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Physical fitness modulates incidental but not intentional statistical learning of simultaneous auditory sequences during concurrent physical exercise

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ABSTRACT

In real-world auditory environments, humans are exposed to overlapping auditory information such as those made by human voices and musical instruments even during routine physical activities such as walking and cycling. The present study investigated how concurrent physical exercise affects performance of incidental and intentional learning of overlapping auditory streams, and whether physical fitness modulates the performances of learning. Participants were grouped with 11 participants with lower and higher fitness each, based on their Vo_2max value. They were presented simultaneous auditory sequences with a distinct statistical regularity each other (i.e. statistical learning), while they were pedaling on the bike and seating on a bike at rest. In experiment 1, they were instructed to attend to one of the two sequences and ignore to the other sequence. In experiment 2, they were instructed to attend to both of the two sequences. After exposure to the sequences, learning effects were evaluated by familiarity test. In the experiment 1, performance of statistical learning of ignored sequences during concurrent pedaling could be higher in the participants with high than low physical fitness, whereas in attended sequence, there was no significant difference in performance of statistical learning between high than low physical fitness. Furthermore, there was no significant effect of physical fitness on learning while resting. In the experiment 2, the both participants with high and low physical fitness could perform intentional statistical learning of two simultaneous sequences in the both exercise and rest sessions. The improvement in physical fitness might facilitate incidental but not intentional statistical learning of simultaneous auditory sequences during concurrent physical exercise.

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1. Introduction

How do learners acquire novel auditory knowledge regardless of intention to learn? According to previous studies, when learners acquire novel auditory knowledge such as language and music, they extract statics potentially embedded in sequential stimuli [1]. This mechanism has been called as statistical learning, which has been considered to be a fundamental, domain-general, and implicit learning process in humans [2]. This suggests that statistical learning could automatically occur in daily life, regardless of attention to the statistical information. To date, statistical learning has been demonstrated by behavioral and neurophysiological studies [3–7].

In our real-world learning environments, we are exposed to sequential information even during routine physical activities such as walking and cycling. How does concurrent physical movement affect auditory statistical learning? According to the previous studies, concurrent physical movement could interfere with statistical learning of ignored sequence (i.e. incidental statistical learning) but not attended sequence (i.e. intentional statistical learning) [8,9]. Furthermore, the performance of learning during and following exercise was higher in learners with higher than lower physical fitness based on a test of the maximal oxygen consumption (Vo_2max) [10,11]. Chang and colleague suggested that physical exercise and cognitive processing require similar neural structures, and learners with higher fitness have more neural resources necessary to perform physical exercise and cognitive processing compared to those with lower fitness. They also suggested that learners with higher fitness need fewer neural resources for the exercise, compared to those with lower fitness.

Real-world auditory environments contain a lot of overlapping sounds such as those made by human voices and musical instruments. In general, healthy humans can simultaneously acquire these auditory knowledge by both intentional and incidental accesses even during concurrent physical movements such as walking and cycling. Although previous studies investigated how concurrent physical movement affects incidental and intentional statistical learning of 'single' sequential stimuli [8,9], statistical learning of multiple pieces of

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sequential stimuli during concurrent physical activities could be more likely to reflect a real-world learning environment in humans. According to the previous studies, two simultaneous tone streams could be encoded separately in the sensory memory trace [12]. On the other hand, it might be difficult to attentionally deal with a lot of information that were concurrently exposed, because of the cognitive capacity limitations in humans [13]. This suggests that incidental learning is necessary in the condition where learners are exposed to multiple pieces of information. However, to the best of our knowledge, there is no study that clarified how incidental and intentional statistical learning of multiple pieces of auditory information is affected by concurrent exercise. In the present study, we examined how concurrent physical exercise affects performance of incidental and intentional learning of overlapping auditory streams, and whether physical fitness modulates the performances of learning.

Two experiments were conducted in the present study. In each experiment, participants were presented simultaneous auditory sequences based on a distinct Markov chain each other while they were pedaling on the bike and seating on a bike at rest. In the experiment 1, participants were instructed to attend to one of the two sequences and ignore to the other sequence. In the experiment 2, the participants were instructed to attend to both of the two sequences. After exposure to the simultaneous sequences, learning effects were evaluated by familiarity test. We compared relationship between the physical fitness levels based on their Vo_2max values and the performance of statistical learning of attended and ignored sequences. Given the previous findings that concurrent physical movement could interfere with incidental but not intentional statistical learning and the performance of learning during concurrent exercise is higher in learners with higher than lower fitness [8–11], we hypothesized that even when participants are presented two simultaneous sequences, the performance of statistical learning of ignored sequence while pedaling on the bike should be higher in the participants with high than low fitness, whereas this difference might not be detected in the statistical learning of attended sequence while seating on a bike at rest regardless of attention to the sequences.

2. Experiment 1

We sought to examine how intentional and incidental statistical learning of two simultaneous auditory streams could be affected by concurrent exercise of cycling when participants attended to one of the two sequences and ignored to the other sequence and how the physical fitness levels could modulate the statistical learning of attended and ignored sequences.

2.1. Methods

2.1.1. Participants

Twenty-two right-handed (Edinburgh handedness questionnaires; laterality quotient ranged from 73.3 to 100.0) [14] healthy participants with no history of neurological and audiological disorders, and physical problems were included (8 females, age: 20–22 years). None of the participants had experiences with living abroad, and none of the participants possessed absolute pitch. This study was approved by the Ethics Committee of Teikyo Heisei University. All participants were well informed of the purpose, safety and protection of personal data in this experiment, and they provided written informed consent for this study.

2.1.2. Stimuli

2.1.2.1. Tones. Using a cascade-Klatt type formant synthesizer [15] HLsyn (Sensimetrics Corporation, Malden, MA, USA), we generated 10 complex tones that consisted of fundamental frequencies (F_0) in a 5-tone equal temperament ($F_0 = 110 \times 2^{(n-1)/5}$ Hz, low pitch: n = 1–5; 110, 126, 145, 167, and 192 Hz, high pitch: n = 11–15; 440, 505, 581, 667, and 766 Hz). Only the F0s were variable, whereas all of the other parameters were constant (duration 270 ms, binaural presentation with the intensity of 80 dB SPL).

2.1.2.2. Sequences. The auditory stimulus sequence was 500 repetitions of the dyads (two-tone chords) that consisted of the low and high pitch each, within which the intervals were apart more than an octave, presented with SOA of 300 ms. The order of low and high voices in the two-tone chords was each defined according to a second-order Markov processes with the constraint that the probability of a forthcoming tone was statistically defined (90% for a tone; 2.5% for the other four tones) by the latest two successive tones (Figure 1). The distinct two of four Markov chains shown in Figure 1 were adopted in the low- and high-voice tone sequence each, and the adoption of the Markov chains were counterbalanced across the participants. In other words, the two-tone chord sequences can also be interpreted as two simultaneous sequences that consisted of low- and high-pitch sequences (Figure 2).

2.1.3. Experimental protocol

The experiment consisted of a Vo_2max test followed by two sessions.

2.1.3.1. Vo_2max test. Before the two sessions, the fitness level for the participants was evaluated from their Vo_2max value. The participant's Vo_2max was estimated from the ratio between values of maximal (HRmax) and resting heart rates (HRrest), using the formula of Uth et al. [16]: Mass-specific $Vo_2\text{max} = (15.0\ \text{ml}^{-1}\ \text{min kg}^{-1}) \times \text{HRmax}/\text{HRrest}$). The HRrest was defined as the lowest value of a

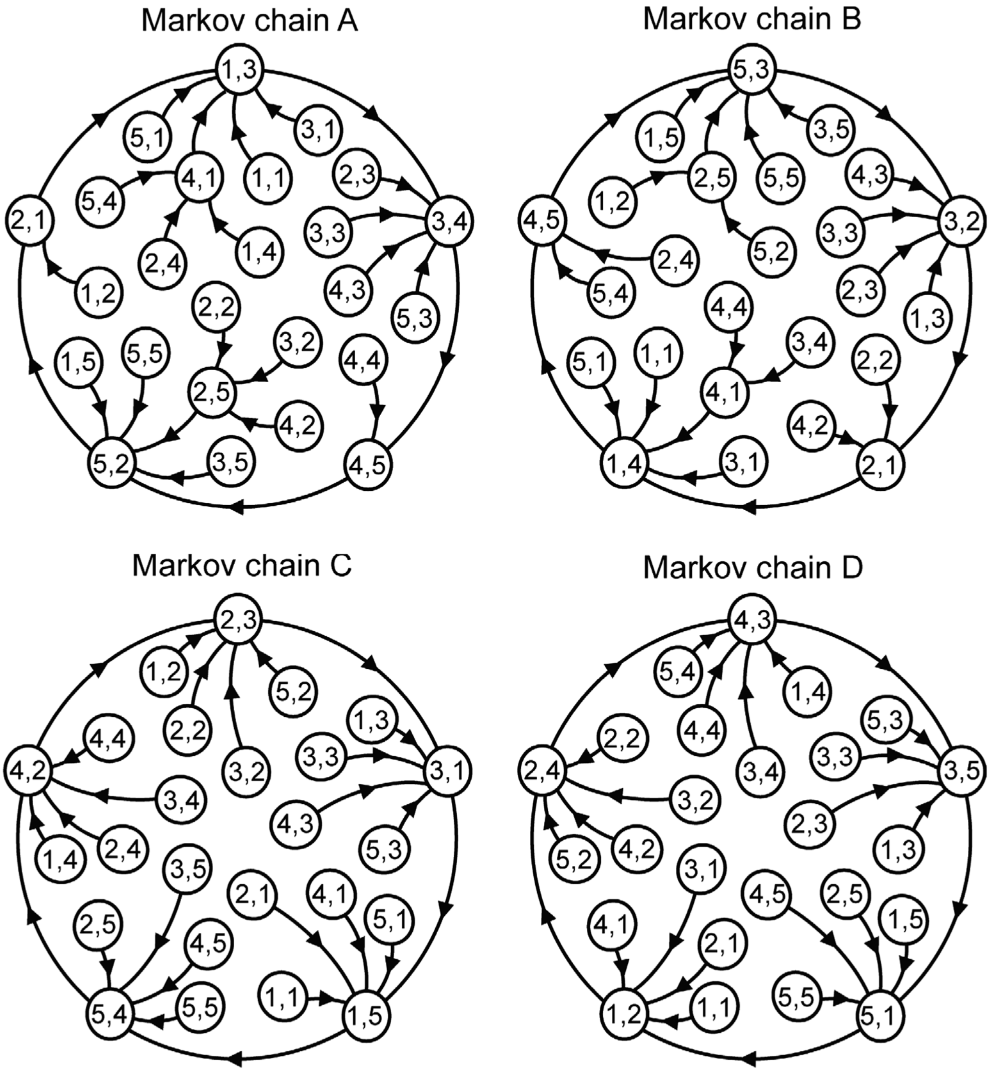

Figure 1. The transitional diagrams used in the present study.
Notes: The paired digits in the circles represent two successive tones in the stimulus sequence. The arrows represent transitions with high probability of 90%. The remaining possible transitions to the other four tones occurred with low probability of 2.5% each.

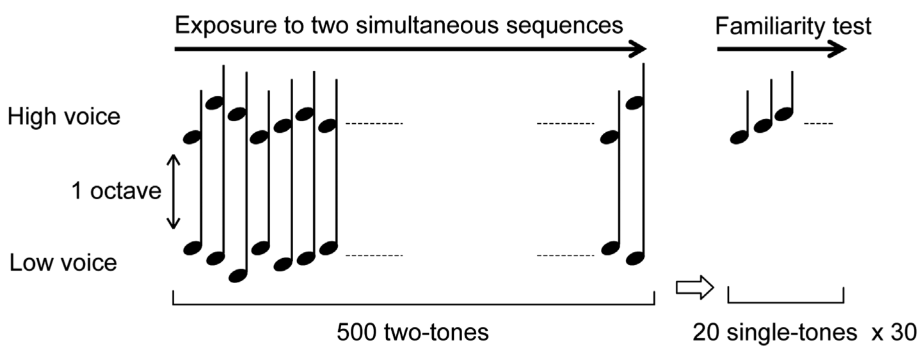

Figure 2. Experimental procedure in a session.

minute after resting for 5 minutes in the supine position. Heart rate was measured with a heart rate monitor (Polar Electro, Kempele, Finland). The HRmax was predicted from age using one of the most widely cited formula for HRmax [17]: HRmax = 220 − age. Instead of experimentally determining HRmax as in the above version of the test, HRmax may also be predicted from the person's age. According to previous studies, use of the age-predicted HRmax value would facilitate the accomplishment of the test and potentially increase its applicability to participants in which maximal effort may be unwarranted, such as patients or elderly individuals, rather than an experimental one that could be evaluated by submaximal workload for several minutes. The previous study demonstrated that the accuracy of the Vo_2max estimation was significantly less when age-predicted HRmax values replaced the experimental ones in the formula [16].

2.1.3.2. Exercise and rest sessions. In each session, the two simultaneous sequences were delivered binaurally to each participant's ears at 80 dB SPL through earphones and the participants were instructed to attend either high- or low-voice tone sequence (attended sequence) and ignore the other sequence (ignored sequence). The adoptions of attended and ignored sequences were counterbalanced across the participants. To distinguish between ignored and attended conditions, only in the attended sequence, a 900 ms silent period was pseudo-randomly inserted within every set of 40 successive tones. Before the session, the participants were instructed to raise their right hands at every silent period in the tone sequence that was adopted as the ignored sequence. On the other hand, the participants were instructed to ignore the tone sequence that was adopted as the ignored sequence. By these approaches, we could confirm that all of the participants correctly raised their right hand at every silent period in the attended sequences, and that they were continuing to pay attention to only the attended sequences.

In the exercise session, participants were presented the sequences while resistance-free pedaling on the cycle (828E Testing Ergometer, Monark, Sweden: Figure 3). In contrast, in the rest session, participants were presented the sequences while seating on a bike at rest. This was to ensure that all participants had the same level of postural discomfort in two sessions. The orders of the two sessions were counterbalanced across the participants. There was a five-minute break for all participants between the exposure to the two simultaneous sequences and the following familiarity test in a session. This was to ensure that the participants in an exercise session returned to near resting metabolic levels so as to minimize any physiological stress during the familiarity test, as adopted in the study by Stevens et al. (2014) [9]. There was a 20-minute break involving familiarity tests for all participants between the exposure to sequences in a former session and that in a latter session so that exercise could not affects learning effects in a following session. Chang et al. suggested that learning administered 11–20 minutes after exercise result in the biggest effects and that these effects subside following a longer than 20-minute delay [10].

After the exposures to the two simultaneous sequences in each session, participants completed an interview in which they were presented with 30 single-tone series with 20 tones while seated in front of a desk (Figure 3). Participants then reported whether each tone series sounded familiar. The 30 single-tone series could be categorised into 3 types, and the presentation order was randomized. In the 10 series, tones were ordered on the basis of the same constraint as the ignored sequence (tone series I). In an additional

Figure 3. Setup for experiment in the present study.

10 series, tones were ordered on the basis of the same constraint as the attended sequence (tone series A). In the remaining 10 series, tones were pseudo-randomly ordered (random tone series). The familiarity test was completed within 10 minutes per participant each.

2.1.4. Data analysis

The logit transformation was applied to normalize the ratios of answering that tone series sounded familiar (familiarity ratios). Based on the results of the Vo2max tests before the 2 sessions, the participants were grouped with 11 participants with lower fitness and higher fitness each. Then, we performed a 2 (fitness: high and low) × 2 (physical condition: rest and exercise) × 3 (series: tone series I, tone series A, and random tone series) analysis of variance (ANOVA) with the logit values of the familiarity ratios for each series. When we detected significant effects, Bonferroni-corrected *post hoc* tests were conducted for further analysis. Statistical significance levels were set at $p < 0.05$ for all analyses.

2.2. Results

2.2.1. Vo_2max data

Based on the results of the Vo2max tests before the two sessions, the Vo_2max value for 22 participants ranged from 33.37 to 57.69 ml/(kg min), and the mean Vo_2max (value ± S.E.M) was 45.90 ± 1.46 ml/(kg min). The participants could be grouped with 11 participants with lower fitness (Vo_2max value ranged from 33.37 to 45.23 ml/(kg min), Mean ± S.E.M: 40.52 ± 1.24 ml/(kg min)) and higher fitness (Vo_2max value ranged from 45.92 to 57.69 ml/(kg min), Mean ± S.E.M: 51.27 ± 1.29 ml/(kg min)) each.

2.2.2. Performance of familiarity test

In the both participants with high and low fitness, the results of the two-tailed t-tests indicated that the familiarity ratios in the tone series A were significantly above chance level in the both rest (low fitness: $t[10] = 4.59$, $p = 0.001$, high fitness: $t[10] = 4.76$, $p = 0.001$) and

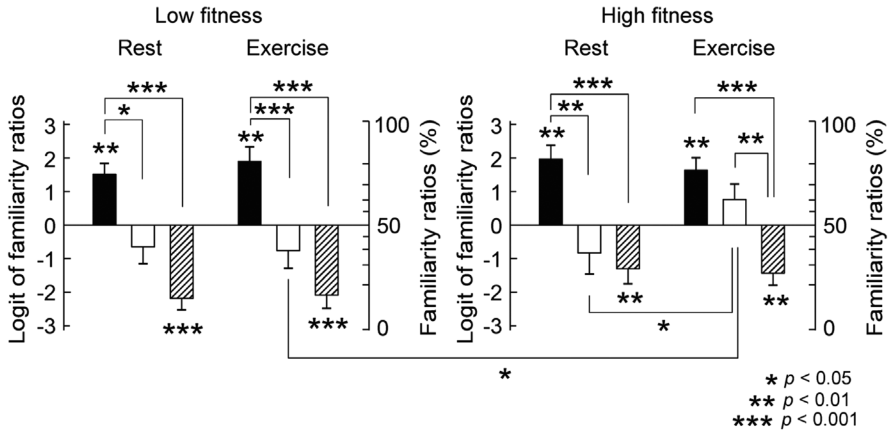

Figure 4. The logit of the ratios of answering that tone series sounded familiar in the experiment 1. In the experiment 1, participants were instructed to attend to one of the two sequences and ignore to the other sequence.
Notes: The closed bars indicate familiarity ratios of the tone series A in which tones were ordered on the basis of the same constraint as the attended sequence. The open bars indicate familiarity ratios of the tone series I in which tones were ordered on the basis of the same constraint as the ignored sequence. The hatched bars indicate familiarity ratios of the random tone series in which tones were pseudo-randomly ordered. The error bars indicate the standard error of the mean. The asterisks indicate the main effects in the ANOVA and the simple main effects in the *post hoc* tests.

exercise sessions (low fitness: $t[10] = 4.36$, $p = 0.001$, high fitness: $t[10] = 4.32$, $p = 0.002$) (Figure 4). The familiarity ratios in the random tone series were significantly below chance level in the both rest (low fitness: $t[10] = -7.06$, $p = 0.001$, high fitness: $t[10] = -4.76$, $p = 0.0001$) and exercise sessions (low fitness: $t[10] = -6.23$, $p = 0.0001$, high fitness: $t[10] = -4.26$, $p = 0.002$). The results of the ANOVA indicated that the main sequence effect was significant ($F[2, 40] = 48.84$, $p = 0.00001$). The familiarity ratios in the tone series A were significantly higher than those in the tone series I ($p = 0.0001$) and random tone series ($p = 0.0001$). The familiarity ratios in the tone series I were significantly higher than those in the random tone series ($p = 0.002$).

The fitness–physical condition–series interaction was significant ($F[2, 40] = 3.29$, $p = 0.048$). In the exercise session, the familiarity ratios in the tone series I were significantly higher in the participants with high fitness than low fitness ($p = 0.043$). In the participants with high fitness, the familiarity ratios in the tone series I were significantly higher in the exercise session than rest session ($p = 0.013$). In the both participants with high and low fitness, the familiarity ratios in the tone series A were significantly higher than those in the random tone series in the both rest (low fitness: $p = 0.0001$, high fitness: $p = 0.0001$) and exercise sessions (low fitness: $p = 0.0001$, high fitness: $p = 0.0001$). In the participants with low fitness, the familiarity ratios in the tone series A were significantly higher than those in the tone series I in the both rest ($p = 0.018$) and exercise sessions ($p = 0.0001$). In the participants with high fitness, the familiarity ratios in the tone series A were significantly higher than those in the tone series I in the rest session ($p = 0.002$). The familiarity ratios in the tone series I were significantly higher than those in the random tone series ($p = 0.003$) although this significance could not be detected in the participants with low fitness ($p = 0.091$).

2.3. Discussion

The experiment 1 examined how intentional and incidental statistical learning of two simultaneous auditory streams could be affected by concurrent exercise when listeners attended to one of the two sequences and ignored to the other sequence, and how physical fitness could modulate the intentional and incidental statistical learning. In the exercise and rest sessions, participants were presented simultaneous sequences while cycling and resting, respectively. As a result, regardless of physical conditions (i.e. exercising and resting) and fitness levels (higher and lower), the familiarity ratios were significantly above chance levels in the tone series A in which tones were ordered on the basis of the same constraint as the attended sequence and below chance levels in the random tone series. In addition, the familiarity ratios were significantly higher in the tone series A than the random tone series. These suggest that, regardless of learner's fitness levels and physical condition during learning, statistical learning could be facilitated by attention to the stimuli, in agreement with the previous neurophysiological and behavioral studies [4,18,19].

On the other hand, in the exercise session, the familiarity ratios in the participants with high fitness were significantly higher in the tone series I than the random tone series, although this effect could not be detected in the participants with low fitness. Furthermore, the familiarity ratios in the tone series I were significantly higher in the participants with high than low fitness. In the participants with high fitness, the familiarity ratios in the tone series I were significantly higher in the exercise than rest session. These results suggest that performance of incidental statistical learning during concurrent physical exercise is higher in the participants with high than low fitness, whereas this difference could not be detected in the intentional statistical learning. Stevens and colleague reported that concurrent physical movement interferes with incidental but not intentional statistical learning, whereas this difference could not be detected in the resting condition [9]. In the present study, we could detect similar findings only in the participants with higher fitness. According to the previous studies, performance of learning while concurrent exercise was higher in learners with high than low fitness [10,11]. They hypothesized that physical exercise and cognitive processing require similar neural structures, and learners with higher fitness have more neural resources necessary to perform physical exercise and cognitive processing compared to those with lower fitness [10]. They also suggested that learners with higher fitness need fewer neural resources for the exercise, compared to those with lower fitness. In the present study, we hypothesized that because learners with higher fitness have more neural resources necessary to perform physical exercise and incidental statistical learning and they need fewer neural resources for the exercise compared to learners with lower fitness, performance of incidental statistical learning in the exercise session might be higher in the participants with high and low fitness, and the difference in performance of learning between participants with high and low fitness might not be detected in the rest session.

3. Experiment 2

We sought to examine how intentional statistical learning of two simultaneous auditory streams could be affected by concurrent exercise of cycling when participants attended to both of the two sequences and how the physical fitness levels could modulate the statistical learning of attended simultaneous sequences.

3.1. Methods

3.1.1. Participants

Twenty-two right-handed (Edinburgh handedness questionnaires; laterality quotient ranged from 62.5 to 100.0) [14] healthy participants with no history of neurological and audiological disorders, and physical problems were included (5 females, age: 20–22 years). None of the participants had experiences with living abroad, and none of the participants possessed absolute pitch. This study was approved by the Ethics Committee of Teikyo Heisei University. All participants were well informed of the purpose, safety and protection of personal data in this experiment, and they provided written informed consent for this study.

3.1.2. Stimuli and experimental procedure

The stimuli and procedure of Vo_2max test were the same as those used in Experiment 1.

In both of the exercise and rest sessions, the participants were instructed to attend both the high- and low-voice tone sequences. To distinguish between two attended conditions, a 900 ms silent period was pseudo-randomly inserted within every set of 40 successive tones independently in each sequence. Before the session, the participants were instructed to raise their right hands at every silent period in the high-voice tone sequence, and their left hands at every silent period in the low-voice tone sequence. The participants were instructed to pay attention to both of the two simultaneous tone sequences. By these approaches, we could confirm that all of the participants correctly raised their right and left hands at every silent period in the attended and ignored sequences respectively, and that they were continuing to pay attention to both of the sequences.

After the exposures to the two simultaneous sequences in each session, participants completed an interview in which they were presented with 30 single-tone series with 20 tones (Figure 2). Participants then reported whether each tone series sounded familiar. The 30 single-tone series could be categorised into 3 types, and the presentation order was randomized. In the 10 series, tones were ordered on the basis of the same constraint as the high-voice tone sequence (high-voice tone series). In an additional 10 series, tones were ordered on the basis of the same constraint as lower pitch sequences (low-voice tone series). In the remaining 10 series, tones were pseudo-randomly ordered (random tone series).

3.1.3. Data analysis

The logit transformation was applied to normalize the ratios of answering that tone series sounded familiar (familiarity ratios). Based on the results of the Vo_2max tests before the two sessions, the participants were grouped with 11 participants with lower fitness and higher fitness each. Then, we performed a 2 (fitness: high and low) × 2 (physical condition: rest and exercise) × 3 (series: high-voice, low-voice, and random tone series) ANOVA with the logit values of the familiarity ratios for each series. When we detected significant effects, Bonferroni-corrected *post hoc* tests were conducted for further analysis. Statistical significance levels were set at $p < 0.05$ for all analyses.

3.2. Results

3.2.1. Vo_2max data

Based on the results of the Vo2max tests before the two sessions, the Vo_2max value for 22 participants ranged from 32.10 to 63.83 ml/(kg min), and the mean Vo_2max (value ± S.E.M) was 49.39 ± 1.65 ml/(kg min). The participants were grouped with 11 participants with lower fitness (Vo_2max value ranged from 32.10 to 48.93 ml/(kg min), Mean ± S.E.M: 43.32 ± 1.64 ml/(kg min)) and higher fitness (Vo_2max value ranged from 51.21 to 63.83 ml/(kg min), Mean ± S.E.M: 55.46 ± 1.21 ml/(kg min)) each.

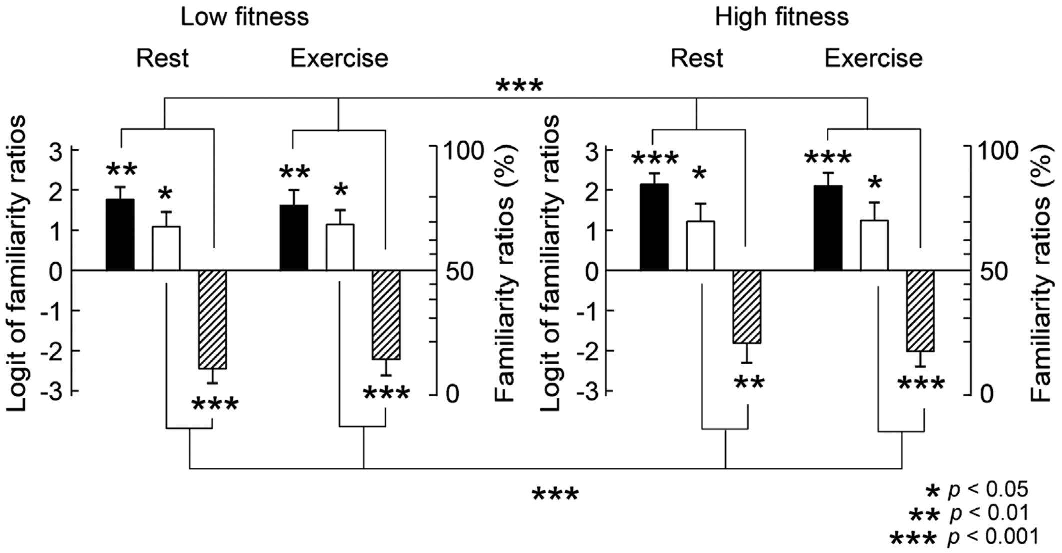

Figure 5. The logit of the ratios of answering that tone series sounded familiar in the experiment 2. In the experiment 2, the participants were instructed to attend to high- and low-voice tone sequence in simultaneous two tone sequences.
Notes: The closed bars indicate familiarity ratios of the high-voice tone series in which tones were ordered on the basis of the same constraint as the high-voice tone sequence. The open bars indicate familiarity ratios of the low-voice tone series in which tones were ordered on the basis of the same constraint as low-voice tone sequences. The hatched bars indicate familiarity ratios of the random tone series in which tones were pseudo-randomly ordered. The error bars indicate the standard error of the mean. The asterisks indicate the main effects in the ANOVA and the simple main effects in the *post hoc* tests.

3.2.2. Performance of familiarity test

In the both participants with high and low fitness, the results of the two-tailed *t*-tests indicated that the familiarity ratios were significantly above chance level in the high-voice tone series in the both rest (low fitness: $t[10] = 4.78$, $p = 0.001$, high fitness: $t[10] = 7.42$, $p = 0.0001$) and exercise sessions (low fitness: $t[10] = 4.17$, $p = 0.002$, high fitness: $t[10] = 6.80$, $p = 0.0001$), and in the low-voice tone series in the both rest (low fitness: $t[10] = 2.90$, $p = 0.016$, high fitness: $t[10] = 2.71$, $p = 0.022$) and exercise sessions (low fitness: $t[10] = 2.73$, $p = 0.021$, high fitness: $t[10] = 2.69$, $p = 0.023$) (Figure 5). The familiarity ratios in the random tone series were significantly below chance level in the both rest (low fitness: $t[10] = -7.41$, $p = 0.0001$, high fitness: $t[10] = -3.71$, $p = 0.004$) and exercise sessions (low fitness: $t[10] = -6.31$, $p = 0.0001$, high fitness: $t[10] = -5.58$, $p = 0.0001$). The results of the ANOVA indicated that the main sequence effect was significant ($F[2, 40] = 99.31$, $p = 0.00001$): participants could perform statistical learning of the tone series A and I (tone series A: $p = 0.0001$, tone series I: $p = 0.0001$).

3.3. Discussion

The experiment 2 examined how intentional statistical learning of two simultaneous auditory streams could be affected by concurrent exercise of cycling when participants attended to both of the two sequences and how the physical fitness levels could modulate the statistical learning of two attended sequences. Previous studies suggested that cognitive performance during concurrent physical exercise was higher in learners with high than low fitness [10,11]. On the other hand, concurrent physical movement might interfere with incidental but not intentional statistical learning. Given these findings in the previous studies, in the present study, we hypothesized that performance of statistical learning of two attended sequences could be higher in the participants with high than low fitness in both the exercise and rest sessions.

As a result, in the both rest and exercise sessions, the familiarity ratios in the both participants with higher and lower fitness were significantly above chance levels in the both high- and low-voice tone series and below chance levels in the random tone series. Furthermore, the familiarity ratios in the both participants with higher and lower fitness were significantly higher in the high- and low-voice tone series than random tone series. This suggested that, regardless of learner's fitness levels and physical condition of exercising and resting while learning, they could perform intentional statistical learning of two simultaneous sequences. Real-world auditory environments contain a lot of overlapping sounds such as those made by human voices and musical instruments. The previous neurophysiological study demonstrated that simultaneous auditory sequences were encoded separately in auditory cortex [20]. Our results imply that even during concurrent exercise, simultaneous auditory sequences can statistically be learned by intentional learning. On the other hand, the familiarity ratios tended to be higher in the high- than low-voice tone series although this difference was not significant. Previous magnetoencephalographic study reported that the learning effects of two simultaneous auditory sequences could be more salient in high than low voices [12,21,22]. Fujioka and colleague suggested that because higher voices (e.g. soprano) often play a role of a leading theme in music, higher voice could be perceptually dominant compared with lower voice.

4. General discussion

The present study investigated how incidental and intentional statistical learning of two simultaneous auditory streams could be affected by concurrent physical exercise, and how the physical fitness levels could modulate the intentional and incidental statistical learning. In the experiment 1, the participants were instructed to attend to one of the two sequences and ignore to the other sequence during two sessions. In the experiment 2, the participants were instructed to attend to both of the two sequences during the two sessions. According to the previous studies, concurrent physical movement could interfere with incidental but not intentional statistical learning and the performance of learning during concurrent exercise is higher in learners with higher than lower fitness as suggested by previous studies [8–11]. Taking these findings in the previous studies into account, in the present study, we hypothesized that when participants are presented two simultaneous sequences, the performance of statistical learning of ignored sequence while exercising should be higher in the participants with high than low fitness, whereas this difference might not be detected in the statistical learning of attended sequence while resting.

Interestingly, the present study suggested that performance of incidental statistical learning during concurrent exercise was higher in the participants with higher than lower fitness, whereas this difference could no be detected in intentional statistical learning. Previous studies implied the spatial dichotomy of neural mechanisms underlying intentional and incidental statistical learning: incidental and intentional cognitive performances predominantly depend on the striatum and frontal lobe, respectively [23,24]. The striatum could be activated during not only incidental statistical learning [25–29], but also physical movement [30–32], suggesting that the neural substrates recruited during incidental statistical learning may overlap with the neural substrates associated with motor control during concurrent physical movement. According to the previous study [33], if implicit learning task and the concurrent task incorporate similar stimuli that can draw upon the same neural areas, implicit learning could be interfered. The previous study suggested that even cognitive tasks that is quite different from statistical learning but shares the same neural resources could interfere with statistical learning [9]. Stevens and colleague demonstrated that when physical movement and incidental statistical learning are concurrently performed, statistical learning might be interfered due to the cognitive capacity limitations within a neural area of the striatum. Chang and colleague suggested that, considering that physical exercise and cognitive processing require similar neural structures and difference in development of neural resources available for physical exercise and cognitive processing between learners with lower and higher fitness, learners with lower fitness might have fewer neural resources necessary to perform physical exercise and cognitive processing, while learners with higher fitness have more neural resources necessary to perform physical exercise and cognitive processing [10]. They also suggested that learners with higher fitness need fewer neural resources for the exercise, compared to learners with lower fitness. The findings of the present study may support this hypothesis: performance of incidental statistical learning during concurrent exercise was higher in the participants with higher than lower fitness, whereas this difference could no be detected in intentional statistical learning. Improvement of physical fitness might facilitate incidental statistical learning of simultaneous auditory sequences while concurrent physical exercise. In other words, improvement in physical fitness could increase neural resources necessary to perform statistical learning as well as physical exercise. Incidental statistical learning is considered to be a domain-general and implicit learning process innate to humans, regardless of learner's ages [1,2], suggesting that we might constantly and unconsciously perform statistical learning of sequential stimuli such as language and music [34,35]. Some researchers reported that dyslexia is difficult to perform statistical learning compared to healthy learners [36,37]. Improvement in physical fitness might be useful as clinical application for rehabilitation of language learning in dyslexia. Statistical learning during concurrent exercise may shed light on the improvement and rehabilitation for motor and cognitive functions that may be essential to adapt in a real-world environment. In the present study, although statistical learning effects were evaluated from behavioral responses of the familiarity tests, neuroimaging and neurophysiological studies will be needed in future to clarify the relationships between striatum and neural basis underlying physical movement and statistical learning, and effects of concurrent exercise on statistical learning.

In conclusion, we demonstrated that performance of incidental statistical learning while concurrent physical exercise could be higher in the learners with high than low physical fitness, whereas this difference could not be detected in intentional statistical learning. The improvement in physical fitness may facilitate incidental statistical learning during concurrent physical exercise.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] Saffran JR, Aslin RN, Newport EL. Statistical learning by 8-month-old infants. Science. 1996;274(5294):1926–1928.

[2] Perruchet P, Pacton S. Implicit learning and statistical learning:onephenomenon,twoapproaches.TrendsCogn Sci. 2006;10(5):233–238. doi:http://dx.doi.org/10.1016/j.tics.2006.03.006

[3] Abla D, Okanoya K. Statistical segmentation of tone sequences activates the left inferior frontal cortex: a near-infrared spectroscopy study. Neuropsychologia. 2008;46(11):2787–2795. doi:http://dx.doi.org/10.1016/j.neuropsychologia.2008.05.012

[4] Daikoku T, Yatomi Y, Yumoto M. Implicit and explicit statistical learning of tone sequences across spectral shifts. Neuropsychologia. 2014;63:194–204. doi:http://dx.doi.org/10.1016/j.neuropsychologia.2014.08.028

[5] Daikoku T, Yatomi Y, Yumoto M. Statistical learning of music- and language-like sequences and tolerance for spectral shifts. Neurobiol Learn Mem. 2015;118:8–19. doi:http://dx.doi.org/10.1016/j.nlm.2014.11.001

[6] Furl N, Kumar S, Alter K, et al. Neural prediction of higher-order auditory sequence statistics. NeuroImage. 2011;54(3):2267–2277. doi:http://dx.doi.org/10.1016/j.neuroimage.2010.10.038.

[7] Paraskevopoulos E, Kuchenbuch A, Herholz SC, et al. Statistical learning effects in musicians and non-musicians: An MEG study. Neuropsychologia. 2012;50(2):341–349. doi:http://dx.doi.org/10.1016/j.neuropsychologia.2011.12.007.

[8] Dakin Steven C. Sensitivity to contrast modulation depends on carrier spatial frequency and orientation. Vision Research. 2000;40:311–329.

[9] Stevens DJ, Arciuli J, Anderson DI. Concurrent movement impairs incidental but not intentional statistical learning. Cogn Sci. 2015;39(5):1081–1098. doi:http://dx.doi.org/10.1111/cogs.12180

[10] Chang YK, Labban JD, Gapin JI, et al. The effects of acute exercise on cognitive performance: a meta-analysis. Brain Res. 2012;1453:87–101. doi:http://dx.doi.org/10.1016/j.brainres.2012.02.068

[11] Tomporowski PD, Ellis NR. Effects of exercise on cognitive processes: a review. Psychol Bull. 1986;99:338–346.

[12] Marie C, Trainor LJ. Development of simultaneous pitch encoding: infants show a high voice superiority effect. Cereb Cortex. 2013;23(3):660–669. doi:http://dx.doi.org/10.1093/cercor/bhs050

[13] Watanabe K, Funahashi S. Neural mechanisms of dual-task interference and cognitive capacity limitation in the prefrontal cortex. Nat Neurosci. 2014;17(4):601–611. doi:http://dx.doi.org/10.1038/nn.3667

[14] Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia. 1971;9(1):97–113.

[15] Klatt DH. Software for a cascade/parallel formant synthesizer. J Acoust Soc Am. 1980;67(3):971–995.

[16] Uth N, Sorensen H, Overgaard K, et al. Estimation of VO_2max from the ratio between HRmax and HRrest? The heart rate ratio method. Eur J Appl Physiol. 2004;91(1):111–115. doi:http://dx.doi.org/10.1007/s00421-003-0988-y

[17] Robergs RA, Landwehr R. The surprising history of the “HRmax=220-age” equation. J Exerc Physiol. 2002;5(2):1–10.

[18] DeKeyser RM. Implicit and explicit learning. In: CJ Doughty, & MH Long (Eds.), Handbook of second language acquisition. Oxford, MA: Blackwell; 2003. p. 313–348.

[19] Ellis R. Implicit and explicit learning , knowledge and instruction. In: Ellis R, Loewen S, Elder C et al., editors. Implicit and explicit knowledge in second language learning , testing and teaching. Bristol: Multilingual Matters; 2009. p. 3–25.

[20] Fujioka T, Trainor LJ, Ross B. Simultaneous pitches are encoded separately in auditory cortex: an MMNm study. NeuroReport. 2008;19(3):361–366. doi:http://dx.doi.org/10.1097/WNR.0b013e3282f51d91

[21] Fujioka T, Trainor LJ, Ross B, et al. Automatic Encoding of Polyphonic Melodies in Musicians and Nonmusicians. Journal of Cognitive Neuroscience. 2005;17(10):1578–1592. doi:http://dx.doi.org/10.1162/089892905774597263.

[22] Zenatti A. Le développement génétique de la perception musicale. Monographies Francaises de Psychologie. 1969;17.

[23] Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci. 2002;3(3):201–215. doi:http://dx.doi.org/10.1038/nrn755

[24] Miller EK, Cohen JD. An integrative theory of prefrontal cortex function. Annu Rev Neurosci. 2001;24:167–202. doi:http://dx.doi.org/10.1146/annurev.neuro.24.1.167

[25] Dennis NA, Cabeza R. Age-related dedifferentiation of learning systems: an fMRI study of implicit and explicit learning. Neurobiol Aging. 2011; 32(12):2318-e2317–2330. doi:http://dx.doi.org/10.1016/j.neurobiolaging.2010.04.004

[26] Peigneux P, Maquet P, Meulemans T, et al. Striatum forever, despite sequence learning variability: a random effect analysis of PET data. Hum Brain Map. 2000;10(4):179–194.

[27] Rieckmann A, Fischer H, Bäckman L. Activation in striatum and medial temporal lobe during sequence learning in younger and older adults: Relations to performance. NeuroImage. 2010;50(3):1303–1312. doi:http://dx.doi.org/10.1016/j.neuroimage.2010.01.015

[28] Turk-Browne NB, Scholl BJ. Flexible visual statistical learning: transfer across space and time. J Exp Psychol Hum Percept Perform. 2009;35(1):195–202. doi:http://dx.doi.org/10.1037/0096-1523.35.1.195

[29] Turk-Browne NB, Scholl BJ, Chun MM, et al. Neural evidence of statistical learning: efficient detection of visual regularities without awareness. J Cogn Neurosci. 2009;21(10):1934–1945. doi:http://dx.doi.org/10.1162/jocn.2009.21131

[30] Bailey KR, Mair RG. The role of striatum in initiation and execution of learned action sequences in rats. J Neurosci. 2006;26(3):1016–1025. doi:http://dx.doi.org/10.1523/JNEUROSCI.3883-05.2006

[31] Jahanshahi M, Rowe J, Fuller R. Impairment of movement initiation and execution but not preparation in idiopathic dystonia. Exp Brain Res. 2001;140(4):460–468. doi:http://dx.doi.org/10.1007/s002210100847

[32] Montgomery EB Jr, Buchholz SR. The striatum and motor cortex in motor initiation and execution. Brain Res. 1991;549(2):222–229.

[33] Chang GY, Knowlton BJ. Visual feature learning in artificial grammar classification. J Exp Psychol Learn Mem Cogn. 2004;30(3):714–722. doi:http://dx.doi.org/10.1037/0278-7393.30.3.714

[34] Daikoku T, Yatomi Y, Yumoto M. Pitch-class distribution modulates the statistical learning of atonal chord sequences. Brain and Cognition. 2016;108:1–10. doi:http://dx.doi.org/10.1016/j.bandc.2016.06.008

[35] Daikoku T, Yatomi Y, Yumoto M. Statistical learning of an auditory sequence and reorganization of acquired

knowledge: A time course of word segmentation and ordering. Neuropsychologia. 2017;95:1–10. doi:http://dx.doi.org/10.1016/j.neuropsychologia.2016.12.006
[36] Kahta S, Schiff R. Implicit learning deficits among adults with developmental dyslexia. Ann Dyslexia. 2016;66(2):235–250.
[37] Schmalz X, Altoè G, Mulatti C. Statistical learning and dyslexia: a systematic review. Ann Dyslexia. 2016. doi:http://dx.doi.org/10.1007/s11881-016-0136-0