

1 **Title: Processing of a spoken narrative in the human brain is shaped  
2 by family cultural background**

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48 **ABSTRACT**

49 Using neuroimaging, we studied influence of family cultural background on processing of an  
50 audiobook in human brain. The audiobook depicted life of two young Finnish men, one with the  
51 Finnish and the other with the Russian family background. Shared family cultural background  
52 enhanced similarity of narrative processing in the brain at prelexical, word, sentence, and  
53 narrative levels. Similarity was also enhanced in brain areas supporting imagery. The cultural  
54 background was further reflected as semantic differences in word lists by which the subjects  
55 described what had been on their minds when they heard the audiobook during neuroimaging.  
56 Strength of social identity shaped word, sentence, and narrative level processing in the brain.  
57 These effects might enhance mutual understanding between persons who share family cultural  
58 background and social identity and, conversely, deteriorate between-group mutual understanding  
59 in modern multicultural societies wherein native speakers of a language may assume highly  
60 similar understanding.

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## Introduction

74        People raised and living in a shared cultural environment and using the same language  
75        largely share similar knowledge, experiences, beliefs, values, attitudes and interaction rules that  
76        together facilitate shared understanding and fosters smooth cooperation. These similarities create  
77        “homophily” – love of the same – that has been studied in sociology for decades using behavioral  
78        methods (1). In a recent landmark study, Parkinson et al. (2) provided neuroimaging evidence for  
79        homophily showing that brain activity is exceptionally similar among friends – in contrast to  
80        acquaintances – when they are viewing audiovisual film clips. The interest toward the effects of  
81        cultural homophily on neural mechanisms of cognitive functions has increased rapidly, as  
82        exemplified in the emergence of the new field of “cultural neuroscience” (3, 4). Previous  
83        behavioral (5–10) and neuroimaging (11) studies, using pictures as stimuli, have shown that  
84        persons living in Eastern (Asian) and Western (American) cultures exhibit robust within-culture  
85        similarities and between-culture differences in their perceptual-cognitive styles (3, 4). A study  
86        that investigated perceptual-cognitive styles of Asian Americans and European Americans found  
87        that those of Asian Americans’ were either identical to those of European Americans’ or fell in-  
88        between the styles of East Asians’ and European Americans’ (12). However, the effects of shared  
89        cultural family backgrounds within modern multi-ethnic nations are less well known than those  
90        arising in inter-national/continental comparative studies. In multicultural societies native speakers  
91        of the same language may assume highly similar understanding of concepts (13). It might go  
92        unnoticed that this is not true and, therefore, might cause communication mismatches.

93        Furthermore, since previous cultural neuroscience studies have mostly used pictures as  
94        stimuli, it is also less clear whether and how shared family cultural background shapes processing  
95        and understanding of natural speech in the brain at different hierarchical levels of language  
96        processing. Such processing levels include prelexical processing, which is taking place in the

97 auditory cortices at superior aspects of temporal lobes, and when individual words or short  
98 sentences are used as stimuli more pronounced brain activity has been described in left-  
99 hemisphere lateral and anterior temporal cortical areas (14). In contrast, presentation of a  
100 narrative in naturalistic experimental settings results in more widespread and bilateral activation  
101 involving prefrontal and parietal areas as well cingulate cortices and precuneus that has been  
102 specifically associated with understanding of the story lines in narratives (15–19). Visual cortex is  
103 also activated during listening to a narrative, likely related to visual imagery elicited by the  
104 narrative (20).

105 Previous behavioral cross-cultural studies have provided evidence that cultural  
106 background can shape understanding of culturally specific aspects in narratives (21). An event  
107 related response study by Ellis et al. (22) provided related results by showing that the so-called  
108 N400 event-related potential response amplitude of fluent Welsh-English bilinguals was  
109 significantly stronger to sentences written in Welsh than to sentences written in English.  
110 Importantly, this difference was only found for the sentences that contained information about  
111 Wales culture but not for the sentences that did not contain culture-related information. The  
112 authors interpreted this to reflect that language interacts with factors related to personal identity,  
113 such as culture, to shape processing of incoming semantic information. Notably, similarities-  
114 differences in language processing might play an important role in mutual understanding and  
115 homophily between individuals with shared cultural backgrounds and also in failures of mutual  
116 understanding between individuals from different cultural backgrounds.

117 Recent methodological advances have made it possible to both record brain activity (2, 15,  
118 17, 18, 23–26) and behaviorally assess subjective interpretations (20) during listening to an  
119 audiobook. Here, we thrived on these advances to investigate whether the family cultural  
120 background modulates inter-subject similarity in how an audiobook is interpreted, and how the  
121 audiobook is processed at multiple different hierarchical levels of language processing in the

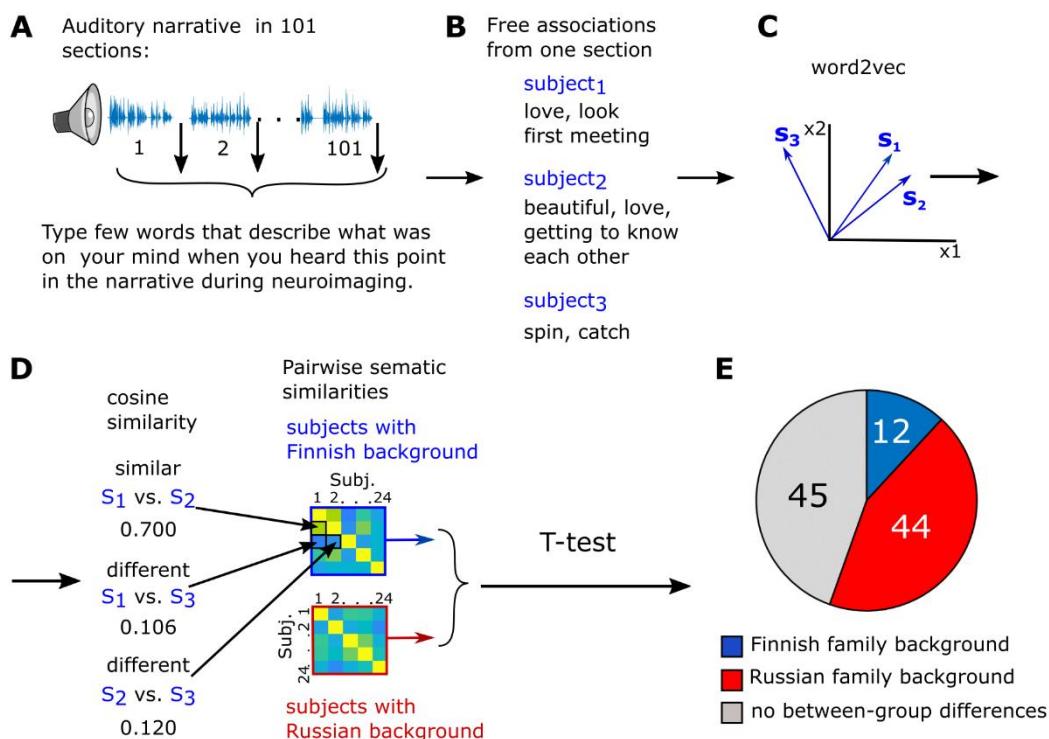
122 human brain. We used dynamic inverse functional magnetic resonance imaging (fMRI) (27)  
123 whose ultra-fast 10-Hz sampling rate we regarded as helpful in studying more accurately the  
124 processing of natural speech wherein individual words are presented at rates of about three words  
125 per second. We recruited 48 healthy residents of Finland, all fluent in Finnish, to the study. Half  
126 of the subjects had Finnish parents and either one or both parents of the other half of the subjects  
127 were Russians. The subjects listened to a 71-min audiobook, a prose depicting life of two young  
128 Finnish men, one with the Finnish and the other with the Russian family background, during the  
129 fMRI. In the audiobook, social interaction scenes were interspersed with descriptions of city  
130 scenery amidst changing seasons. Afterwards, the subjects performed an association task on the  
131 story replayed in short segments where they were asked to produce words describing what the  
132 previous segment had brought to their minds during the neuroimaging session. By mapping the  
133 words to semantic vector space (28), we estimated the similarity of the meanings and imagery  
134 elicited by the story (20). Additionally, we measured, using Implicit Association Test (IAT),  
135 whether the subject unconsciously associate her/his family's culture to the more positive  
136 attributes than the other culture (29). The subjects also filled a questionnaire with items relevant  
137 to the family cultural background, including how Russian the subjects self-identify themselves  
138 and how well they speak Russian in addition to Finnish. We hypothesized to find family cultural  
139 background specific enhancements of similarity in how different parts of the story are interpreted  
140 as well as in similarity of brain hemodynamic activity in brain areas known to be involved in  
141 processing of natural speech to pinpoint the level(s) of hierarchy of language processing  
142 (prelexical > word meanings > story line) and visual imagery that family cultural background  
143 might shape.

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## Results

### 146 Cultural family background increased similarity of audiobook interpretation

147 We estimated similarities in interpretation of the audiobook using the association task.  
148 Subjects listened to the audiobook in 101 segments and, after each segment, typed in the  
149 following 20–30 sec a list of words that best described what had been on their minds at that point  
150 in the audiobook during neuroimaging (Fig. 1; for the description of the method, see also (20)).  
151 The semantic similarity of the subjects' word lists was estimated by transforming the lists into the  
152 vector representations in a semantic space and by calculating the cosine similarities between the  
153 resulting semantic vectors (28). There were significant effects both in segments depicting  
154 interacting protagonists and in segments with descriptions of city scenery amidst changing  
155 seasons. The Russian-background subjects listed 33% more words than the Finnish-background  
156 subjects (18 724 vs. 12 536 words;  $p < 0.01$ , as assessed with a paired T-test). The similarity was  
157 significantly higher in 44/101 segments ( $p < 0.05$ , as assessed with a paired t-test, false discovery  
158 rate (FDR) -adjusted). However, in Finnish-background *vs.* Russian-background subjects the  
159 similarity was significantly higher in 12 out of 101 segments ( $p < 0.05$ , FDR-adjusted). The  
160 segments where there were significant effects are indicated in the English-translated transcription  
161 of the audiobook in Supplementary Materials.



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163 **Fig. 1. Schematic illustration and results of the behavioral association task.** (A) In the association task, the  
164 audiobook was presented to the subject in 101 segments after the fMRI session. (B) After each segment, the subject  
165 typed in 20–30 sec words that described what was on his/her mind at that point of the audiobook during fMRI (20).  
166 (C) The associated words were transformed into the vector representations in a semantic space (word2vec). For each  
167 segment, a vector sum was calculated over the vector representations of the words the subject had produced. (D)  
168 Thereafter, pairwise cosine similarities were calculated between these semantic vectors. Then, t-statistics was used to  
169 examine whether the cosine similarities differ between the word lists produced by the two groups of subjects. (E) The  
170 Finnish-background subjects produced semantically more similar word lists in 12 out of 101 segments, the Russian-  
171 background subjects listed semantically more similar words in 44 out of 101 segments. There were no significant  
172 effects in 45 segments.

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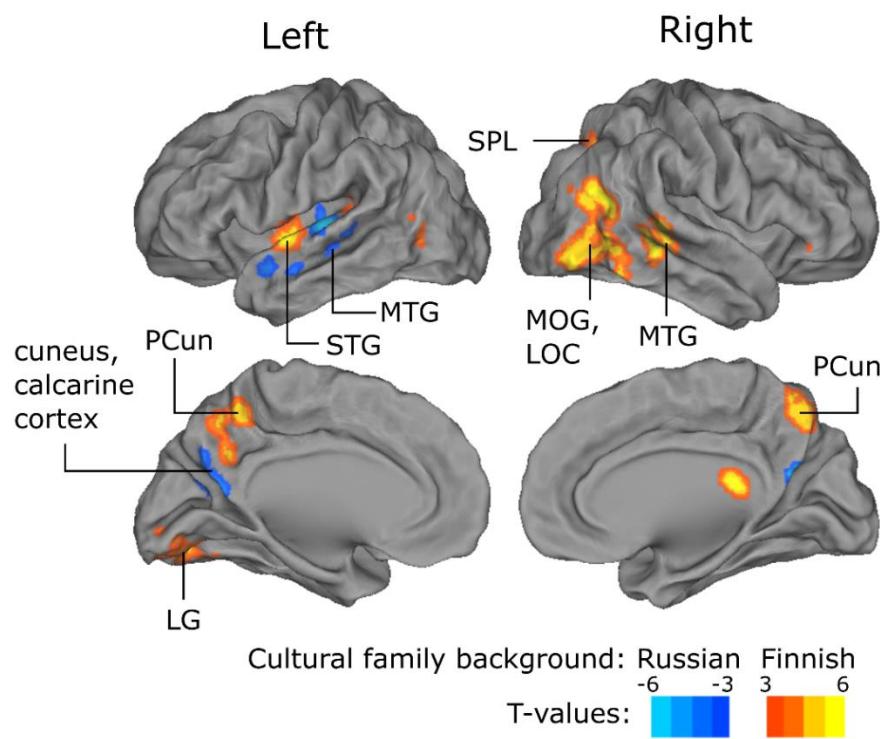
#### 174 Cultural family background modulated inter-subject correlation of brain activity

#### 175 during audiobook listening

176 Audiobook listening elicited significant ISC in several brain regions in both groups (Fig.

177 S1 and Table S1; statistical maps can be found from

178 Neurovault: <https://neurovault.org/collections/LINKKSTF/>). In the subjects with Finnish *vs.*  
179 Russian background stronger ISC was found in the left hemisphere in an area extending from the  
180 Heschl's gyrus (HG) and insula to the superior temporal gyrus (STG) as well as in an area  
181 extending from the lingual gyrus (LG) to the middle occipital gyrus (MOG) and cerebellum (Fig.  
182 2, cerebellum not shown; Table S2). In the right hemisphere, ISC was stronger for the Finnish-  
183 background subjects in an area including parts of the middle temporal gyrus (MTG), MOG,  
184 lateral occipital cortex (LOC) and cerebellum. The ISC was stronger in the Russian *vs.* the  
185 Finnish -background subjects in left-hemisphere areas extending from the HG to STG and MTG,  
186 as well as bilaterally in posterior-inferior parts of the PCun and anterior parts of the cuneus.



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189 **Fig. 2: Brain areas where the activity was shaped by family cultural background.** The brain areas where ISC was  
190 significantly different between the subjects with the Finnish *vs.* Russian family backgrounds ( $p < 0.05$ , adjusted with  
191 cluster-based thresholding using 5000 permutations and cluster-defining threshold of  $p < 0.001$ , uncorrected).  
192 Abbreviations: STG = superior temporal gyrus, MTG = middle temporal gyrus, LOC = lateral occipital cortex,  
193 MOG = middle occipital gyrus, PCun = precuneus, SPL = superior parietal lobule, LG = lingual gyrus. The loci of  
194 ISC were labelled according to the Harvard-Oxford Cortical Structural Atlas (30) implemented in FSL.

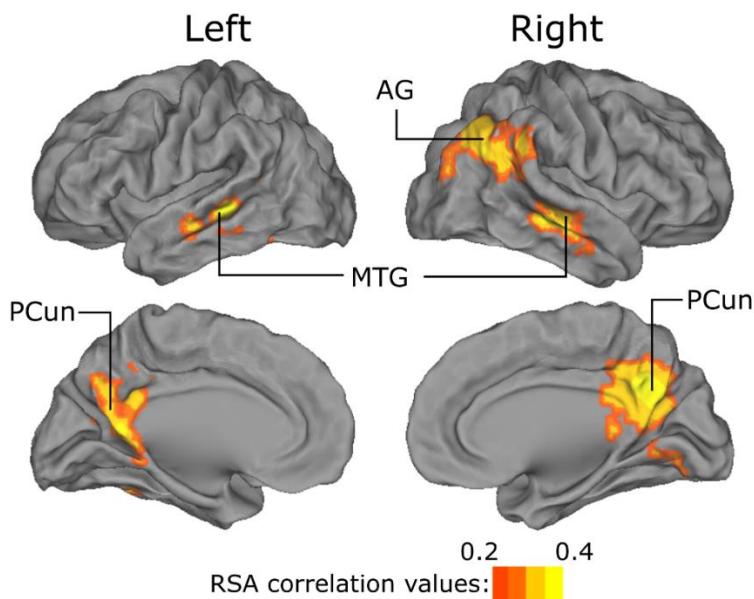
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196 **Cultural identification modulated inter-subject correlation of brain activity during**  
197 **audiobook listening**

198 To investigate which of the background variables (Table 1 in Methods and IAT scores in  
199 Supplementary materials) are reflected in ISC values, the representational similarity analysis  
200 (RSA) was conducted between each of the background similarity matrices and ISC matrix in each  
201 voxel. Only the between-subject similarities in the social identification (“how Russian the subject  
202 feels herself / himself”) predicted BOLD-similarities between the Russian-background subjects  
203 bilaterally in the MTG and PCun as well as in the right angular gyrus (AG, see Fig. 3 and Table  
204 S3). We failed to observe significant effects within the Finnish-background subject group,  
205 perhaps due to less variability in their social identity self-ratings. The results were obtained using  
206 fMRI data that was temporally smoothed with a 2-sec time window (50% overlap). We also  
207 studied how the background variables are reflected in the associated words reported in the  
208 association experiment. The analysis and results are described in Supplementary text and Fig. S2.

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### Implicit association test results

IAT (29) was used to investigate whether the subjects unconsciously favored Finland or Russia. Subjects categorized positive and negative adjectives as well as words and pictures related to Finland and Russia while their reaction times were measured (see Supplementary materials for the detailed description). The IAT effect was different between the Finnish- and Russian-background subjects ( $p < 0.001$ , Fig. S3). Wilcoxon test showed that Finnish-background subjects preferred Finland over Russia ( $p < 0.001$ , mean d-score: 0.51, std: 0.44, negative values mean preference for Russia and positive for Finland) whereas the Russian-background subjects favored neither country ( $p = 0.69$ , mean d-score: -0.07, std: 0.45). Between-group differences in other background variables are shown in Table 1 (Methods).

229        **Discussion**

230        In the present study, the behavioral word-listing experiment (20) disclosed that 56 out of  
231        the 101 audiobook segments elicited significantly different associations between the subjects with  
232        the Finnish and Russian family backgrounds (Fig. 1), even though all subjects were fluent in  
233        Finnish and 44 of had been born and raised in Finland and the remaining four had moved to  
234        Finland as small children. The semantic similarity of the associated words was higher among the  
235        Russian-background subjects in 44 segments of the story compared to the Finnish-background  
236        subjects and vice versa in 12 segments. This suggests that those story segments contained  
237        elements that elicit family cultural background related associations specific to each group, and  
238        may have been understood more similarly within each group. These segments contained both  
239        culture-specific but also non-specific elements (see English-translated text of the audiobook in  
240        Supplementary Materials) suggesting that the family cultural background can also modify  
241        perception of elements that are not at least obviously related to the culture. Interestingly, out of  
242        the cultural background variables 1) the IAT scores, 2) the question how Russian the subjects felt  
243        themselves, and 3) the question how Finnish the subjects felt themselves best explained the  
244        similarities-differences in the word listings, and for example level of command of Russian  
245        language had a negligible effect (Fig. S2, Supplementary text). Overall, the Russian-background  
246        subjects produced 33% more words than the Finnish-only background subjects, which could be  
247        explained by the Finno-Ugric culture having been observed to be a less talkative one (31).  
248        Interestingly, then, it seems that the family background can override the general tendency of the  
249        mainstream culture towards small talk.

250        Using fMRI, we were able to reveal, for the first time, that the differences in the family  
251        cultural backgrounds of the subjects were reflected as between-group differences in ISC of brain  
252        hemodynamic activity in surprisingly many brain regions (Fig. 2), even when both subject groups  
253        had equally good command of Finnish and were citizens of Finland. This is an important

254 extension to the previous behavioral studies that have found cross-cultural differences between  
255 subjects during story reading as well as neuroimaging studies that have mainly used simple  
256 isolated pictures to investigate perception differences of people from Western and Eastern  
257 cultures. STG, MTG and PCun have been associated with speech comprehension and processing  
258 of semantic information in several previous neuroimaging studies ((32), for a review, see (33)).  
259 Lerner et al. (15) showed that words and sentences activated areas in the temporal cortices, and  
260 when the sentences formed full paragraphs, the activation extended also to the frontal cortices and  
261 PCun. Further, it has been shown that PCun exhibits increased ISC between subjects who have  
262 understood visual and auditory narratives more similarly (25), is involved in processing  
263 paragraphs about in-group *vs.* out-group characters (34) and, especially posterior PCun, is also  
264 important in episodic memory retrieval (35). In the light of these previous studies and the results  
265 of the association task, the between-group differences in the ISC in STG, MTG and PCun could  
266 be explained by the family cultural background shaping the processing of semantics at multiple  
267 timescales as well as in the process of linking the story events into the subject's prior experiences  
268 and memories. Between-group differences in the ISC in the LOC, LG and MOG possibly  
269 reflected differences in visual imagery elicited by listening to the audiobook (36, 37). The  
270 between-group differences in ISC may additionally reflect identifying only with the subjects' own  
271 culture and differential viewing of the protagonists belonging to the subjects' own *vs.* other  
272 cultural group. Indeed, the RSA revealed that out of the cultural background variables, the  
273 question how Russian the subjects feel themselves predicted the similarities-differences of the  
274 ISC between the Russian-background subjects in the MTG, PCun and AG (Fig. 3., Table S3).  
275 Thus, it seems that the sense of belonging to a cultural group, social identity (38), shapes the  
276 narrative processing in the brain. Interestingly, between-group differences in ISC were also found  
277 in the primary auditory cortex at HG. This suggests that the cultural family background modulates

278 even prelexical processing of speech, perhaps via top-down influences from the higher-level  
279 speech processing areas.

280 In conclusion, our results suggest that even a relatively subtle differences in cultural  
281 background can result in higher similarity within one group compared to the other in how natural  
282 speech is interpreted and how it is processed at multiple hierarchical levels in the human brain.

283 Our results suggest that the strength of social identity most robustly shapes narrative processing in  
284 lateral-temporal and temporo-parietal areas that likely process natural speech at word and  
285 sentence levels, as well as in precuneus that is known to process natural speech at narrative level.  
286 These effects might play an important role in enhancing mutual understanding between  
287 individuals with shared cultural backgrounds. Awareness of these effects could help overcome  
288 potential challenges in mutual understanding between individuals with different cultural  
289 backgrounds and social identities in modern multicultural societies wherein individuals from  
290 different backgrounds speak the same native language and might erroneously take for granted  
291 highly similar understanding. Enhanced awareness and scientific understanding of these  
292 differences in language use is important to understand and avoid obstacles in social interactions at  
293 many levels of society.

294

## 295 **Materials and Methods**

296 **Subjects**

297 Forty-eight subjects participated in the study: 24 subjects with Finnish family background and 24  
298 subjects with Russian family background. The subjects with the Finnish family background had  
299 Finnish parents and were born and raised in Finland. They were aged between 19–35 years (mean  
300 age: 24.7 years). 12 of the Russian-background subjects had both parents Russian, 11 had Russian  
301 mother and one had Russian father. The subjects with Russian family background were aged  
302 between 18–35 years (mean age: 24.7 years). 20 of the Russian-background subjects were born in

303 Finland, one subject had moved to Finland at the age of eight, one at the age of one, and two at  
304 the age of three years. 10 of the subjects with the Russian family background were exposed to  
305 both Finnish and Russian in first years of life, 13 started to acquire Finnish at the age of three  
306 years when they went to preschool and one at the age of 8 years. All subjects were using Finnish  
307 actively in their daily live. Of the subjects with the Russian family background, 19 felt Finnish  
308 and two felt Russian as their stronger language, and three felt that both languages are equally  
309 strong. The subjects did not constitute a representative sample of Finnish and Russian family  
310 background residents of Finland, and therefore, the results cannot be generalized to the whole  
311 population with Russian family background people in Finland.

312 All subjects were right-handed (Edinburgh Handedness Inventory (39)). When asked, none of the  
313 subjects reported any neurological or audiologic deficits. All subjects were residents of Finland  
314 (11 Russian background subjects had also Russian citizenship), fluent in Finnish and had  
315 graduated from the Finnish primary school. Half of the subjects in both groups were females. In  
316 both groups, one of the subjects had vocational examination and not Matriculation examination  
317 and the others had Matriculation examination, undergraduate examination or university degree  
318 examination. Prior to participation, all subjects gave their written voluntary informed consent.  
319 The study was approved by the Aalto University Research Ethics Committee and conducted in  
320 accordance with the Declaration of Helsinki.

321

## 322 **Stimulus**

323 During the fMRI the subjects were presented with a 71-min fictional audiobook in Finnish  
324 (custom written by author IPJ; in the end of the Supplementary materials is the English-translated  
325 textual version that conveys the events of the story however without artistic level of literacy of a  
326 professional translation). The narrative included episodes related to and occasionally contrasting  
327 Finnish and Russian cultures (e.g. religion, food, literature, history and traditions). The

328 protagonists of the narrative were two friends, young adults with, Finnish and Russian  
329 backgrounds, both living in Helsinki, Finland. In short, the Finnish man was courting a Russian-  
330 background woman, whereas the Russian man was in the relationship with a Finnish woman. The  
331 characters were described as having personality and behavioral characteristics stereotypically  
332 associated with Finns or Russians (e.g. Russian characters were more emotional and conservative  
333 than Finns) however without exaggerating to present the protagonists as realistic persons. Cultural  
334 differences in expressing emotions, style of thinking, behavioral patterns, values and attitudes  
335 resulted in difficulties in understanding each other and in conflicts between the characters. At the  
336 end of the story, the Russian-background man ended up in a relationship with the Russian-  
337 background woman and the Finnish man with the Finnish woman. The aim of the story was that  
338 the Finnish-only background subjects would identify more with the Finnish protagonists and  
339 understand the Finnish-culture specific elements, while the subjects with the Russian background  
340 would have greater understanding and thus identification with the Russian protagonists than the  
341 Finnish-only background subjects and, further, that the culture-specific elements. In the  
342 audiobook, periods describing interactions between protagonists were interspersed with periods  
343 describing the seasons in the city without social interactions or culture-specific elements. The  
344 audiobook was recorded with a sampling frequency of 44 100 Hz in a professional recording  
345 studio. For the fMRI experiment, the auditory file of the audiobook was divided into 10 segments  
346 and for the association task into 101 segments.

347

### 348 **Experimental procedures**

349 Subjects filled out the background questionnaire (Table 1) as part of behavioral questionnaires.  
350 Thereafter, subjects participated in fMRI measurement and simultaneous  
351 magnetoencephalography / electroencephalography (MEG / EEG) measurement sessions that  
352 were separated by at least one month in order to reduce possible learning effects. The order of the

353 neuroimaging sessions was counterbalanced across the family backgrounds and genders of the  
354 subjects. MEG/EEG results will be reported separately.

355 **Table 1. Results from the background questionnaire.** Results are mean values  $\pm$  SEM. Level of command of  
356 Russian language: 1 = I don't speak Russian, 2 = poor, 3 = satisfactory, 4 = good, 5 = native; Visits in Russia: 1.  
357 never visited, 2. visited few times, 3. visited several times, 4. visited regularly, 5. lived longer time periods; How  
358 Finnish I feel myself: 0 = not at all, 100 = strongly, How Russian I feel myself: 0 = not at all, 100 = strongly; How  
359 positively / negatively I see Finns: 0 = very negatively, 100 = very positively; How positively / negatively I see  
360 Russians: 0 = very negatively, 100 = very positively. Significance levels of between-group differences: n.s.  $> 0.05$ ,  
361  $*p < 0.05$ ,  $**p < 0.01$ ,  $***p < 0.001$ , tested with 50 000 permutations.

Cultural background	Level of Russian language ***	Visits to Russia ***	How Finnish do I feel myself? (scale 1–100) **	How Russian do I feel myself? (scale 1–100) ***	How positively/negatively do I see Finns (scale 1–100) n.s.	How positively/negatively do I see Russians (scale 1–100) n.s.
Finnish	1.2 $\pm$ 0.1	1.4 $\pm$ 0.1	93.3 $\pm$ 1.9	1.6 $\pm$ 0.3	86.3 $\pm$ 2.2	59.7 $\pm$ 2.7
Russian	4.7 $\pm$ 0.1	3.9 $\pm$ 0.1	69.6 $\pm$ 3.1	55.8 $\pm$ 3.2	77.3 $\pm$ 2.6	67.3 $\pm$ 2.8

362  
363 After the neuroimaging measurements, the subjects performed the IAT which aims at measuring  
364 automatic associations or beliefs that the subject is not willing or self-aware to report (29).  
365 Further, subjects filled an on-line association task at home. In this, the audiobook was re-  
366 presented to the subject in 101 segments and at the end of each the subjects were instructed to  
367 type a few words that best describe what was on his/her mind at the end of the segment when  
368 he/she had heard that segment first time during neuroimaging. The segments are indicated in the  
369 English-translated version of the audiobook in the end of the Supplementary Materials.

370  
371 **Semantic similarity analysis of the self-reported word lists**  
372 To examine between-group differences in word lists produced by the subjects in the association  
373 task, word2vec skip-gram method (28) was first used to transform the individual words into  
374 vectors representing semantic-content. Here, the word2vec skip-gram model (Gensim Python

375 Library, <https://pypi.org/project/gensim/>) was trained using the Finnish Internet Parsebank corpus  
376 (40) (<http://bionlp.utu.fi/finnish-internet-parsebank.html>) with 500 dimensions and a window of  
377 10 words. The words that occurred less than 50 times in the corpus were excluded from the model  
378 training. The vector embeddings were adjusted by passing the corpus through the word2vec skip-  
379 gram model five times.

380 The model contained 98% of the words produced by the subjects, and the rest of the words were  
381 discarded. The word lists produced by the subjects were first corrected for spelling errors and  
382 stop-words were removed in the case the subject had written sentences. Thereafter, word2vec was  
383 used to map each word to a semantic vector. The semantic representation of each list was  
384 obtained by calculating the vector sum over the words in the list. The list vector was computed for  
385 101 narrative segments. Between-subject pairwise semantic similarities were then obtained by  
386 calculating cosine distances between the list vectors.

387 The pairwise cosine similarities within the Finnish-background subjects was compared to the  
388 pairwise cosine similarities between Russian-background subjects using a nonparametric T-test  
389 where the null-distribution was created by randomly permuting the cosine similarities between  
390 groups 50 000 times (41). T-test was calculated separately for each of the 101 segments. In  
391 addition, the semantic similarities of the associated words across the whole audiobook were  
392 estimated by calculating an average over the pairwise cosine similarities over the 101 audiobook  
393 segments after weighting the cosine similarities by the length of the segment. Thereafter, the T-  
394 test was calculated between the resulting cosine similarities obtained for the subjects with the  
395 Finnish and Russian family backgrounds.

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399 **fMRI acquisition**

400 The fMRI session consisted of the following 13 runs: 1) T1-weighted anatomical, 2) a run  
401 comprising of four repetitions of the introduction of the narrative (5.93 min), 3) the narrative  
402 presented in 10 runs (durations: 4.8–8.4 min), 4) the run comprising of four repetitions of the  
403 introduction of the narrative (5.93 min), 5) resting state (3 min) and 6) T2-weighted anatomical.  
404 Each functional run started with a period of 12.3 s and ended with a period of 15 s without  
405 auditory stimulation. The repetitions of the introduction were separated by a period of 16 s  
406 without auditory stimulation. The subject was shown a white fixation cross on a black background  
407 during the functional runs (including resting state) and images of Helsinki between the runs and  
408 during the measurement of reference scans. 24 subjects wanted to have one, six subjects 2–4, and  
409 18 subjects zero breaks outside of the scanner between runs.

410 Anatomical and functional MRI data were acquired with a 3T MRI whole-body scanner  
411 (MAGNETOM Skyra, Siemens Healthcare, Erlangen, Germany) using a 32-channel receiving  
412 head coil array. In the beginning of the measurement session, anatomical images were measured  
413 using a  $T_1$ -weighted MPRAGE sequence (TR=2530 ms, TE = 3.30 ms, field of view (FOV) = 256  
414 mm, flip angle = 7 degrees, slice thickness = 1 mm). Whole-brain fMRI data was measured using  
415 an ultra-fast simultaneous multislice (SMS) inverse imaging (InI) sequence (27). The SMSInI has  
416 higher spatial resolution with lower signal leakage and higher time-domain signal-to-noise ratio  
417 than inverse imaging without SMS, and detects subcortical fMRI signals with similar sensitivity  
418 and localization accuracy as echo planar imaging (27). Here, the SMSInI enabled more accurate  
419 removal of physiological artifacts (42) and utilization of the higher sampling rate under conditions  
420 of listening to natural connected speech wherein words occur at rates of ~three per second.  
421 Instead of completely relying only gradient coils in spatial encoding, InI achieves spatial  
422 encoding by solving the inverse problems utilizing the spatial information from channels in a  
423 radio-frequency coil array and gradient coils. In this study, InI-encoding direction was superior-

424 inferior, whereas frequency and phase encoding were used to recover the spatial information in  
425 anterior-posterior and left-right directions, respectively. 24 axial slices (7 mm) were first collected  
426 without gap between slices. Thereafter, the slices were divided into two groups of 12 slices, and  
427 each of the slice groups was excited and read in 50 ms resulting in a TR of 100 ms. Simultaneous  
428 echo refocusing (43) was used to separate adjacent slices in each group, and aliasing was further  
429 controlled with blipped controlled aliasing in parallel imaging (44). Other measurement  
430 parameters were: TE=27.5 ms, flip angle=30°, FOV=210 x 210 x 210 mm<sup>3</sup>, and in-plane  
431 resolution = 5 mm x 5 mm.

432 Solving an inverse problem in InI reconstruction requires sensitivity map of the channels in the  
433 coil array (27). This information was included in a 6-sec reference scan measured before each  
434 functional run. In the reference scan, partition-encoding steps were added after slice group  
435 excitation in InI-encoding direction. The reference scan and accelerated scans were acquired with  
436 the same other imaging parameters. Before each reference scan, shimming was used to minimize  
437 inhomogeneity in the magnetic field.

438 During the fMRI measurements, stimulus presentation was controlled with Presentation software  
439 (Neurobehavioral Systems, Albany, NY, USA). The auditory stimuli were presented to the  
440 subject through Klaus A. Riederer (KAR) ADU2a insert earphones. The intensity level of the  
441 stimulus was adjusted on an individual subject basis at a comfortable listening level that was  
442 clearly audible above the scanner noise. The audio out from the sound card of a computer was  
443 recorded with the BIOPAC MP150 Acquisition System (BIOPAC System, Inc.). In the data  
444 analysis, this allowed us to determine the exact times when the auditory stimulus has started. The  
445 BIOPAC MP150 system was also used to record heart rate and respiration signals during the  
446 fMRI measurement. Heart rate was measured using two BIOPAC TSD200 pulse plethysmogram  
447 transducers placed on the palmar surfaces of the subject's left and right index fingers. Respiratory  
448 movements were measured using a respiratory-effort BIOPAC TSD201 transducer attached to an

449 elastic respiratory belt, which was placed around the subject's chest. Heart rate and respiratory  
450 signals were sampled simultaneously at 1 kHz using RSO100C and PPG100C amplifiers,  
451 respectively, and BIOPAC AcqKnowledge software (version 4.1.1).

452  
453 **fMRI reconstruction and preprocessing**

454 Anatomical images were reconstructed using Freesurfer's automatic reconstruction tool (recon -  
455 all; <http://surfer.nmr.mgh.harvard.edu/>) and functional images using the regularized sensitivity  
456 encoding (SENSE) algorithm with a regularization parameter of 0.005 (45, 46). The reconstructed  
457 images were registered to the Montreal Neurological Institute 152 (MNI152) standard space  
458 template by first calculating transformation parameters from structural to standard space and from  
459 the reference scan to structural space. Thereafter, these transformations were concatenated and  
460 used to co-register functional images to the MNI152 standard space with 3-mm resolution. The  
461 co-registrations were performed by Freesurfer and FSL tools (47, 48). A period of 12.3-s of fMRI  
462 data measured before the start of the audiobook was removed from each fMRI measurement. To  
463 remove the scanner drift, the data was detrended using a Savizky-Golay filter (order: 3, frame  
464 length: 240s). Physiological and movement artifacts were suppressed using MaxCorr method  
465 (49). Specifically, from the data of each subject, we regressed out ten components that correlated  
466 maximally within the white matter and cerebrospinal fluid of that subject but were minimal in the  
467 other subjects' white matter and cerebrospinal fluid. Since these components were subject-  
468 specific, they were assumed be to the artifacts rather than brain activity elicited by the audiobook.  
469 Thereafter, DVARS (50) was used to identify the data potentially affected by head motions. No  
470 differences were found in DVARS values between the two subject groups suggesting that the  
471 between-group differences found in the ISC values should not be related to the head movements  
472 (Finnish family background:  $1.64 \pm 0.46$ , Russian family background:  $1.59 \pm 0.41$ , T-value: 0.70,  
473 p=ns., nonparametric T-test with 5000 permutations). The fMRI data was filtered between 0.08

474 and 4 Hz using a zero-phase filter and smoothed spatially with a 6-mm full-width-half-maximum  
475 Gaussian kernel.

476

477 **Inter-subject correlation (ISC) analysis of BOLD-responses**

478 BOLD-responses between subjects were compared using ISC analysis as implemented in the ISC-  
479 toolbox (<https://www.nitrc.org/projects/isc-toolbox/>) (51). For each voxel and for each of the 10  
480 runs, Pearson's correlation coefficients were calculated across the time-courses of every subject  
481 pair, resulting in  $1128 (n \times (n - 1)/2$ , where  $n = 48$ ) ISC values per voxel. To calculate ISC  
482 values across the whole audiobook, average ISC values were calculated over the run-wise ISC  
483 values that were first transformed to z-values using Fisher's transformation and weighted with the  
484 length of the run. The statistical significance of the ISC values was evaluated by a nonparametric  
485 voxel-wise resampling test to account for the temporal autocorrelations in the BOLD data (51). In  
486 short, a null-distribution was created from ISC values calculated after circularly shifting the time  
487 series for each subject by a random amount such that the timeseries between subjects became  
488 unaligned in time. The null-distribution was approximated with 0.5 million realizations  
489 randomized across voxels and time-points. The null-distribution across the whole audiobook was  
490 determined by taking a weighted average over the ten run-wise null-distributions. The threshold  
491 for significant ISC was determined by first computing p-values for the true realizations for each  
492 voxel based on the null-distribution and, thereafter, correcting the resulting p-values for multiple  
493 comparisons using the FDR-correction. Between-group differences of Fischer's z-transformed  
494 ISC values (z-scores) were studied using a nonparametric cluster-based two-sample T-test where  
495 the statistical significance was tested by 5000 random permutations of the z-scores between the  
496 two groups (41, 52, 53). The null-distribution was created from the maximum cluster sizes  
497 obtained by thresholding the statistical images at the cluster-defining threshold of 0.001 at each

498 permutation. Corrected p-value for each suprathreshold cluster was obtained by comparing its size  
499 to the permutation distribution.

500

501 **Background variables which most accurately predict the ISC between subjects**

502 The voxel-wise between-subjects RSA (54) was used to test in which brain regions greater  
503 similarity in background variables between pairs of subjects predicts greater BOLD-similarity  
504 between pairs of subjects. First, ISC matrices were calculated separately between the Finish and  
505 Russian family background subjects using temporally smoothed fMRI data (time window of 2  
506 sec, 50% overlap). Next, the corresponding similarity matrices were created for each background  
507 question using the score differences between each subject pair. Third, the correlation was  
508 calculated between each of the background similarity matrices and BOLD-similarity matrix in  
509 each voxel. The statistical significance of the results was tested using a cluster-wise non-  
510 parametric permutation test (52) with 5000 subject-wise permutations (cluster-defining threshold  
511  $p < 0.001$ , uncorrected; the 0.05 family-wise-error corrected cluster size was 261 voxels).

512

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535 **Data availability:** Stimulus material and codes used in the current study are available from the  
536 corresponding author on reasonable request. Pseudonymized fMRI are available within European  
537 Union (EU) from the corresponding author by reasonable request in respect of the privacy of the  
538 subjects following the guidelines of the Data Protection Act of Finland (includes EU's General  
539 Data Protection Regulation, GDPR). Since the facial features of the anatomical T1 MRI images  
540 are needed in the analysis of magnetoencephalography data also measured in this study, T1  
541 images will be available within EU by reasonable request following the guidelines of the Data  
542 Protection Act of Finland only after the end of the project when facial features of the MRI  
543 volumes can be removed.

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