**Lexical learning shapes the development of speech perception
until late adolescence**

Running Head: Lexical learning shapes speech development

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30 **Abstract:**

31 The role of neurobiologically-constrained critical periods for language learning remains
32 controversial. We provide new evidence for critical periods by examining speech sound
33 processing across the lifespan. We tested perceptual acuity for minimal word-word (e.g.
34 bear-pear), and word-pseudoword (e.g. bag-pag) pairs generated using trial-unique audio-
35 morphed speech tokens. Participants (N=1537) performed a 3-interval, 2-alternative forced-
36 choice perceptual task indicating which of two cartoon characters said a referent word
37 correctly. We adaptively reduced the contrastive acoustic cues in speech tokens to measure
38 the Proportion of Acoustic Difference Required for Identification (PADRI) at 79.4% correct.
39 Results showed effects of age, lexical context, and language experience on perceptual
40 acuity. However, for native-listeners responding to word-word trials, age-related
41 improvements stopped at 16.7 years. This finding suggests a role for continued lexical
42 experience in shaping perceptual acuity for spoken words until late adolescence consistent
43 with interactive models of speech perception and critical periods.

44

45

46 **Introduction**

47 Learning to recognise sequences of familiar speech sounds is the foundation of language. At
48 birth, infants are able to differentiate speech sounds from all the world's languages (Kuhl,
49 2004). From this universal starting point, acquisition of native language knowledge becomes
50 apparent within the first year. Infants first show specialisation for speech sounds in their
51 ambient language between 6- and 12-months of age (Best, 1994; Kuhl, 2000; Werker &
52 Tees, 1999). This facilitates the use of language-specific cues to segment connected speech
53 into potential words (Jusczyk & Aslin, 1995). These perceptual abilities precede a rapid
54 increase in word knowledge (the so-called vocabulary explosion) during the second year of
55 life (Bloom, 2001; Ganger & Brent, 2004; McMurray, 2007). This timetable for early speech
56 acquisition suggests that the perceptual foundations of word recognition and word learning
57 are largely in place during the second year of life.

58 Three main sources of developmental evidence suggest neurobiological constraints
59 on the timing of speech sound acquisition during childhood and early infancy; a 'critical
60 period' for language learning (Lenneberg, 1967; Werker & Hensch, 2015). These
61 neurobiological influences are most apparent from the dramatic effects of language
62 deprivation during the first few years of life (see review by Pallier, 2013). Severe language
63 impairments can result from social deprivation in early life (Fromkin, Krashen, Curtiss, Rigler,
64 & Rigler, 1974). Language impairment is also apparent for profoundly hearing-impaired
65 individuals who are not exposed to sign language (Newport, 1990), or only receive a
66 cochlear implant after the first two years of life (Nicholas & Geers, 2007; Tomblin et al,
67 2005). The severely impaired speech outcomes that result from language deprivation during
68 infancy and early childhood provide compelling evidence for a critical period for early
69 language learning.

70 Evidence from second language learners suggests a longer-lasting critical period for
71 acquisition of native-like speech sound processing abilities. Evidence for age-related

72 differences in second language speech sound acquisition comes from studies of
 73 international migrants who join a new language community at different ages. For example,
 74 Korean migrants that moved to the US before 5 years of age speak English without a marked
 75 foreign accent unlike individuals who moved to the US later in life (Flege, Yeni-Komshian, &
 76 Liu, 1999). Similar findings have been obtained using perceptual measures; late-learners of a
 77 second language have a limited ability to discriminate pairs of speech sounds that do not
 78 differentiate word pairs in their native language (Baker, Trofimovich, Flege, Mack, & Halter,
 79 2008; Best, 1994). For example, the /r-l/ contrast is difficult for Japanese native speakers to
 80 discriminate (Iverson et al., 2003). Even intensive training in the perception and production
 81 of non-native speech sounds can be insufficient for adult learners to achieve native-like
 82 proficiency in speech sound perception (Bradlow & Pisoni, 1997; Giannakopoulou, Uther, &
 83 Ylinen, 2013; Iverson, Hazan, & Bannister, 2005; McClelland, Fiez, & McCandliss, 2002;
 84 Strange & Dittmann, 1984), particularly for tests involving generalisation to novel speakers
 85 or phonetic contexts (Ingvalson, Holt, & McClelland, 2012).

86 A third observation that suggests critical periods in the acquisition of speech sound
 87 perception comes from studies of international adoptees who lose contact with their native
 88 language. Studies conducted in French-speaking and Dutch-speaking adults adopted from
 89 other countries shows near-complete attrition of native language perceptual contrasts, even
 90 for adoptees who moved countries later in childhood (up to 8 years of age in some studies;
 91 Bowers, Mattys, & Gage, 2009; Choi, Broersma, & Cutler, 2017; Pallier et al., 2003;
 92 Ventureyra, Pallier, & Yoo, 2004). However, residual knowledge of an otherwise forgotten
 93 language has been demonstrated to confer benefits when relearning native language speech
 94 sounds (Au, Knightly, Jun, & Oh, 2002; Oh, Au, & Jun, 2010); even for languages that were
 95 only heard in the first two years of life (Bowers et al., 2009; Choi et al., 2017). Similar loss of
 96 native-language perceptual abilities would not be expected for individuals who move to a
 97 new language community in later life. Thus, attrition of language knowledge is more

98 apparent in early childhood, consistent with a critical period during which a second language
99 can more completely displace native language knowledge.

100 Despite abundant evidence for critical periods for native-like acquisition of spoken
101 language, the underlying cause of critical period effects remains a topic of debate. It has
102 been proposed that children have more effective mechanisms for speech sound learning
103 than adults (i.e. increased cortical plasticity, see, Werker & Hensch, 2015). Hence, critical
104 periods for speech sound acquisition are explained by the time-limited operation of neural
105 mechanisms for learning (see Hartshorne, Tenenbaum & Pinker, 2018, for similar arguments
106 concerning syntax learning). At present, however, there is insufficient evidence to determine
107 the critical age or the underlying neural mechanisms by which younger language learners
108 achieve better speech sound acquisition. These arguments for neurobiologically-determined
109 critical periods are particularly controversial for second-language learners. There are
110 significant changes in the learning environment and degree of native language exposure
111 experienced by younger and older migrants (Flege, 2018) which provide an alternative
112 explanation for why older learners might struggle to achieve fully-native perception and
113 production of second language speech sounds.

114 *Development of speech perception in native listeners*

115 Here we provide new evidence concerning critical periods in the development of
116 speech sound perception. We study perception of English consonantal contrasts in native
117 listeners and assess changes in perceptual acuity as a function of age. Existing evidence –
118 that we will review in the next section – is consistent with progressive improvements in
119 speech perception abilities for an extended period throughout childhood. We will assess
120 whether these improvements continue into adolescence and adulthood. Continuous
121 improvements throughout the lifespan have been shown for vocabulary knowledge in a
122 recent large scale online study (Brysbaert, Stevens, Mandera, & Keuleers, 2016). Although
123 the rate of syntactic learning for second language learners shows a dramatic slowing in late

124 adolescence, performance of monolingual participants continues to improve in adulthood
 125 (Hartshorne, Tenenbaum, & Pinker, 2018). Such findings may be inconsistent with critical
 126 periods since they suggest continuing development of lexical and syntactic knowledge
 127 beyond the ages at which second language learning abilities are reduced.

128 In the present work we assess changes in perceptual acuity for speech sounds across
 129 the lifespan in a large scale public experiment. Evidence for a discontinuity in developmental
 130 profile (i.e. a change in the rate at which perceptual acuity improves with age) would
 131 provide a novel source of evidence for a critical period for native-language speech sound
 132 learning. Importantly, by assessing perceptual acuity in native speakers we can exclude the
 133 environmental changes that confound research in migrant populations. Furthermore, by
 134 comparing native and non-native speakers of English we can rule out other, incidental
 135 cognitive changes due to age (such as domain-general improvements in focussed attention
 136 or motivation) that should be similarly apparent in non-native participants.

137 Studies of speech perception in native speakers have previously suggested
 138 differences between children and adults in their perception of ambiguous speech sounds.
 139 For example, category boundaries for phonetic continua (e.g. for *coat-goat* minimal pairs)
 140 are increasingly sharp in 12-year olds compared to 6-year olds, and for adults compared to
 141 12-year olds (Hazan & Barrett, 2000; McMurray, Danelz, Rigler, & Seedorff, 2018). That is,
 142 older participants gave more consistent categorisation responses to intermediate, or
 143 ambiguous speech tokens. However, this study, along with most published studies of speech
 144 perception, tested perceptual categorisation using repeated presentation of a limited set of
 145 speech tokens from a small number of words. For these tasks, developmental changes in
 146 speech perception can also arise from improvements in attentiveness, response consistency,
 147 or in the ability to learn the correct response for ambiguous tokens without any
 148 accompanying change in perceptual acuity.

149 We therefore devised a new speech perception test using a highly varied set of
150 phonetic continua generated from natural speech using audio-morphing (Kawahara,
151 Masuda-Katsuse, & de Cheveigné, 1999; Rogers & Davis, 2017; Rogers & Davis, 2009). By
152 using trial-unique stimuli we can rule out differences in response consistency or perceptual
153 learning as a cause of age-related changes in perceptual acuity. This varied set of materials
154 also makes it less likely that results are influenced by differential sensitivity to a limited set
155 of acoustic cues as has been suggested for synthetic or manually-edited speech
156 tokens (Nittrouer & Miller, 1997). Our test uses a novel measure of perceptual ability – the
157 proportion of acoustic difference required for correct identification (PADRI). This is the
158 degree of acoustic ambiguity created using morphing that participants can accommodate
159 while identifying spoken words with above-threshold accuracy (in this case, 79.4% correct
160 identification in a 2-alternative task). We measure perceptual acuity for word-word (e.g.
161 bear-pear), and word-pseudoword (e.g. bear-gare) minimal pairs. Comparing our PADRI
162 measure for these two types of trial can help determine the mechanisms that support age-
163 related improvements in speech perception by distinguishing between changes in the
164 perception of words (which should be more apparent for word-word pairs), or their
165 constituent speech sounds (apparent for both trial types; see Rogers & Davis, 2017). Using
166 these data, we will assess whether – like vocabulary acquisition – we see continuous
167 improvements throughout the lifespan. Or if, consistent with critical periods, we see a
168 discontinuity in learning such that improvements in perceptual acuity are absent above a
169 certain critical age.
170

171 **Method**

172 ***Participants***

173 Data on perceptual acuity for speech is reported for 1537 individuals (self-reported 820
174 female, 1151 Native English speakers) who visited the Science Museum in London on one of
175 26 testing days between 30th January and 30th March 2013. These participants had a mean
176 age of 21.6 years (SD = 14.4 years, see Figure 2, Table 1). The 1537 datasets reported here
177 come from a larger sample of 2422 visitors who were tested. Reasons for exclusion include
178 participants who: (1) more than 70 years or less than 4 years old, (2) failed to give full
179 consent in line with requirements of the Science Museum and the Cambridge Psychology
180 Research Ethics Committee, (3) self-reported as having hearing impairment or language
181 difficulties, (4) failed to provide consistent measures of perceptual acuity for one or both of
182 our test conditions (assessed using statistical methods described below), (5) not giving a
183 rating of English proficiency (for non-native participants). The study was approved by the
184 Cambridge Psychology Research Ethics Committee (CPREC 2012.74).

186 ***Speech materials***

187 Our listening task used 60 monosyllabic, monomorphemic English word targets, selected
188 from the CELEX database (Baayen et al., 1995), see full list in Appendix A. Words were
189 chosen that were: (1) likely to be known by participants aged 6 years or younger (mean
190 rated age-of-acquisition = 4.5 years, range = 2.9 to 5.9 years) based on age-of-acquisition
191 (AoA) norms reported by Kuperman, Stadthagen-Gonzalez & Brysbaert (2012), (2) could be
192 depicted with a simple, recognisable photograph, (3) had an additional early acquired word
193 as a phonological neighbour, for the real word distractor condition. These neighbouring
194 words had a frequency of occurrence of more than 10 per million and an average AoA of 4.8
195 in the Kuperman et al. norms (ratings missing for 10 of 60 distractors, though these were
196 also judged by native speakers to be early acquired). The neighbouring words involved

197 changing a single articulatory feature in an onset consonant (35 out of 60 words, e.g. *bear-*
 198 *pear*) or coda consonant (25/60, e.g. *fork-fort*). The consonants that changed were most
 199 often an oral stop (30 out of 60 word pairs), though fricatives (17/60, e.g. *sing-thing*),
 200 approximants (9/60, *rake-lake*) and nasals (4/60, *meat-neat*) were also changed. Changes
 201 were made to place of articulation (52/60 word-word pairs, *goat-boat*) or to voicing (8/60
 202 word-word pairs, *bear-pear*). Previous work has shown that single-feature changes lead to
 203 effective phonetic continua when intermediate syllables are synthesized using an automated
 204 audio-morphing procedure (Rogers & Davis, 2017).

205 In addition to the word distractors described above, we also generated a
 206 pseudoword neighbour for each of our target words (e.g. *bag-pag* or *gate-gake*), by making
 207 similar changes to place of articulation (51/60 word-pseudoword pairs) or voicing (9/60
 208 pairs) for consonants at syllable onset (33/60 word-pseudoword pairs) or coda (27/60 pairs).
 209 The overall composition of segments changed at onset and coda was similar for these word-
 210 pseudoword pairs (28/60 stops, 16/60 fricatives, 11/60 approximants, 5/60 nasals).

211 Each of the resulting 180 syllables (120 words and 60 pseudowords) listed in
 212 Appendix 2 was recorded using a high-quality microphone (AKG) and digital-recorder
 213 (Marantz, 44.1Khz sampling rate, 16-bit depth) in a sound-proof booth by a male native
 214 speaker of Southern British English (author SE). In addition, a female native speaker
 215 recorded all 60 target words (author JSHT). The resulting word lists were edited into single
 216 sound files and trimmed for length at zero-crossings using Adobe Audition software (Adobe).
 217 The male speaker recordings of the minimal pairs were then processed using software
 218 components from the Straight channel vocoder (Kawahara et al., 1999) implemented in
 219 Matlab (Mathworks Inc). The periodic and aperiodic spectral-envelope of the words was
 220 time-aligned using dynamic time-warping code (from
 221 www.ee.columbia.edu/~dpwe/resources/matlab/). These time-aligned representations of
 222 the syllable pairs were then averaged in different proportions and resynthesized in Straight

223 to implement the automated audio-morphing procedure described in Rogers & Davis (2017).
 224 We used this method to create high-quality, natural-sounding intermediate tokens between
 225 each of the 60 pairs of word-word and 60 word-pseudoword endpoints. In addition to
 226 resynthesized version of the two original speech tokens we synthesized 99 intermediate
 227 tokens to create a 101-step continuum between each of the minimal pairs (i.e. 1% steps
 228 between 0% and 100%). The female speaker target items were RMS equalised to the
 229 intensity of the referent items, to ensure that all stimuli were of approximately equal
 230 loudness.

231

232 ***Procedure***

233 Before commencing the listening test, participants responded to a series of questions on a
 234 touch screen display (iPad Version 4, Apple Inc, Cupertino, California) concerning their age,
 235 native language, other languages spoken and their self-rated proficiency (on a 5-point scale)
 236 for each of these. They were further asked to report any known hearing or language
 237 impairments (and given additional space to disclose relevant information), and confirm that
 238 they consented to take part in the experiment. Experimenters were on hand at all times to
 239 ensure that participants fully understood these questions and responded accurately.
 240 Unfortunately, due to a programming error, the first 240 participants tested only provided
 241 their age in years. For these participants, it was assumed that they were half-way through
 242 the year. After completing this questionnaire, all participants were instructed to put on
 243 headphones and were presented with a short instruction video to explain the listening test
 244 that they would complete. This also served to establish that the video, and speech materials
 245 that followed were presented at a comfortable listening level and provided an opportunity
 246 for participants to adjust the volume using buttons on the iPad.

247 Our test measured the Proportion of the Acoustic Difference Required for
 248 Identification (PADRI) by assessing the amount of acoustic difference that participants need

249 in order to identify morphed syllable pairs correctly on 79.4% of trials (Levitt, 1971). We
 250 used an adaptive three-interval, two-alternative forced-choice task (2-AFC) to measure
 251 participants' perceptual acuity. We ran two interleaved tracks such that, on each trial,
 252 speech tokens from word-word and word-pseudoword minimal pairs were randomly
 253 presented and perceptual acuity could be separately measured for these two types of trial.
 254 This procedure was implemented as a touchscreen computer game with child-friendly
 255 animations to help ensure attentive responding from participants of all ages (see Figure 1A).

256

257 INSERT FIGURE 1 ABOUT HERE

258

259 Each trial consisted of presentation of three spoken syllables (XAB), with X being the
 260 referent word and AB being two potential target syllables for the 2AFC task. Participants first
 261 heard an original, unmodified recording of one of the referent words (e.g. *bear*) spoken in a
 262 female voice (author JSHT), accompanied by a photograph of the referent object. These
 263 object pictures help support accurate perception of the referent word and minimize short-
 264 term memory demands in retaining that word while listening to two subsequent target
 265 syllables. The referent word in each trial was selected at random without replacement from
 266 the set of 60 words. Each referent word was followed by either a word or pseudoword
 267 minimal pair (depending on which track was selected for that trial). These target words were
 268 audio-morphed tokens recorded in a male voice (author SE). This change between female
 269 (referent) and male (target) recordings ensure that echoic (auditory) comparisons between
 270 spoken items could not contribute to task performance (Pisoni & Tash, 1974).

271 Auditory presentation of the two target syllables was combined with child-friendly
 272 animations of two cartoon aliens who were described as "learning to speak English".
 273 Participants indicated which of the syllables was more correct ("who said it right?") and
 274 made their response by touching one of the aliens on the touchscreen. Participants were

275 informed that on some trials it might seem that both the aliens say words that sound correct
276 and at other times both aliens might say words that sound incorrect. Their task was to
277 indicate which of the two aliens said the word more correctly. Participants received
278 feedback on their accuracy after each trial. The cartoon aliens smiled and a rewarding sound
279 was played for correct responses. The aliens frowned following incorrect responses. After six
280 correct responses in a row a star was displayed and an additional rewarding sound was
281 played. At two points during the protocol, participants were given a short break during
282 which they were shown short videos (about MRI scanning and functional brain imaging)
283 intended to give a break, and maintain their interest and motivation. Depending on the
284 number of trials required for the adaptive procedure to converge participants completed the
285 experiment in approximately 10 to 15 minutes (including video breaks).

286 An adaptive procedure was used to progressively reduce the magnitude of acoustic
287 difference between the two targets presented on each trial. On the first (easiest) trial of the
288 experiment, the two alternatives were resynthesized versions of the two original syllables
289 (i.e. 0% and 100% tokens) such that participants heard syllables with 100% of the original
290 acoustic difference between the two speech tokens. If participants got the answer right then
291 the amount of acoustic difference was reduced for subsequent trials – initially using a step-
292 size of 16% – such that participants heard acoustically more similar tokens (e.g. synthetic
293 stimuli with 16% and 84% of the original acoustic difference, i.e. an acoustic difference of
294 68%). Our adaptive procedure followed a 3-down, 1-up protocol (cf. Levitt, 1971) such that
295 the magnitude of acoustic difference was reduced after three successive correct responses
296 and increased after a single incorrect response. This procedure converges on an estimate of
297 the Proportion of Acoustic Difference Required for Identification (PADRI) with 79.4% correct
298 responses. The step size was initialized at 16% and changed by a multiple of 0.707 ($1/\sqrt{2}$)
299 on each successive turning point, up to a minimum step-size of 4% (reached after 4 turning
300 points). The procedure then continued for a further 4 turning points to make 8 turning

points in all for each track (word-word and word-pseudoword pairs). The most difficult trials used in the experiment had an acoustic difference of 4% (i.e. speech tokens that contained 48% and 52% of the two original recordings). We anticipated that these would be too difficult for participants to complete correctly and therefore designated the third trial at this difficulty level as a turning point (though this wasn't counted as an error if participants responded correctly). For a subset of participants (1274 of the 2422 tested), we included additional catch trials so that one in ten trials used unmodified speech tokens (i.e. 100% acoustic difference), selected from an additional set of 12 minimal pairs with similar properties as the test set (6 word-word and 6 word-pseudoword item pairs). Inclusion of these filler trials was intended to counter feedback from participants that later stages of the experiment included large numbers of difficult to discriminate speech tokens.

Data Cleaning

Our analysis protocol had the goal of summarising the proportion of acoustic difference required for 79.4% correct identification (hereafter PADRI 79%) for individual participants during perception of syllable pairs from word-word and word-pseudoword morphed syllable pairs. These PADRI thresholds (for which low values indicate good performance) are then entered into statistical analyses looking for effects of age and language status on the acuity of speech perception. Rather than computing PADRI thresholds directly from the adaptive tracks (by averaging the turning points) we opted to fit psychometric functions to all the data from a single participant (i.e. the trial-by-trial record of the magnitude of acoustic differences and response accuracy). These psychometric functions could then be used to compute PADRI 79% and provide additional information on the goodness of fit of the psychometric function to guide data cleaning. We used logistic regression analysis, implemented in R using the Dose-Response Curves (DRC) package (Ritz et al, 2015) to fit psychometric functions separately for each of the two adaptive tracks

327 leading to two PADRI estimates (one for word-word pairs, one for word-pseudoword pairs)
 328 for each participant. We used a 4-parameter model and specified the 50% chance rate for
 329 our 2AFC task and a binomial response type.

330 Inspection of single participant trial-by-trial data, and psychometric functions
 331 showed that the adaptive track failed to generate trustworthy PADRI estimates for some
 332 participants. This is likely due to inconsistent responding, distraction, or other challenges in
 333 completing an auditory task in a non-laboratory setting. In order to ensure that we only
 334 analysed data from participants for whom our adaptive procedure generated a reliable
 335 estimate of the PADRI threshold for both conditions we devised a data cleaning procedure in
 336 which consistent, automated criteria could be applied to accepting or rejecting individual
 337 participants' data. This was necessary because the large number of participants and tracks
 338 tested precluded using conventional methods for data cleaning based on visual inspection of
 339 psychometric functions or trial-by-trial plots of adaptive tracks.

340 For the first 300 participants tested with catch trials, two independent raters
 341 (authors KMM and AG) who were blind to the age and language status of each participant
 342 inspected plots of (1) trial-by-trial task difficulty and success and (2) fitted psychometric
 343 functions, in order to provide a 4-point rating of the accuracy of the estimated PADRI
 344 threshold, and hence the acceptability of the data collected in each adaptive track for each
 345 participant (see Figure 1B and C, for an example of a good quality dataset for a participant
 346 with a low PADRI threshold (good performance). Analysis of inter-class correlation
 347 coefficients (ICC) showed that these raters had "strong agreement" in their assessment of
 348 data quality for these 300 participants (word-word trials, ICC=.708, word-pseudoword trials,
 349 ICC=.694, both significantly different from zero, $F(299,299)=6.294$, $F(299,299)=5.719$,
 350 $p<.001$; intraclass correlation coefficients between 0.6 and 0.74 are proposed to indicate
 351 good agreement (Chicetti & Sparrow, 1981)).

352 We then used logistic regression to generate an automated procedure that could
 353 replicate these subjective judgements based on objective parameters of data from single
 354 participants and tracks. Specifically, we entered the slope, accuracy of responses to catch
 355 trials (if present), estimated PADRI threshold, and residual variance (i.e. variance
 356 unexplained by the psychometric function) as predictor variables, and constructed logistic
 357 regression models to predict (based on these variables) which participants would receive the
 358 lowest rating of data quality (1 out of 4). To avoid over-fitting, regression models trained on
 359 ratings of data quality for the first 300 participants were used to predict ratings of data
 360 quality for a further 300 participants assessed by a single rater (author KMM). The best
 361 performing model used two parameters to accept or reject participants, (1) the slope
 362 estimated from the psychometric function for non-catch trials, this measures whether
 363 perceptual acuity shows a consistent threshold for correct identification, and (2) accuracy
 364 on catch trials. In combination these achieved 67.4% sensitivity and 98.4% specificity for
 365 word-word tracks and 83.9% sensitivity, 96.7% specificity for word-pseudoword tracks;
 366 rejecting participants who produced inconsistent or error prone responses. However, we
 367 opted for a simpler single-parameter model using only the slope parameter since this
 368 achieved comparable performance in a cross-validation test (sensitivity of 65.1% and 82.1%,
 369 specificity of 98.1% and 96.7% for word-word and word-pseudoword tracks respectively).
 370 More importantly, this model could also be applied to data from participants who
 371 completed the experiment without catch trials.

372 A single logistic regression model using the slope parameter from individual
 373 participants' psychometric functions was then fitted to all the data with ratings of data
 374 quality (600 word-word and 600 word-pseudoword tracks). This fitted model achieved
 375 79.3% sensitivity and 96.8% specificity by accepting data for which the following inequality
 376 held: $-7.339 + 10.917 * \log(\text{Slope}) > 0$ (i.e. rejecting participants whose slope parameter was
 377 less than 4.70). We also rejected tracks for which the estimated PADRI threshold was >1 or

<0 and hence outside the possible range of test trials. Applying this model to the full set of 2422 participants revealed that 641 participants failed to provide a consistent PADRI measure for one or both adaptive tracks. Combined with the other criteria for data rejection described previously led to analysis of data from 1537 participants, following the demographics shown in Table 1. Histograms showing the distribution of age are provided in Figure 2.

FIGURE 2 ABOUT HERE

Table 1: Demographic information on the 1537 participants included in the group analysis

Group	N	Mean Age (min/max/std dev)	English Proficiency (1=low, 5=high) mean (std dev)
Native English Listeners	1151	21.43 years (4.13/69.93/15.05)	n/a
Non-Native English Listeners	386	22.26 (4.51/69.18/12.13)	3.75 (1.09)
Total	1537	21.64 years (4.13/69.93/14.37)	

Statistical Analysis

Data from the remaining 1537 participants were then subjected to statistical analyses using simultaneous regression and repeated measures ANCOVAs to assess how the PADRI measure (PADRI 79%) was affected by lexicality (i.e. word-word vs. word-pseudoword trials), age, language status (native/non-native listeners), and self-rated proficiency (for analyses of data from non-native participants, reported on a 1 to 5 scale, 5 = high proficiency, collected

for 310 of the 386 non-native speakers). Given our interest in assessing evidence for a discontinuous relationship between age and perceptual acuity – in particular testing for a “critical period” during perceptual development – we also used Segmented regression (<https://cran.r-project.org/web/packages/segmented>) to compare models in which developmental changes continue in a consistent way over the lifespan (including continuous acceleration/deceleration for non-linear models) or models that include more pronounced changes that are time-limited to periods of childhood and/or adolescence. To compare continuous and discontinuous models which necessarily differ in the number of free parameters, we used changes in Akaike Information Criterion (AIC, see Wagenmakers & Farrell, 2004).

405

406 **Results**

Two-dimensional histograms show PADRI 79% thresholds as a function of age for word-word (Figure 3a,3b) and word-pseudoword trials (Figure 3c,3d) for the 1537 participants divided into native and non-native listener groups. The mean PADRI 79% threshold as a function of age is summarized by smoothed curves (computed using local regression, loess in R) for word-word and word-pseudoword trials in native listeners (Figure 4a) and non-native listeners (Figure 4b).

Initial analysis used curve estimation in SPSS to explore the relationship between age and PADRI 79% threshold, collapsing over native and non-native English listeners. We tested 8 different single parameter models for the relationships between age and PADRI thresholds (Linear, Logarithmic, Inverse, Compound, Power, S, Growth and Exponential). This analysis revealed that an inverse regressor (i.e. using the reciprocal predictor, $1/\text{age}$) explained the most age-related variance in PADRI 79% thresholds (word-word PADRI: $F(1,1535)=205.96$, $\beta=.848$ $R^2=.118$, $p<.001$, word-pseudoword PADRI: $F(1,1535)=17.07$, $\beta=.280$, $R^2=.011$, $p<.001$). In addition, we compared the best of these single parameter

models to two and three parameter models (quadratic and cubic). For word-word PADRI thresholds the inverse model explains more variance than either the quadratic or cubic models ($R^2=.091$, $R^2=.109$, for quadratic and cubic respectively) despite these models having additional parameters. For word-pseudoword PADRI 79% thresholds, age is a less informative predictor than for word-word thresholds, and quadratic and cubic models explain additional variance ($R^2=.013$, $R^2=.014$ for quadratic and cubic models respectively).

INSERT FIGURE 3, 4 ABOUT HERE

Effect of age, language status and lexical knowledge on perceptual acuity

To compare perceptual acuity for different tracks and listener groups, we submitted PADRI 79% thresholds to ANCOVAs in SPSS using reciprocal age ($1/\text{age}$) as a covariate and track (word-word/word-pseudoword) as a repeated measures factor. We also included an additional between-subjects factor to assess the difference between native and non-native listeners and tested for 2- and 3-way interactions among these factors. This analysis showed significant main effects of lexical knowledge (word-word/pseudoword, $F(1,1533)=76.27$, $p<.001$, $\eta_p^2=.047$), age (reciprocal age, $F(1,1533)=66.91$, $p<.001$, $\eta_p^2=.042$), and language status (native/non-native, $F(1,1533)=34.27$, $p<.001$, $\eta_p^2=.022$). These comparisons highlight greater perceptual acuity: for word-word than word-pseudoword pairs, in older than younger individuals, and in native English than in non-native listeners (Figure 2a). Furthermore, there was a significant interaction between track and age ($F(1,1534)=30.42$, $p<.001$, $\eta_p^2=.019$). In line with the results of the curve fitting, this confirms that reciprocal age was a better predictor of PADRI 79% measure of perceptual acuity for word-word than for word-pseudoword contrasts. Developmental changes in perceptual acuity are thus most apparent when listeners use their knowledge of spoken words in identifying speech sounds,

446 consistent with lexical contributions to speech perception. We will consider potential
 447 explanations of this finding in the Discussion.

448 There was also a two way interaction between age and language status
 449 ($F(1,1533)=5.19$, $p=.023$, $\eta_p^2=.003$) such that the effect of age on perceptual acuity was more
 450 pronounced for native than for non-native English listeners. This is consistent with effects of
 451 age being partly due to greater English language experience, and not only due to
 452 improvements to domain-general cognition. If the effect of age was to improve attention,
 453 motivation or other domain-general abilities we would expect to see similar effects of age in
 454 non-native listeners. The other two-way interaction (track by language status) was non-
 455 significant ($F(1,1533)=1.39$, $p=.239$), and the three-way interaction (track by age by native
 456 language) was also non-significant ($F<1$).

457 To follow-up on these findings, we focused on perceptual acuity for word-word
 458 continua by conducting a further ANCOVA assessing the effect of reciprocal age and
 459 language status on PADRI 79% values. Once more, reciprocal age ($F(1,1533)=237.19$, $p<.001$,
 460 $\eta_p^2=.133$) and native/non-native language status ($F(1,1533)=58.75$, $p<.001$, $\eta_p^2=.037$) were
 461 reliable predictors of PADRI thresholds, with adult native speakers having greater perceptual
 462 acuity (Figure 2c). However, the interaction between these two factors only approached
 463 significance ($F(1,1533)=3.27$, $p=.071$, $\eta_p^2=.002$).

464 Returning to results for non-native listeners, regression analysis confirmed that (for
 465 the 310 non-native English participants who self-reported their proficiency in English)
 466 reciprocal age ($\beta=.223$, $t(307)=4.035$, $p<.001$) and self-rated proficiency ($\beta=-.123$, $t(307)=-$
 467 2.234 , $p=.026$) were both reliable predictors of word-word PADRI 79% thresholds (see Figure
 468 6). Interestingly, effects of reciprocal age were non-significant for word-pseudoword PADRI
 469 thresholds ($\beta=.020$, $t(307)=.348$, $p=.728$), though effects of self-rated proficiency remained
 470 reliable ($\beta=-.117$, $t(307)=-2.070$, $p=.039$). This suggests that for non-native speakers, English
 471 proficiency as well as age influences perceptual acuity.

472

473 **Insert Figure 5 about here**

474

475 *Evidence for developmental discontinuities in native listeners*

476 To assess evidence for critical periods in native listeners we used segmented
 477 regression analyses to determine whether the effect of age on perceptual acuity was
 478 consistent throughout development, or showed a discontinuity above a specific age. That is,
 479 do age-related improvements in perceptual acuity continue throughout the lifespan, or stop
 480 at a certain age. Given that effects of age were more apparent for word-word continua, we
 481 first report analysis of word-word PADRI estimates from 1151 native listeners. This analysis
 482 was conducted using the “segmented regression” package in R (Muggeo, 2008) with
 483 reciprocal age as a predictor for PADRI values. This analysis determines whether a model
 484 that includes a ‘breakpoint’ (an age above which perceptual acuity no longer improves)
 485 provides a better fit to observed PADRI 79% thresholds, and if so, at what age that
 486 breakpoint occurs.

487

488 **Insert Figure 6 about here**

489

490 This analysis clearly favoured a model in which there is a breakpoint separating an
 491 initial period of improvement (predicted by reciprocal age) followed by steady state
 492 performance. This three parameter model (intercept, slope, and breakpoint, $AIC_{\text{breakpoint}} = -$
 493 1990.8) was favoured compared to a two parameter (intercept and slope, $AIC_{2\text{-parameter}} = -$
 494 1966.7) model as shown in Figure 6. The difference between AIC values for these two
 495 models ($\Delta AIC = 24.11$), shows a substantial improvement in model fit based on an estimated
 496 breakpoint of 16.7 years (standard error = 1.9 years). According to established criteria
 497 (Burnham & Anderson, 2002) this AIC difference provides no evidence in favour of a simpler

498 2-parameter model in which perceptual acuity continues to improve into adulthood. We also
 499 tested a more complex, four parameter model in which there is an additional slope
 500 parameter such that perceptual acuity changes with age at a different rate after the
 501 breakpoint. However, model comparisons provided no evidence in favour of this more
 502 complex four-parameter breakpoint+slope model over the three-parameter breakpoint
 503 model described previously ($AIC_{\text{breakpoint+slope}} = -1991.8$, $\Delta AIC=1.05$).

504 Thus, we conclude that there is substantial evidence in favour of a model in which
 505 native listeners' perceptual acuity for distinguishing pairs of familiar spoken words reaches
 506 asymptote during late adolescence. These findings provide statistical evidence for a critical
 507 period for improvements in speech perception in native listeners. In the general discussion
 508 we will relate the observed breakpoint of 16.7 years to the age at which the speech
 509 perception and production begins to decline in second language learners decline (Flege et al,
 510 1999).

511 In contrast to these positive findings concerning critical period effects for native
 512 listeners and word-word pairs, we found no evidence for models in which improvements in
 513 perceptual acuity with age show discontinuous changes over the lifespan for word-
 514 pseudoword pairs with native listeners, or for non-native listeners. For word-pseudoword
 515 pairs in native listeners there was a much smaller change in AIC between the 2-parameter
 516 model in which reciprocal age predicts performance throughout the lifespan and the 3-
 517 parameter break-point model ($AIC_{2\text{-parameter}} = -1580.0$, $AIC_{\text{breakpoint}} = -1581.2$, $\Delta AIC=1.18$).
 518 Similarly, for non-native listeners responding to word-word pairs or word-pseudoword pairs
 519 there was no evidence in favour of the more complex breakpoint model (word-word pairs:
 520 $AIC_{2\text{-parameter}} = -571.93$, $AIC_{\text{breakpoint}} = -571.32$, $\Delta AIC = 0.617$; word-pseudoword pairs¹: $AIC_{2\text{-parameter}} = -485.01$, $AIC_{\text{breakpoint}} = -487.90$, $\Delta AIC = -2.89$).

522 Discussion

523 The results of this study demonstrate that age, language experience, and lexical context all
524 affect the perception of speech. Perceptual acuity is better for older listeners, for native
525 listeners, and for trials in which listeners distinguish familiar words from other familiar
526 words rather than from equally-similar but unfamiliar pseudowords. Furthermore, we
527 observed a two-way interaction such that the effect of age is more apparent for word-word
528 than for word-pseudoword trials. Thus, developmental changes in speech perception are
529 most apparent when lexical knowledge can be used to support perceptual acuity. While the
530 main effects observed are in line with previous studies that have compared abilities in
531 categorical speech perception as a function of age (Hazan & Barrett, 2000), language
532 background (Baker et al, 2008), or lexical knowledge (Samuel, 2001), our study goes beyond
533 the existing literature in the following ways.

534 One key contribution of our study is that we measured listeners' ability to
535 discriminate speech sounds using highly-varied, trial-unique stimuli. We included a large set
536 of phonetic continua with changes to the place-of-articulation or voicing of stops, fricatives
537 and affricate consonants at word onset, or offset. We used an automated audio-morphing
538 procedure to modify all of the multiple acoustic cues that convey these contrasts in parallel
539 (Rogers & Davis, 2017). Age-related changes in perceptual acuity cannot therefore arise
540 from greater ability at learning or responding to specific speech tokens. It's also unlikely –
541 given that multiple cues were modified in parallel – that improvements in perceptual acuity
542 with age can arise from developmental differences in the perceptual weighting of any
543 specific acoustic cue(s) (Mayo & Turk, 2004; Nittrouer & Miller, 1997). We are therefore
544 confident that our results reflect genuine improvements in perceptual acuity for speech over
545 the lifespan.

546 A second contribution is that age-related changes in perceptual acuity are more
547 apparent for trials requiring identification of words paired with other words rather than

548 paired with pseudowords. The interaction between age and lexical status cannot easily be
549 explained as due to differences in vocabulary (since our target and distractor words were
550 chosen to be known by even very young participants). Rather, it suggests that additional
551 experience with the heard form of pairs of similar sounding words allows older listeners to
552 achieve greater perceptual acuity. That is, perceptual acuity depends on lexical knowledge
553 to a greater extent than can be explained by accounts in which the function of speech
554 perception is to distinguish individual speech sounds.

555 A third contribution is that we measured perceptual acuity from many more
556 listeners and at a wider range of ages than have been tested in previous studies. This larger
557 dataset allowed us to more precisely determine the nature of the relationship between age
558 and perceptual acuity. We show that perceptual improvements are best predicted by
559 reciprocal age (i.e. $1/\text{age}$). This is consistent with a cumulative process such that the effect of
560 age on perceptual performance reduces as individuals get older. This finding is in line with a
561 previous study of perceptual development for speech perception in noise (Leech et al,
562 2007).

563 However, we go beyond these previous findings by showing that the age-related
564 development of perceptual acuity for native language speech contrasts appears to stop in
565 late adolescence. Despite a PADRI value well above the minimum value tested (mean PADRI
566 for word-word trials, in native-English adults is 18.1%, compared to the lowest value tested
567 of 4%), native listeners over 17 years of age no-longer show age-related improvements in
568 perceptual acuity. This finding suggests a limited period during infancy and adolescence
569 during which improvement in the acuity of speech perception are observed. We did not see
570 an equivalent discontinuity in perceptual development for non-native listeners, or for native
571 listeners responding to word-pseudoword pairs. Thus age-related improvements in speech
572 perception are unlikely to be due to maturation of executive or decision making processes

(common to all participants, and conditions), but rather, improved perceptual acuity for word-word pairs is linked to increased lexical experience in older native listeners.

Implications for theories of speech perception

Accounts of speech perception have proposed multiple, hierarchically-organised mechanisms involved in recognising familiar words: transducing acoustic signals (auditory processing), mapping sounds onto representations of phonetic features or phonemes (pre-lexical processing), before accessing the form and meaning of familiar words (lexical access). Our finding of greater perceptual acuity for word pairs than word-pseudoword pairs suggests interactions between lexical and pre-lexical processes. Such interactions are included in all models of speech perception, though the underlying mechanisms (interactive activation vs predictive processes), and specific function of top-down processes (for immediate perception and/or learning) differ between accounts (see McClelland, Mirman, & Holt, 2006; Norris, McQueen, & Cutler, 2000; Norris, McQueen, & Cutler, 2016). However, only interactive accounts propose – in line with our findings – that the function of top-down processes is to enhance discrimination of ambiguous speech sounds.

Some proponents of largely bottom-up accounts of speech perception have argued that top-down processes are limited to supporting offline perceptual learning shown previously for word-pseudoword pairs (cf. Norris, McQueen, & Cutler, 2003). However, since the design of our experiment avoided repetition of specific speech tokens, included a range of segmental contrasts, and randomised presentation of word-word and word-pseudoword pairs, we think that our findings are unlikely to be due to perceptual learning. Instead, we propose that our results support interactive accounts of speech perception such as the TRACE model (McClelland & Elman, 1986), or our own predictive coding account (e.g. Blank & Davis, 2016). These are accounts in which lexical and sub-lexical processes interact

598 and lexical identification contributes to perceptual identification of speech sounds
 599 (McClelland & Elman, 1986; Samuel, 2001).

600 Our conclusion that lexical knowledge influences the perception of speech also has
 601 some precedent in computational accounts of speech sound development. It was previously
 602 suggested that language-specific phonemic knowledge develops in advance of word
 603 knowledge (summarised by the time-line in Kuhl, 2004). For example, changes in sensitivity
 604 to non-native phonetic contrasts are apparent by 12 months of age (see Werker & Tees,
 605 1999) before the rapid expansion of vocabulary in the second year of life (Bloom, 2000;
 606 McMurray 1997). Yet, recent computational accounts have – in line with our proposal –
 607 suggested that the developing lexicon directly contributes to the acquisition of phonetic
 608 categories. For example, computational simulations of infant vowel category learning
 609 reported by (Feldman, Griffiths, Goldwater, & Morgan, 2013), show that learning the
 610 distributional properties of vowel formants directly leads models to under-estimate the
 611 number of vowel categories in child-directed English. Whereas, a hierarchical model which
 612 the model that builds a lexicon at the same time as learning individual speech sounds
 613 develops an appropriate number of vowel categories. These simulations suggest an
 614 advantage for interactive accounts in which lexical and phonetic learning operate in parallel
 615 throughout early language acquisition (see Feldman, Myers, White, Griffiths, & Morgan,
 616 2013; Yeung & Werker, 2009, for empirical evidence in line with this proposal). This
 617 resembles the proposal made by interactive models of adult speech perception, such as
 618 TRACE, in which segment level processing is guided by lexical identification. We note,
 619 however, that current implementations of TRACE does not include word learning
 620 mechanisms.

621 The evidence presented here further suggests that lexical learning only shapes the
 622 perception of speech sounds for native-speakers during a limited period of childhood and
 623 adolescence. Although lexical learning continues beyond the end of adolescence (as shown

by improvements in vocabulary size up to age 50 and beyond, Brysbaert et al., 2016; Hartshorne & Germine, 2015) perceptual acuity for word-word trials in native listeners plateaus after 16.7 years of age. Since this evidence comes from listeners without any obvious discontinuity in language exposure, and who (presumably) would continue to learn new words in adulthood, we take these observations to suggest there is only a limited period of childhood and adolescence during which lexical learning can enhance perceptual acuity for speech sounds.

Implications for Critical periods

Thus, measures of perceptual acuity in native listeners provide additional evidence for a neurobiologically constrained critical period in speech sound perception and learning. Our data from native listeners joins previous findings from bilingual individuals who learn a second language at different ages in suggesting an extended critical period for language learning during childhood and adolescence. However, determining the age at which declines in second-language learning ability are apparent in the existing literature is complicated. For example, accent-strength data reported by Flege et al. (1999) shows an initial decline in the nativeness of speech production for Korean migrants arriving in the US after 5 years of age which continues until late adolescence. Only for migrants arriving in adulthood does the effect of age on accent strength becomes less apparent. This data resembles ours to the extent that it: (1) shows age-related improvements in speech sound learning during childhood and adolescence, and (2) suggests only limited changes in speech sound learning ability after adolescence. Yet, the limited evidence for second language speech sound learning in adulthood might still have other (non-biological) explanations given differences in language exposure and use in younger and older migrants (Flege, 2018). By showing age-related improvements in perceptual acuity for native listeners that similarly stop in late adolescence in the absence of any change in language exposure or use we suggest that our work provides additional evidence for a neurobiologically-constrained critical period.

650 A similar decline in language ability as a function of age of second-language
651 acquisition was recently shown in a very large scale study comparing syntactic judgements in
652 more than half a million monolingual and bilingual English speakers (Hartshorne et al.,
653 2018). The best fitting statistical model for this data included a precipitous drop in language
654 learning rate at the end of adolescence with a breakpoint of 17.4 years that is close to that
655 which we observed for native listeners. Hartshorne and colleagues explained the decline in
656 proficiency of non-native speakers who learned English after age 10 to 12 years as being due
657 to: “Those who begin (learning) later literally run out of time before the sharp drop in
658 learning rate at around 17–18 years of age” (Hartshorne et al., 2018, p 270). We speculate
659 that a similar explanation might also apply for speech sound learning. Acquiring a sufficient
660 vocabulary of words before the end of adolescence may similarly be vital if a language
661 learner is to perceive speech sounds in those words with optimal perceptual acuity.
662 However it will be for future research in second language learners to assess whether the
663 similarity between the critical period that we have observed for speech sound perception in
664 native listeners and syntactic learning in second language learners is in line with this
665 underlying mechanism.

666

Figure 1: (A) Example visual display and choice alternatives from a trial in the experiment. Listeners hear a female voice say the name of the referent object (*bear*) accompanied by presentation of a colour picture. Then two animated aliens say the same word (*bear*), and a minimally different word (*pear*) or pseudoword (*gare*). Participants indicate with a touchscreen response which alien said the word correctly. (B) Example trial-by-trial record for one adaptive (word-word) track from one participant. At first, the two response alternatives are resynthesized versions of the original speech tokens (i.e. the full acoustic difference between tokens). Correct responses lead to a reduction in the magnitude of the acoustic difference by presenting intermediate audio-morphed tokens (e.g. 16% and 84% morphs, which include only 68% of the original acoustic difference between *bear-pear*). An adaptive, 3-down/1-up procedure was used such that most trials were concentrated at a level of difficulty at which participants were mostly, but not fully, successful at the task and each run terminated after 8 turning points. Word-word trials and word-pseudoword trials were presented in two interleaved adaptive tracks in the experiment, trials from only one track are shown here for clarity. (C) A psychometric curve fit to data from the participant and track shown in (B) is used to estimate the Proportion of Acoustic Difference Required for Identification at 79.4% accuracy. The slope parameter provides an estimate of response consistency and an indication of data quality that was used to exclude participants for whom we could not estimate a reliable PADRI threshold.

Figure 2: Histogram showing distribution of participant ages as a function of language status (bin size is 2 years).

Figure 3: Results. (A) Two-dimensional histogram shows the distribution of Native-English listeners with different PADRI thresholds (low-values = good performance) as a function of age for word-word trials (e.g. *bear-pear*). Bin size for age is 2 years and for PADRI is 0.05. (B) Histogram for Non-Native listeners and word-word trials, plotted as in (A). (C) Two-dimensional histogram shows PADRI thresholds as a function of age for Native-English listeners and word-pseudoword trials (e.g. *bag-pag*). (D) Histogram for Non-Native listeners and word-pseudoword trials.

Figure 4: Mean PADRI threshold (low-values = good performance) as a function of age for (A) Native-English Listeners and (B) Non-Native Listeners. Solid lines show the mean PADRI threshold for word-word trials estimated using local polynomial regression (using “loess” in R) with a span of 0.5 years. Broken lines show the mean PADRI threshold for word-pseudoword trials plotted as before. Shaded areas show the 95% confidence interval.

709
710

711 **Figure 5:** PADRI threshold (low-values = good performance) for word-word trials as a
 712 function of self-rated English proficiency (high-values = high self-rated proficiency) for
 713 individual non-native participants (white dots) and violin plots (blue shapes) trimmed to the
 714 range of the data.

715

Figure 6: Scatter plot (grey dots) with density contours (thin green lines) showing PADRI thresholds (low-values = good performance) against age for 1151 native-English listeners. The thick green line shows the best fitting regression line predicting PADRI threshold as a function of (reciprocal) age over the lifespan. Black line shows improved fit from a segmented regression model with stable performance above a breakpoint at 16.7 years (black dot and dashed black line).

726 **Authorship contributions:**

727

728 MHD developed the study concept, MHD and SE developed the study design and
729 experimental materials, testing and data collection were performed by all authors, MHD and
730 KMM analyzed the data, MHD, SE, KMM, LE, AG, JSHT drafted the paper. All authors
731 approved the final version of the manuscript for submission.

732

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744

745 **Declaration of Conflicting Interests:**

746

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749

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754

755 **Footnotes:**

756 (1) for word-pseudoword pairs the best fitting breakpoint model included better

757 performance for younger non-native listeners (below a breakpoint of 5.9 years) to explain

758 good performance by the ten youngest participants

759 **Supplemental Material:**

760

761 **Appendix 1: List of Languages Spoken by Participants**

762

Albanian	2
Amharic	2
Arabic	13
Basque	2
Bengali	11
Bulgarian	1
Catalan	4
Chinese*	8
Czech	2
Danish	9
Dutch	50
English	1151
Flemish	2
French	36
Galician	1
German	26
Greek	6
Gujarati	3
Hebrew	4

Hindi	2
Hungarian	2
Italian	24
Japanese	4
Korean	5
Latvian	3
Lithuanian	1
Malay	1
Maltese	1
Marathi	2
Nepali	3
Norwegian	6
Polish	19
Portuguese	31
Punjabi	1
Romanian	4
Russian	10
Samoan	1
Shona	1
Slovak	2
Somali	4
Spanish	45
Swedish	6

Tamil	12
Thai	1
Turkish	4
Urdu	7
Vietnamese	1
Welsh	1

763

764 *combining participants who opted for Chinese (simplified) and Chinese (traditional)

765

766

767

768 **Appendix 2: List of stimulus items**

target	distractor word	manner of articulation	word contrast	distractor nonword	nonword contrast	manner of articulation
ant	and	stop	offset/voice	ank	offset/place	stop
bag	back	stop	offset/voice	pag	onset/voice	stop
bear	pear	stop	onset/voice	gair	onset/place	stop
bed	beg	stop	offset/place	beb	offset/place	stop
bib	big	stop	offset/place	dib	offset/place	stop
bus	buzz	fricative	offset/voice	dus	onset/place	stop
cake	cape	stop	offset/place	pake	onset/place	stop
cat	cap	stop	offset/place	gat	onset/voice	stop
chick	chip	stop	offset/place	jik	onset/voice	fricative
cone	comb	nasal	offset/place	pone	onset/place	stop
duck	tuck	stop	onset/voice	dut	offset/place	stop
fork	fort	stop	offset/place	sork	onset/place	fricative
gate	date	stop	onset/place	gake	offset/place	stop
glass	class	stop	onset/voice	glazz	offset/voice	fricative
goat	boat	stop	onset/place	goap	offset/place	stop
hay	say	fricative	onset/place	thay	onset/place	fricative
hot	hop	stop	offset/place	fot	onset/place	fricative
kite	tight	stop	onset/place	kide	offset/voice	stop
knife	nice	fricative	onset/place	mife	onset/place	fricative
knob	nod	stop	offset/place	knop	offset/voice	stop
leaf	leave	fricative	offset/voice	weaf	onset/place	approximant
leap	leak	stop	offset/place	leat	offset/place	stop
lip	lick	stop	offset/place	yip	onset/place	approximant
lock	rock	approximant	onset/place	yok	onset/place	approximant
meat	neat	nasal	onset/place	meep	offset/place	stop
mouth	mouse	fricative	offset/place	nouth	onset/place	nasal
mug	mud	stop	offset/place	mub	offset/place	stop
page	cage	stop	onset/place	patche	offset/voice	fricative
paste	taste	stop	onset/place	paske	offset/place	stop
peach	teach	stop	onset/place	peadg	offset/voice	fricative
pen	ten	stop	onset/place	pem	offset/place	nasal
pig	pick	stop	offset/voice	pib	offset/place	stop
rake	lake	approximant	onset/place	jaike	onset/place	approximant
rug	rub	stop	onset/place	rud	onset/place	stop
sauce	force	fricative	onset/place	thauce	onset/place	fricative
screen	scream	nasal	offset/place	screeng	offset/place	nasal
seed	feed	fricative	onset/place	seeb	offset/place	stop
shake	fake	fricative	onset/place	shate	offset/place	stop

shave	save	fricative	onset/place	shathe	offset/place	fricative
sheet	sheep	stop	offset/place	theet	onset/place	fricative
shelf	self	fricative	onset/place	felf	onset/place	fricative
shirt	hurt	fricative	onset/place	shirp	offset/place	stop
sign	shine	fricative	onset/place	thine	onset/place	fricative
sing	thing	fricative	onset/place	shing	onset/place	fricative
sink	think	fricative	onset/place	shink	onset/place	fricative
soap	hope	fricative	onset/place	foap	onset/place	fricative
sweet	sweep	stop	offset/place	sweek	offset/place	stop
swing	swim	nasal	offset/place	swin	offset/place	nasal
tape	take	stop	offset/place	pape	onset/place	stop
thumb	hum	fricative	onset/place	thun	offset/place	nasal
top	pop	stop	onset/place	dop	onset/voice	stop
tub	tug	stop	offset/place	tud	offset/place	stop
wag	rag	approximant	onset/place	wab	offset/place	stop
weight	late	approximant	onset/place	jait	onset/place	approximant
wing	ring	approximant	onset/place	ling	onset/place	approximant
wipe	white	stop	offset/place	lipe	onset/place	approximant
wrist	list	approximant	onset/place	jist	onset/place	approximant
write	light	approximant	onset/place	jite	onset/place	approximant
yawn	lawn	approximant	onset/place	rawn	onset/place	approximant
yell	well	approximant	onset/place	rel	onset/place	approximant

770 **Open Practices:**

771 We will share data, stimulus items, sound files and a Matlab script to run the task on a
772 desktop PC or Mac.

773

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