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New evidence of a rhythmic priming effect that enhances grammaticality judgments in children

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ABSTRACT

Musical rhythm and the grammatical structure of language share a surprising number of characteristics that may be intrinsically related in child development. The current study aimed to understand the potential influence of musical rhythmic priming on subsequent spoken grammar task performance in children with typical development who were native speakers of English. Participants (ages 5–8 years) listened to rhythmically regular and irregular musical sequences (within-participants design) followed by blocks of grammatically correct and incorrect sentences upon which they were asked to perform a grammaticality judgment task. Rhythmically regular musical sequences improved performance in grammaticality judgment compared with rhythmically irregular musical sequences. No such effect of rhythmic priming was found in two nonlinguistic control tasks, suggesting a neural overlap between rhythm processing and mechanisms recruited during grammar processing. These findings build on previous research investigating the effect of rhythmic priming by extending the paradigm to a different language, testing a younger population, and employing nonlanguage control tasks. These findings of an immediate influence of rhythm on grammar *states* (temporarily augmented grammaticality judgment performance) also converge with previous findings of associations between rhythm and grammar *traits* (stable generalized grammar abilities) in children. Taken

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together, the results of this study provide additional evidence for shared neural processing for language and music and warrant future investigations of potentially beneficial effects of innovative musical material on language processing.

Introduction

Framed by a large literature showing associations between language and music skills in children, there is great interest in the possibility that one domain may affect the other via shared neural resources (Kraus & Slater, 2016). Sensitivity to musical features in particular has been hypothesized to be fundamental to early language and grammar acquisition (Brandt, Gebrian, & Slevc, 2012). Grammar, also called morpho-syntax, is the use of rules about how words change their form and combine with other words to make phrases and sentences that enable individuals to communicate with each other. Recent evidence suggests that children with enhanced rhythm perception ability tend to have better spoken grammar skills (Gordon, Shivers, et al., 2015) and children with grammatical deficits tend to have impaired rhythm (Cumming, Wilson, Leong, Colling, & Goswami, 2015). This shared variance could be explained in part by similarities in how rhythm and grammar employ hierarchical structures emerging from rule-based expectancies that unfold over time at multiple levels (Fitch & Martins, 2014) and, more generally, by shared brain mechanisms for temporal attention (Jones & Boltz, 1989), sequencing, and segmentation (Kotz, Schwartze, & Schmidt-Kassow, 2009). Other work has shown that these processes are highly relevant for many aspects of speech and language perception (Falk, Lanzilotti, & Schön, 2017; Grube, Cooper, & Griffiths, 2013), with grammatical task performance at the intersection between timing, rhythm, sequencing, and language (Kotz et al., 2009; Przybylski et al., 2013).

Several studies have explored potential shared neural resources for rhythm/timing and syntactic processing in adults using the event-related potential (ERP) method. For instance, altering temporal intervals between word onsets has shown that regular predictable presentation improves syntactic processing, reflected by an increase of the P600 ERP component (Schmidt-Kassow & Kotz, 2009). Interestingly, prior listening to rhythmically regular musical stimuli restored the (otherwise missing) P600 to grammatical (linguistic) violations in patients with basal ganglia lesions (Kotz, Gunter, & Wonneberger, 2005) and Parkinson's disease (Kotz & Gunter, 2015), thereby suggesting that rhythmic stimulation can improve detection of grammatical violations in subsequently presented sentences.

To evaluate potential benefits of rhythmic listening on subsequent syntactic processing in children with typical development (TD) and their peers struggling with language, Przybylski et al. (2013) tested native French-speaking children (ages 6–11 years) with TD, specific language impairment, and dyslexia. Performance on a grammaticality judgment task improved after listening to a rhythmically regular musical sequence (characterized by its strong metrical structure) compared with a rhythmically irregular (nonmetrical) musical sequence. Converging with data demonstrating relationships between rhythm and grammar traits in children (Gordon, Jacobs, Schuele, & McAuley, 2015; Gordon, Shivers, et al., 2015), these studies show that musical rhythm with a strong beat structure can influence language states (see also Bedoin, Brisseau, Molinier, Roch, & Tillmann, 2016; Bedoin et al., 2017).

This rhythmic priming effect (RPE), the positive influence of rhythmically regular musical stimulation on grammar task performance, has been reported in German (Kotz & Gunter, 2015; Kotz et al., 2005) and French native speakers (Bedoin et al., 2016, 2017; Przybylski et al., 2013), thereby covering the two rhythmic classes of stress-timed and syllable-timed languages (Lehiste, 1977; Lee & Todd, 2004; Arvaniti, 2009). Our aim was to test this RPE in children with TD who speak English (another example of a stress-timed language) given the prior evidence suggesting that RPE may be generalizable broadly across languages that have different isochrony patterns. In addition, work with native English speakers has shown the importance of the 2-Hz syllable rate in infant-directed speech (e.g., Leong, Kalashnikova, Burnham, & Goswami, 2017). We also sought to determine whether RPE (originally demonstrated in children with a mean age of 9 years) would be present in a younger population of children (mean age of 6 years) who are still developing their grammatical skills. These investigations were needed as a future step toward use of RPE in Anglophone children in applied (educational and clinical) settings, complementing findings described above in children who speak French (a syllable-timed language).

Moreover, additional work on RPE included a condition with neutral environmental sounds (Bedoin et al., 2016), demonstrating that RPE is linked to a benefit from listening to regular stimuli rather than a detriment from irregular stimuli. Given that music listening might lead to small and temporary enhancements in cognitive performance (i.e., mixed findings for the Mozart effect; Pietschnig, Voracek, & Formann, 2010), it is also crucial to test whether RPE could be attributed to a general effect of arousal on task performance or a more specific effect from shared neural mechanisms between rhythm and language processing. Thus, we tested the influence of rhythmic priming on two nonlinguistic (math and visuospatial) control tasks.

Method

Participants

A total of 16 native English-speaking children aged 5;6 (years;months) to 8;7 (*M* = 6;5, *SD* = 11 months; 8 children between 5;0 and 5;11, 4 children between 6;0 and 6;11, 3 children between 7;0 and 7;11, and 1 child between 8;0 and 8;11; 9 boys and 7 girls) participated in this study, which received Vanderbilt University Institutional Review Board approval. Parents gave informed consent, and children gave verbal assent. Parents reported no concerns about their children's cognitive, motor, emotional, sensory, or language development. Participants were recruited from a larger ongoing study examining rhythm and language, and all children scored higher than 85 on all subtests of the Test of Language Development (Newcomer & Hammill, 2008), with nonverbal IQ in the normal range (*M* = 117.4, *SD* = 18.6) on the Primary Test of Nonverbal Intelligence (Ehrler & McGhee, 2008). Hearing was screened, and all participants were found to have normal hearing. Parent education level (proxy for socioeconomic status) and music experience as assessed in Gordon, Shivers, et al. (2015) are reported and described in Supplementary Table 1 of the online supplementary material along with other participant characteristics. Children received a small toy, and parents received a $30 gift card, for compensation. Study data were managed and stored using REDCap electronic data capture tools (Harris et al., 2009).

RPE paradigm–grammaticality judgment task

Musical stimuli

Stimuli consisted of the same two 32-s musical sequences from Przybylski et al. (2013) (Supplementary Fig. 1) containing the same number of tones but differing in rhythmic structure such that meter was strong (regular) or weak/unmetrical (irregular). Two percussion instruments from the instruments bank MakeMusic GM (a tam-tam at 175 Hz and maracas at 466 Hz) were used to play the stimuli (see .mp3 files in supplementary material).

Linguistic stimuli

Material was composed of 72 grammatically correct (36) and violation (36) English sentences. Each grammatically correct sentence had an equivalent violation sentence; each sentence was heard once in either the correct or incorrect form. Two types of violations were used: subject–verb agreement (e.g., "Every day, the mom toast/toasts the bread for their breakfast") and tense agreement (e.g., "Yesterday, the men punched/punch a bag at the gym"). Sentences were recorded by a female speaker in an anechoic chamber and edited in Praat software (Boersma, 2001) with a cross-splicing method (from onset of the verb clause), allowing each violation sentence to be created from two grammatically correct sentences (e.g., the underlined portion of "Yesterday, the men punched a bag at the gym" was

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combined with underlined portion of "The men punch a bag at the gym), ensuring that they were spoken with natural prosody. Sentences had an average length of 9.72 words (range = 9–10) and 13.22 syllables (range = 10–16) and an average duration of 3044 ms (±498). Two experimental lists were generated such that sentences were counterbalanced across participants and conditions (regular vs. irregular primes and correct vs. incorrect grammar).

Experimental paradigm

Each block of sentences contained three grammatically correct and three violation sentences, with a total of 36 sentences across the six blocks (randomized within each block). Half of the blocks were preceded by the regular stimulus, and half were preceded by the irregular stimulus (see Fig. 1; pairing of prime and sentence blocks were counterbalanced across participants, and primes alternated between regular and irregular).

Procedure

Testing was presented as a computer game. For each block, children were asked to listen to the music while being shown a guitar symbol on the screen. A sentence was then presented auditorily, and children were asked to indicate whether the "correct" or "incorrect" dragon had spoken by pointing to the appropriate picture (dragons appeared on the screen on opposite sides). Before starting, participants were administered four practice items (two grammatically correct and two violations) without music and were told that "this dragon [satisfied-looking dragon] always says things right, and this dragon [confused-looking dragon] always says things wrong." If participants provided the wrong answer for any practice item, the experimenter explained why the sentence was correct or incorrect. Sounds were presented over speakers (Alesis Elevate 5) hand-calibrated to 70 dB at a range of 3 feet.

Control tasks

Two nonlinguistic control tasks that differed from the language tasks in their task requirements and domain were chosen and preceded by the rhythmic primes to test for a general influence of rhythmic priming on cognitive performance. The *math task* consisted of two forms (19 items each; equivalent in content and difficulty) derived from the Wide Range Achievement Test 4 (Wilkinson & Robertson, 2006) and used a mix of visual and auditory items to assess counting, identifying numbers, and solving simple problems (e.g., "How many are 3 apples and 4 apples?"). Each form was preceded by either the regular or irregular rhythmic sequence. In both control tasks, order of musical sequences and forms was counterbalanced across participants. Forms for each condition were scored as proportion of total items answered correctly. The *visuospatial task* consisted of the cancellation subtest from the Wechsler Intelligence Scale for Children—fourth edition (Wechsler, 2003). As with the math task,

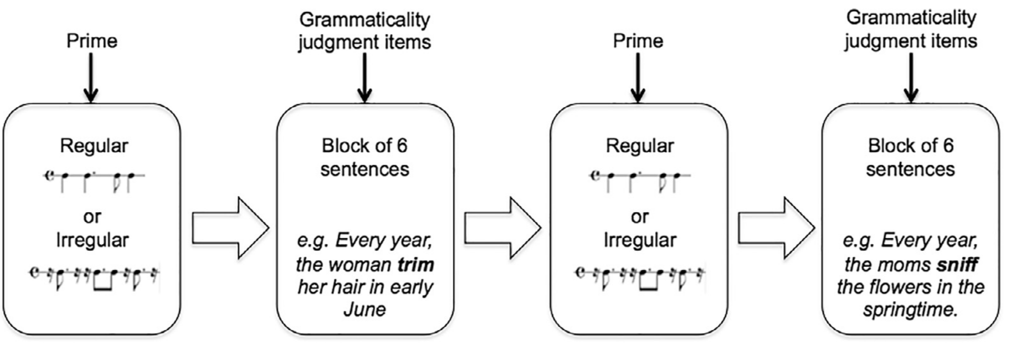

Fig. 1. Rhythmic priming effect experimental paradigm. The musical prime (regular or irregular) is heard once, and then a block of six sentences is presented. Children are asked to perform grammaticality judgment on each sentence item.

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two equivalent forms (32 items each) were used with each participant, each preceded by a musical sequence. Children were asked to mark animal targets interspersed among common nonanimal targets (e.g., car, tree) within 23 s. Forms were scored as total number of targets marked correctly subtracted by number of targets marked incorrectly. All participants completed the math task, and 11 completed the visuospatial task (due to experimenter logistics).

Data analysis

Grammaticality judgment performance was subjected to signal detection analysis, yielding d', a measure of discriminability, and c, a measure of response bias (Macmillan & Creelman, 2005). Paired t tests were performed to determine whether there was significant difference in performance after listening to regular stimuli compared with irregular stimuli. To estimate effect sizes, we calculated Cohen's d (small = 0.20, medium = 0.50, and large = 0.80).

Results

Grammaticality judgment performance was significantly better ($t = 3.07$, $df = 15$, $p = .008$, Cohen's $d = 0.57$, medium-sized effect; see Fig. 2) after listening to regular musical sequence primes (mean d' = 1.11, SE = 0.18) compared with irregular musical sequence primes (mean d' = 0.60, SE = 0.26). Performance after listening to regular or irregular stimuli did not change significantly between the first and second halves of each block (Supplementary Table 2 and Supplementary Fig. 2). Of the 16 participants, 13 demonstrated improved performance after listening to regular primes (vs. irregular primes).

Analysis of c showed relatively small response biases. Participants showed a slight bias to respond "incorrect" after having listened to regular musical stimuli ($c = -0.22 \pm 0.08$) and irregular musical stimuli ($c = -0.04 \pm 0.12$). There was no significant difference in c for the two conditions ($t = -1.72$, $df = 15$, $p = .11$, Cohen's $d = 0.45$).

After listening to regular versus irregular stimuli ($mean_{reg}$ and $mean_{irreg}$, respectively), there were no significant differences in visuospatial test performance ($p = .63$; $mean_{reg}$ correct = 15.90, SE = 0.99; $mean_{irreg}$ correct = 15.60, SE = 1.26) or math test performance ($p = .15$; $mean_{reg}$ proportion correct = .81, SE = .04; $mean_{irreg}$ proportion correct = .84, SE = .04) (Supplementary Table 3).

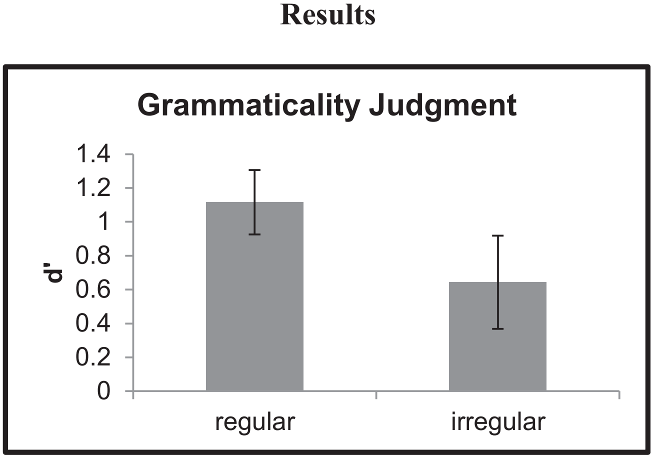

Fig. 2. Rhythmic priming effect on grammaticality judgment task. Findings in 16 children show that sentences preceded by regular primes led to better grammaticality judgment performance.

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Discussion

This study examined whether rhythmically regular and irregular musical stimuli differentially influenced performance of English-speaking children with TD in a subsequent grammar task. As hypothesized, performance improved after listening to regular musical stimuli compared with irregular stimuli. This effect of the musical prime on the d' of the grammar task was of medium effect size. However, for the nonlinguistic control tasks, there was no significant difference in math or visuospatial performance after listening to regular versus irregular musical stimuli. Thus, the findings in the language task likely cannot be attributed to general cognitive benefits due to enhanced arousal from listening to musical stimuli (e.g., Pietschnig et al., 2010). Rather, these findings would suggest some sharing of neural resources between rhythm and language. Other work has shown that the use of specific rhythmic primes (matched to the exact prosodic features of subsequently presented speech) can enhance speech processing (Cason & Schön, 2012; Falk et al., 2017). In comparison, our study showed the influence of musical stimuli with a strongly metrical structure (vs. irregular structure) on subsequent sentence processing without the exact match to the speech rhythm of the sentences, thereby priming on a more global level (via temporal attention). Our finding converges with recent work in French-speaking children (Przybylski et al., 2013), suggesting that RPE not only occurs in French (and German; Kotz et al., 2005) but also occurs in English and potentially other languages. Moreover, here we observed RPE in a younger population compared with prior work, highlighting possible relevance for language development. Intriguingly, in this study and prior work, RPE occurs with enhanced grammar task performance in children with typical language (and, thus, no deficit in grammatical skill), suggesting a robust benefit of rhythmic listening.

Adding to the growing literature showing shared processing of music and linguistic stimuli (e.g., Kraus & Slater, 2016), our results are consistent with theories of overlapping early development of rhythm and language (Brandt et al., 2012). The process of prosodic bootstrapping suggests that toddlers make use of prosodic cues, such as timing and intonation of phrase boundaries, to parse syntax during language acquisition (de Carvalho, Dautriche, Lin, & Christophe, 2017). Sensitivity and preference to sounds that fit the patterns of native meter in both the musical and linguistic domains may develop in parallel (Jusczyk, 2000). Meter perception and sensitivity to different rhythmic patterns has been demonstrated in infants with a variety of methods (e.g., Hannon & Trehub, 2005; Zhao & Kuhl, 2016), suggesting that the distinction between regular and irregular stimuli employed by RPE, as implemented in the current study, would be highly relevant to the development of music perception from a very early age.

Sensitivity to rhythmic structures of music and speech continues to play an important role in normal and disordered language acquisition (Cumming et al., 2015). The current findings converge with recent work showing benefits from short-term passive musical listening on grammar processing in children with disordered language (Bedoin et al., 2016; Przybylski et al., 2013). Taken together, these results suggest an immediate activation of shared or connected brain networks involving even less effort than music training (see Fujii & Wan, 2014; Patel, 2014).

A potential mechanism driving RPE can be framed in the context of dynamic attending theory, which hypothesizes that rhythmic patterns in speech and music enable entrainment of attention and generate temporal expectancies for future events, facilitating perception, segmentation, and integration (Jones & Boltz, 1989). Such entrainment has been suggested to occur through neural resonance (Large, Herrera, & Velasco, 2015), enabling hierarchical organization of stimuli with different subdivisions. As proposed in prior work, rhythmic priming may modulate temporal attention, mobilizing neural oscillators also involved in generating hierarchical expectancies that allow listeners to parse the speech stream and process syntax (Bedoin et al., 2016; Przybylski et al., 2013).

Neural mechanisms supporting RPE could include the basal ganglia, which play a role in both musical beat perception and language processing (Krishnan, Watkins, & Bishop, 2016; Merchant, Grahn, Trainor, Rohrmeier, & Fitch, 2015); neural responses to grammatical violations by rhythmic priming were restored in individuals with basal ganglia lesions (Kotz & Gunter, 2015; Kotz et al., 2005). Left inferior frontal gyrus (LIFG) plays an important role in hierarchical processing of language and music (Fitch & Martins, 2014) and may also be involved in brain networks that lead to RPE.

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Moreover, imaging evidence in jazz musicians indicates that detection of deviations in musical rhythm is associated with activation of areas involved in linguistic syntax, including LIFG (Donnay, Rankin, Lopez-Gonzalez, Jiradejvong, & Limb, 2014). Further work is needed to understand the neural processes and regions driving RPE and to what degree generalized dynamic attending processes are recruited. Kotz et al. (2009) proposed two pathways (pre-supplementary motor area [pre-SMA]–basal ganglia and cerebellar–thalamic–pre-SMA) involved in sequencing and temporal attention. Potential clinical benefits of RPE in individuals with atypical language, who may show deficits in one pathway, may arise from rhythmic compensation through the other pathway or enhanced use of the impaired one (Przybylski et al., 2013).

To have clinical relevance, therapeutic interventions employing this rhythmic priming must induce a stable trait effect on language ability as opposed to a temporary state effect. It will be important to quantify how many sessions (perhaps combining RPE and language treatment activities or active rhythm tasks) are needed to reach sustained improvements in grammatical skill (Schön & Tillmann, 2015). This prospect is especially promising for remediating the reported comorbid grammatical and rhythm deficits in children with language impairments (Cumming et al., 2015) and for use during language therapy sessions, as shown in children with cochlear implants (Bedoin et al., 2017).

Future work should also address some of the limitations of the current study. First, the oral grammaticality judgment task, although relevant for school activities, is not as ecological as a conversational language task would be. Investigations of RPE on spoken elicitation tasks, thus, should be considered (e.g., Hidalgo, Falk, & Schön, 2017), and additional nonlinguistic control tasks with more trials could be interspersed within the same protocol. It would also be informative to explore other potential control tasks with more similar task demands to the grammar/language tasks. However, from a divergent validity standpoint, the benefit of the visuospatial and math tasks in the current study is that they are quite different in nature from the grammaticality judgment task, strengthening their utility as control conditions.

More work is needed to demonstrate to what degree rhythmical regularity is specifically relevant for boosting language (or grammar) compared with other domains of cognitive processing. In fact, Kotz et al. (2009) suggested that temporal processing may be linked to processes such as cognitive sequencing, segmentation, temporal prediction, and attention. Integration of these processes facilitates both the perception of sensory predictable cues (i.e., beats in metrical structures; Haegens & Zion Golumbic, 2018) and the synchronization between rhythmically regular external stimuli and neural oscillators (i.e., as suggested by dynamic attending theory; Jones & Boltz, 1989). These same processes may also apply to other aspects of language such as phonological processing. Other work has indeed shown improved phonological awareness in children with dyslexia after rhythmic training (Flaugnacco et al., 2015) and improved phonological performance after the use of regular musical primes in speech therapy sessions (Bedoin et al., 2017).

Thus, the effect of rhythmic priming on other levels of linguistic processing (e.g., phonological, semantic; Cason & Schön, 2012; Falk et al., 2017) should be addressed in future studies to investigate potential linguistic specificity in the relationship between rhythmic and grammatical processing. To this point, Cason and Schön (2012) found that a matching rhythmic cue resulted in improved performance in phonological processing, whereas Falk et al. (2017) found that differing degrees of neural entrainment to nonverbal, rhythmically regular musical cues explained trial-by-trial variance in memory task performance on a subsequent speech stimulus (a spoken utterance whose speech rhythm matched the musical rhythm of the regular cue). In addition, Bedoin et al. (2017) showed an effect of the rhythmic prime on language training sessions not only in posttest grammar tasks but also for word/nonword repetition, requiring phonological processing and segmentation.

Expansion of the repertoire of rhythmic stimuli, such as a baseline/neutral stimulus, would help to confirm the benefit of the regular rhythm (with relevance for rehabilitation and training purposes) and potentially rule out RPE as a detriment of the irregular rhythm. In addition, comparisons between metrically simple and complex rhythms in each condition in future studies should also be considered (i.e., Bedoin et al., 2016; Grahn & Brett, 2007; Povel & Essens, 1985).

Moreover, study of this phenomenon in larger samples will allow for the exploration of individual differences in temporal processing ability and language skill as predictors of benefits derived from RPE (e.g., associations between rhythm and grammar skills; Gordon, Shivers, et al., 2015) and for the

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pursuit of mediating neural mechanisms. More broadly, this line of research could address questions about whether the rhythmic structure of background music could affect our efficacy of reading, writing, and speaking.

In conclusion, there is an accumulation of evidence for a positive impact of listening to regular musical rhythms (with a strong metrical structure) on subsequent grammatical (syntactic) processing. This RPE has been observed in school-aged children with typical and atypical language development, in adults with basal ganglia lesions and Parkinson's disease, and in native speakers of French and German, and it is due to a benefit of regular musical rhythms rather than a detriment of irregular rhythms (Bedoin et al., 2016; Kotz & Gunter, 2015; Kotz et al., 2005; Przybylski et al., 2013). The current study enhances this literature by demonstrating RPE in English, in younger children, and that RPE is a shared effect on rhythm and language rather than a more general effect of music on cognition. Taken together with recent reports of individual differences in musical rhythm perception that predict grammar traits (Gordon, Shivers, et al., 2015), these findings suggest that rhythmic stimuli (i.e., music) can influence language processing states (i.e., grammar task performance).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jecp.2018.04.007.

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