible adult age effects on statistical learning [10, 14]. In contrast to earlier findings on visual statistical learning, however, no evidence for an age-related decline in the sensitivity to statistical regularities was observed. Our findings suggest that the general ability of statistical learning is preserved over the adult life span, even though perceptual effort due to poorer hearing poses a challenge to auditory statistical learning.

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