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The Contribution of Auditory Imagery and Visual Rhythm Perception to Sensorimotor Synchronization With External and Imagined Rhythm

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Sensorimotor synchronization (SMS) refers to the temporal coordination of an external stimulus with movement. Our previous work revealed that while SMS with visual flashing patterns was less consistent than with auditory or tactile patterns, it was still evident in a sample of nonmusicians. Although previous studies have speculated the potential role of auditory imagery, its contribution to visual SMS performance is not well quantified. Utilizing a synchronization–continuation finger-tapping task with a visual stimulus that included implied motion, we aimed to examine how participants' imagery ability, musicality, and rhythm perception affected SMS performance. We quantified participants' SMS consistency in synchronization (with visual cues) and continuation (without visual cues) phases. Participants also performed a perception task assessing their ability to detect temporal perturbations in the visual rhythm and completed musical ability and imagery questionnaires. Our linear regression model for SMS consistency included the trial phase, self-reported auditory imagery control and musicality, and visual rhythm perception as predictors. Significant effects of trial phase and auditory imagery scores on SMS consistency suggested that participants performed SMS more consistently while the guiding visual stimulus was present and that the higher one's self-reported auditory imagery ability, the better their SMS when continuing with unguided rhythm. One's visual rhythm perception accuracy significantly correlated with SMS consistency during the synchronization phase, and there was no correlation between rhythm perception and auditory imagery control. Overall, our results suggested relatively independent contributions of auditory imagery and visual rhythm perception to SMS with visual rhythm.

Public Significance Statement

Existing research predominantly focuses on sensorimotor synchronization (SMS) performance with auditory cues when exploring human propensity for rhythm. However, the significance of SMS linked to visual rhythm cannot be understated, particularly in activities like various sports where it plays a pivotal role. In the present study, while synchronizers' ability to perceive visual rhythm significantly correlated with SMS consistency during the synchronization phase, their self-reported control of auditory imagery significantly correlated with their finger-tapping SMS consistency during the continuation phase of a synchronization–continuation task. Our research contributes to a better understanding of factors that influence SMS performance that can facilitate the further development of SMS training. For example, it is possible that training imagery abilities in young athletes could enhance imagery control as well as SMS performance (Munroe-Chandler et al., 2012). Furthermore, the amalgamation of imagery training and physical exercise can alleviate bradykinesia, a significant and incapacitating symptom of Parkinson's disease (Stern, 2009; Tamir et al., 2007).

Keywords: sensorimotor synchronization, auditory imagery, visual rhythm perception, musicality, visual imagery

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Sensorimotor synchronization (SMS), the temporal coordination of movement with a rhythmic sequence, for example, the sound of music or flashing light, is a fundamental process that underlies cognitive and social interactions that involve event prediction (Choi et al., 2023; von Schnehen et al., 2022). While most SMS studies have focused on auditory SMS (Repp, 2005), tennis (and many other sports) involves visual SMS during the perception of, and interaction with, the moving ball and an opponent's body movements (Bisio et al., 2021). The rhythmic precision involved in a sport such as downhill slalom skiing is analogous to auditory time-keeping during a steady beat in musical performance, where the skier attempts to maintain a rhythm between evenly spaced slalom gates (Callow et al., 2013). While we understand more about rhythmic production and comprehension in the context of sound, the factors that influence SMS with rhythmic visual cues remain underinvestigated.

The well-established finger-tapping paradigm is straightforward to perform and a valuable tool for assessing SMS performance (Repp, 2005). Finger- and foot-tapping are frequently observed when music is present, and most finger-tapping studies show that SMS abilities are generally stronger in terms of accuracy (i.e., average relative phase) and consistency (i.e., standard deviation of relative phase) for auditory stimuli than for visual (Comstock et al., 2018; Elliott et al., 2010; Patel et al., 2005). However, in our prior work, while participants were entrained better to auditory stimuli than visual, SMS with spatially stationary visual flashes was still evident in participants (Whitton & Jiang, 2023). SMS with visual rhythms can be improved by including a spatial component in the stimulus to convey movement information, as suggested by studies that compared SMS with a spatially stationary flashing stimulus to SMS with a bouncing ball (Gan et al., 2015; Iversen et al., 2015). Thus, enhancing the spatiotemporal properties of a rhythmic visual stimulus can aid a synchronizer's SMS performance. In addition to stimulus properties, subject-specific factors such as self-reported imagery ability might also have a significant impact on SMS performance (Guttman et al., 2005; Iversen et al., 2015).

When synchronizing with a visual rhythm, participants may internally sing along, tapping with imagined auditory rather than perceived visual stimuli (Guttman et al., 2005). There might be an obligatory activation of imagery in the most task-appropriate modality to assist with visual SMS performance (Kraeutner et al., 2020). The contribution of auditory imagery to visual SMS performance, however, is not well understood. Auditory imagery can be defined as the cognitive ability to imagine a sound or a sequence of sounds (Hinwar & Lambert, 2021). Hence, a stimulus need not necessarily originate externally; it can be generated through mental imagery. One's self-reported experience of auditory imagery shows considerable variation between individuals (Lima et al., 2015), ranging anywhere from anauralia, the inability to generate imagery of sound (Hinwar & Lambert, 2021), to hyperauralia, the experience of intensely vivid auditory imagery. How vividly the imagined stimulus is generated might influence the consistency of synchronization to a rhythm that is either perceived externally or simulated internally (Kraeutner et al., 2020; Okawa et al., 2017). Interestingly, SMS performance, auditory imagery ability, and musicality have been found to all positively correlate in musicians, suggesting that there is a relationship between music experience and self-reported auditory imagery abilities (Pecenka & Keller, 2009). Visual rhythmic information is experienced frequently by the general population outside of musical contexts, for example, during sports performances. However, the potential relationship between imagery ability and visual SMS performance has not been investigated in nonmusicians.

In addition to possible reliance on auditory imagery during visual SMS performance, other imagery modalities could be utilized. It has been shown that we recruit a common sensorimotor circuit for generating auditory and visual imagery, and vividness of imagery scores in these two modalities are positively correlated (Lima et al., 2015). Most imagery studies have concentrated on static visual imagery, overlooking the additional dimension of visual imagination involving spatial and temporal dynamics (Cumming & Eaves, 2018; Keogh & Pearson, 2018; Zeman et al., 2020). Internal visual imagery (IVI) allows an individual to generate a spatiotemporal first-person simulation of viewed movements while observing the present environment (Hardy & Callow, 1999), especially useful while navigating in busy environments. Likewise, athletes and musicians often rehearse kinesthetic imagery of movements to improve sensorimotor performance, for example, rehearsing a golf swing or basketball free throw (Lotze, 2013; Theiler & Lippman, 1995). Kinesthetic imagery is also employed in general fitness training, imagining one's past movement to improve the accuracy of the next (Dickstein & Deutsch, 2007). Finger-tapping is felt kinesthetically, and the feeling of finger movement to a guiding rhythm might be utilized to maintain synchronization. Finally, we note that imagery in one modality might inform or interact with another (Scott et al., 2022).

The potential reliance on imagery abilities during SMS reflects a mechanism driven by the simulation of a rhythmic stimulus. As posited by the neural resonance theory: neural oscillations synchronize with an external rhythm and subsequently influence motor and attentional systems (Comstock et al., 2018). If an individual relies on an external stimulus during SMS performance, rhythm perception of the stimulus might be an important factor in SMS performance. For example, in our previous study, when the rhythmic deviation of the stimulus was increased, SMS consistency worsened (Whitton & Jiang, 2023). With rhythmic deviation, inconsistency of the stimulus pattern is introduced, making the perception of rhythm more difficult (McAuley & Semple, 1999). Importantly, once an auditory representation of a stimulus is formed, subsequent visual (or tactile) SMS might be performed utilizing auditory imagery. One study found that visual rhythm perception improved after auditory training, but not after visual training (Barakat et al., 2015), suggesting that the improvement might occur through enhanced "auditory representations." How rhythm perception, imagery ability, and visual SMS performance are related, and possibly interact, remains to be established.

Last but not least, the synchronizer's musicality can affect SMS performance. One's degree of musical familiarity and aptitude can take many forms and an individual does not have to be a musician to be highly musical. While self-reported musical training is often used as a measure of musicality (Białuńska & Dalla Bella, 2017; Chen et al., 2002), the comprehensive Goldsmiths Musical Sophistication Index (Gold-MSI) includes components such as self-reported musical active engagement, and musical perceptual abilities (Müllensiefen et al., 2014). As suggested in previous studies, components of the Gold-MSI serve as more specific musicality covariates than simply using musical training (Matthews et al., 2016; Stupacher, 2019). We previously found that the higher one's self-reported level of (musical) general sophistication, the more consistent their SMS to the most rhythmically deviated stimulus (Whitton & Jiang, 2023). This correlation held for visual, auditory, and tactile stimuli, suggesting that the

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self-reported musical general sophistication of the synchronizer can be utilized irrespective of stimulus modality.

In the present study, using a synchronization–continuation paradigm (McPherson et al., 2018; Wing & Kristofferson, 1973), we examined how the presence (absence) of a guiding visual stimulus, along with the synchronizer's self-reported imagery abilities and musicality, and visual rhythm perception impacted SMS performance. We quantified participants' SMS consistency in synchronization (with visual cues) and continuation (without visual cues) phases of continuous trials. Participants also completed imagery and musicality questionnaires and performed a visual rhythm perception task that assessed their ability to detect rhythm perturbations in the presented stimulus.

Consistent with previous studies that reported better consistency of externally-guided than unguided finger-tapping (Jantzen et al., 2005; Serrien, 2008), we predicted that SMS consistency would be better during the guided (synchronization) phase than during the unguided (continuation) phase. Our novel prediction was that visual SMS consistency would be better in participants who self-reported higher auditory imagery abilities, as previously found for auditory SMS consistency (Colley et al., 2018). Based on our previous work (Whitton & Jiang, 2023), we expected better SMS consistency in those who self-reported higher musical general sophistication, and further, an interaction between musical general sophistication and phase on SMS consistency. Hence, consistency would be less influenced by the absence of cues during the continuation phase if one's self-reported level of musicality is higher. We hypothesized better SMS consistency in participants with more accurate visual rhythm perception, suggesting a beneficial influence of stimulus perception on finger-tapping consistency.

Method

Participants

We conducted an a priori power analysis using G*Power (Faul et al., 2009) for sample size estimation, based on our previous work (Whitton & Jiang, 2023). A medium effect size (equivalent to $\eta_p^2 = 0.29$) was estimated using Cohen's (1988) criteria and a linear multiple regression-based power analysis. With a significance criterion of $\alpha = .05$ and power $= 0.8$, the minimum sample size required is $N = 22$. We recruited 23 right-handed participants (nine women, 14 men, age $M = 25.8$, $SD = 4.6$) from the general population of the greater Reno area.

Stimuli

We used a visual stimulus to create a tempo of 100 beats per minute (bpm), and an interstimulus interval (ISI) of 600 ms at 1.7 Hz. This tempo has been found as optimal for perception and production (London, 2004), and sits within the range of average spontaneous motor tempo (SMT) found in numerous studies (Delevoye-Turrell et al., 2014). Using MATLAB R2018b and PsychToolbox, we generated a white disc (2.5° diameter) illuminated for 33.3 ms as our flashing visual stimulus (Brainard, 1997; Pelli, 1997). A small fixation dot (0.5°) was presented in the center of the screen throughout. The position of the flash moved in 7° increments from one side of the screen (10.5° from the center) to the other side. The direction switched once the last position on one side was reached (Figure 1a). By using flashes that sequentially changed position, we introduced implied motion to better facilitate entrainment (Armstrong & Issartel, 2014). Visual stimuli were delivered through a Display++ system with a refresh rate of 120 Hz (Cambridge Research Systems, Rochester, United Kingdom).

Procedure

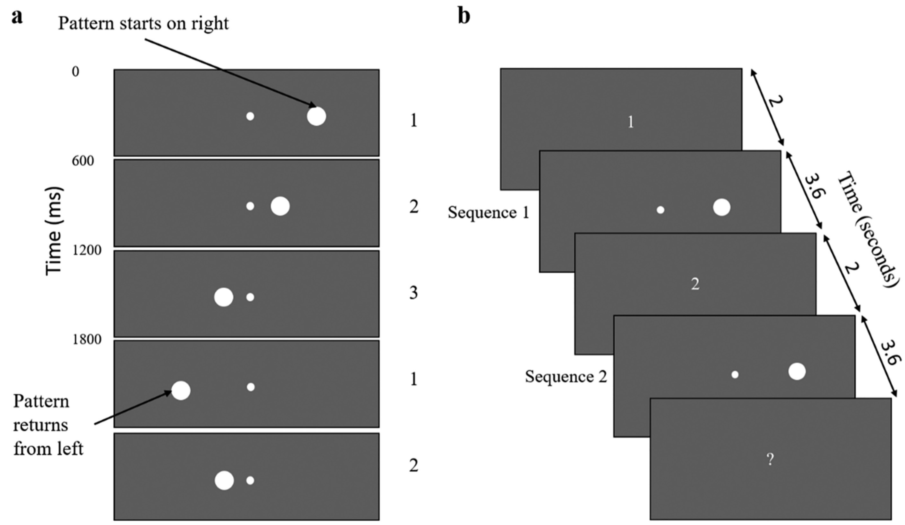
After giving informed consent, participants completed the Bucknell Auditory Imagery Control Scale (BAIS-C), auditory imagery vividness (BAIS-V), internal visual movement imagery (VMIQ-IVI), kinesthetic imagery (VMIQ-KIN), and Gold-MSI questionnaires (Appendices A and B, respectively). Separate scores of vividness and control on the BAIS represent an individual's self-reported ability to generate, maintain, and manipulate auditory imagery, respectfully (Halpern, 2015). While evidence validating the BAIS in predicting auditory imagery for a rhythmic task is limited, a recent study reported a positive correlation between BAIS-C scores and consistency on an SMS task involving auditory rhythms (Colley et al., 2018). The revised vividness of motor imagery questionnaire (VMIQ-2) is a psychometrically validated tool that incorporates the temporal aspect of vision to determine one's self-reported visual imagery ability (Roberts et al., 2008). The VMIQ-IVI represents one's self-reported ability to generate and maintain visual imagery of movements (Smith & Holmes, 2004). The same VMIQ-2 list of questions can also be used as a measure of kinesthetic imagery, that is, the self-reported ability to imagine the sensation of physical movement (VMIQ-KIN). In addition to providing a self-reported measure of participants' musical general sophistication, the Gold-MSI contains the individual component of musical perceptual abilities, and high scores on this component have been shown to predict better accuracy on auditory rhythm perception tasks (Müllensiefen et al., 2014).

Participants sat at a desk 70 cm from the Display++ monitor with a keyboard (HHKB Lite 2) that had a constant latency of 20 ms (factored into raw data recording). Participants wore earplugs throughout. Before the main experiment, we measured SMT (in beats per minute) while participants tapped their dominant index finger on the spacebar at an undirected, spontaneous rate between "start" and "finish" visual cues, resulting in four 30 s SMT trials. A significant difference between participants' average spontaneous intertap interval and the experimental tempo would suggest that the experimental tempo is outside of participants' preferred SMS tempo. Notably, while one's SMT might be optimal for performing SMS (Delevoye-Turrell et al., 2014), it has been recently shown that SMT values did not predict SMS performance (McPherson et al., 2018). Separately, the consistency of SMT is a potential factor to be included in the modeling of SMS performance. Worse consistency of SMT suggests a lower level of intrinsic rhythmicity, and a higher potential to rely on external stimuli during SMS (McPherson et al., 2018).

For the main experiment, we used a synchronization–continuation paradigm to measure SMS performance to external and imagined stimuli. The task was to synchronize finger taps with the rhythm of sequentially illuminated visual stimuli as closely as possible while fixating on a central fixation dot (Figure 1a). Sequentially illuminated discs served as guiding visual stimuli during the first half of the trial (i.e., synchronization phase). During the second half of the trial (i.e., continuation phase), the guiding stimuli disappeared, and participants continued to fixate on the central fixation dot and tap while instructed to "imagine the stimulus was still present." Each trial started with an introduction phase of three sequences (nine flashes) to allow the participant to comfortably begin synchronizing,

Figure 1

Synchronization–Continuation and Rhythm Perception Task Paradigm



Note. (a) Example trial in the synchronization–continuation task where flashing stimulus starts from the right side of the screen. Each white disc flash on the monitor was sequentially illuminated white for 33 ms at a rate of 1.7 Hz (600 ms ISI). Participants fixated on the central white fixation dot throughout. (b) Example trial in the rhythm perception task. One discrete sequence of six flashes was presented, followed by another after a 2-s interval. The participant then responded to "Which sequence contained the timing error?" Stimulus depictions are not to scale. ISI = interstimulus interval.

denoted by a dark gray fixation dot that changed to white when the synchronization phase began. For the synchronization phase, the total number of discs illuminated (and taps) in each trial was 15 (five sequences of three) lasting 9 s. Immediately following the synchronization phase, the continuation phase ended when 15 taps had been recorded (9 s). Between trials, text was presented instructing the participant to stop tapping and press the space bar when ready to start the next trial. With the introduction, synchronization, and continuation phases, each trial lasted 23.4 s. Two trials were given as practice trials. Fourteen trials were performed in three blocks. The total experiment lasted approximately 25 min.

In addition to the main experiment, we carried out a visual rhythm perception task to assess participants' ability to detect a timing perturbation in one of two discrete sequences. We used the same flashing stimulus from the main experiment, limited to a sequence of six flashes, starting from right to left and returning from left to right. In each trial, one sequence was presented, followed by a brief pause (2 s) and the second sequence (Figure 1b). One of the sequences was perfectly rhythmic. In the other, the fourth flash was presented either earlier or later resulting in a change in both the ISI between Flash 3 and 4 and the ISI between Flash 4 and 5. By shifting the temporal position of the fourth flash by 17, 33, 67, 100, or 133 ms, five counterbalanced perturbation levels were used. Four trials were given as practice. Twenty-five trials were performed in four blocks, with five per perturbation levels. The total experiment lasted approximately 25 min.

Data Analysis

We analyzed SMS performance using circular statistics (Fisher, 1995). Each raw data trial was 30 taps long. We divided trials into "synchronization" (15 taps) and "continuation" (15 taps) phases. For both phases, we took similar preprocessing steps and utilized measures of accuracy, consistency, and autocorrelation.

SMS during synchronization phase: To determine how tapping occurred relative to the constant tempo of the visual stimulus, each data point was between 0 and ± 300 ms of the tap timing relative to the corresponding beat. Taps with timing outside of these criteria were recoded or removed from the sequence. For example, if any tap occurred greater than 300 ms after the previous cue, it was treated as a tap corresponding to the next cue in the sequence. If a tap occurred less than 300 ms from the last tap, it was detected as a double tap and removed. If no tap occurred between two consecutive cues, it was detected as a missed tap and removed. These tapping measures were divided by the ISI (600 ms) to convert into relative phase (RP). RP, ranging from -0.5 to $+0.5$, as previously utilized (Iversen et al., 2015). Negative (positive) values represent tapping before (after) the target beat, and zero represents perfect accuracy. A trial was rejected if we failed to reject the null hypothesis ($p > .001$) of circular uniformity on Rayleigh's test, a criterion used in previous studies to suggest random tapping (Iversen et al., 2015; Ruxton, 2017). The mean trial rejection rate was 1.5%. For the synchronization phase of each trial, we quantified accuracy as the mean RP, with a smaller mean RP (i.e., closer to zero) suggesting better accuracy. We quantified consistency as the circular standard deviation (SD_{circ}) of tapping RPs, defined as sqrt ($-2 \ln \mathrm{R}$), where R is the mean of the RP vectors. A lower SD_{circ} signifies better consistency.

SMS during the continuation phase: Due to the absence of a guiding stimulus in the continuation phase of each trial, we quantified performance based on intertap intervals (ITIs). As the trial progresses into the continuation phase, the ITIs might deviate from the fixed ISI

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introduced during the synchronization phase (600 ms). Hence, during the continuation phase, we used the standard deviation of recorded ITIs as our measure of consistency (SD_{ITI}).

Autocorrelation during synchronization and continuation phases: The time-keeping strategies used by the synchronizer to achieve SMS consistency can be revealed by the autocorrelation structure of the tapping time course (Iversen et al., 2015). Autocorrelation describes how one tap is related to the timing of preceding taps, reflecting a recurring timing pattern in the time course (Vorberg & Wing, 1996). For example, the correlation between one tap and the previous tap is known as lag-1 or autocorrelation-1 (AC-1). A Significantly negative AC-1 reflects predictive error correction, where the last tap was slightly early (late), and the next tap is delayed (quickened) in an anticorrelated fashion. We used partial autocorrelation (AC) of successive taps within the 30-tap time series as our third measurement, to reveal possible differences between trial phases in timing mechanisms underlying SMS performance. We calculated mean AC values for each lag for separate trial phases, each containing 14 intertap intervals (ITIs). We obtained 95% confidence intervals (± 0.086) via the equation $\pm 1.96/\mathrm{sqrt}$ (N), where N is the Number of ITIs (14) $\times$ Minimum Trials (37). We analyzed the first eight lags, doubling the number we predicted to be significant, considering the recurring pattern every three beats and the prevalent four-beat rhythmic grouping in Western music (Benjamin, 1984; Box et al., 1994).

Visual rhythm perception performance: To quantify rhythm perception in the two-alternative force choice task, proportion correct responses at each of the five perturbation levels (17, 33, 67, 100, or 133 ms) were fit with a psychometric (cumulative distribution) function. A perturbation threshold corresponding to 75% accuracy was extracted for each participant and used as their level of rhythm perception for subsequent analysis. The lower the perturbation threshold, the better a participant's rhythm perception. We used correlation analyses to test our predictions that SMS consistency would be better in those with better rhythm perception, and in those with a higher level of musicality as reflected by higher musical general sophistication and musical perceptual ability scores.

SMT performance: We quantified each participant's average SMT and their SMT consistency. Average SMT was simply the average of the ITIs, and SMT consistency was the standard deviation of ITIs (SD_{ITI}), our measure of participants' intrinsic rhythmicity.

Modeling analyses: We ran a linear mixed model with trial phase ("synchronization"; "continuation"), auditory imagery control (continuous variable of BAIS-C score), SMT consistency, and musicality (continuous variable of Gold-MSI score) as fixed factors, participant as a random factor, with the dependent variable of tapping consistency (*SD*). We ran model comparisons using Akaike information criterion (AIC) scores to determine which combination of fixed factors provided the best fit for our data. Alternative models contained BAIS-V, visual VMIQ-2, or kinesthetic VMIQ-2 scores as the imagery factors instead of auditory BAIS-C scores. We also compared an alternative model containing scores on the musical perceptual ability component (instead of musical general sophistication) as our measure of self-reported musicality. Based on our previous work, we predicted that individuals with higher self-reported levels of musical general sophistication would exhibit less degradation in SMS consistency in the absence of cues during the continuation phase (Whitton & Jiang, 2023). We included this as a possible interaction, along with other logical potential dependencies between factors to test the predictive abilities of our models.

We plotted overall patterns of ACs in each trial phase and ran planned comparisons of association between auditory imagery scores and ACs at significant lags. In addition, we used a within-subjects *t*-test to compare the difference between our experimental tempo and the subjects' mean SMT. All statistical analyses were performed in R statistical software (R Core Team, 2013).

Transparency and Openness

We have reported how we determined our sample size (see the Participants section) and all data exclusions and measures in the study. The data for all experiments have been made publicly available via the ResearchBox page (https://researchbox.org/2277). The design and analysis plan for the experiments were not preregistered. The data were analyzed using R and MATLAB statistical software, and the code is included in the ResearchBox depository. Further information about the stimuli used in these experiments can be obtained from the corresponding author (sim@nevada.unr.edu).

Results

Consistent with our previous results, our sample of nonmusicians in the present study could synchronize with a visual flashing rhythm (Whitton & Jiang, 2023). In the present study, the accuracy (mean RP) of SMS to the visual stimulus during the synchronization phase ($M = 0.023$, $SD = 0.025$) was close to zero, suggesting almost perfect synchrony. This highly accurate SMS performance is potentially due to our inclusion of implied motion in the stimulus, as suggested by previous studies (Gan et al., 2015; Iversen et al., 2015).

SMS Consistency Was Influenced by the Trial Phase and Auditory Imagery Control

Linear mixed-effects model comparisons with SMS consistency (*SD*) as the dependent variable revealed a model of best fit (lowest AIC) that included the predictor variables trial phase (synchronization; continuation) and auditory imagery control (BAIS-C) with no interaction. There were main effects of the trial phase, $F(1, 22) = 8.467$, $p < .01$, $\eta_p^2 = 0.28$, and BAIS-C, $F(1, 21) = 5.561$, $p < .05$, $\eta_p^2 = 0.21$. When a less well-fitting model containing auditory imagery vividness (BAIS-V), instead of auditory imagery control (BAIS-C), was compared, there was also a significant effect of auditory imagery vividness, $F(1, 21) = 6.512$, $p < .05$, $\eta_p^2 = 0.24$. The BAIS-C and BAIS-V measures were highly correlated, $r(21) = .787$, $p < .001$. Scores for each participant on all imagery questionnaires are shown in Appendix A.

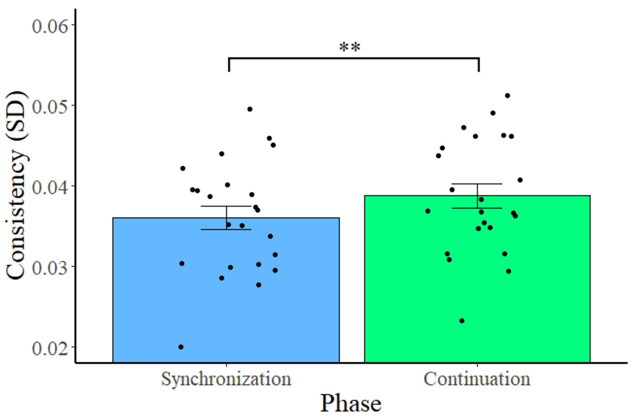
When we tested models containing the other self-reported imagery measures of IVI or kinesthetic imagery separately, there was no main effect of imagery (*p*s $> .632$). Furthermore, when either self-reported Gold-MSI factors of general sophistication or musical perceptual abilities were used in the model, there was no main effect (*p*s $> .214$).

Although the difference was small, at the level of the trial phase, tapping consistency (*SD*) was significantly smaller (i.e., better consistency) during synchronization ($M = 0.036$, $SD = 0.007$) than during continuation ($M = 0.039$, $SD = 0.007$, Figure 2). Within participants, consistency in synchronization and continuation phases were highly correlated, $r(21) = .802$, $p < .001$.

The significant negative correlation between BAIS-C scores and SMS consistency (*SD*) suggests that one's SMS ability was significantly better when their self-reported auditory imagery control

Figure 2

Bar Plot of Sensorimotor Synchronization Performance During Synchronization (in Blue [Left]) and Continuation (in Green [Right]) Phases



Note. Black jitter dots depict individual mean consistency (*SD*) for synchronization and continuation phases. The lower on the *y* axis, the better consistency. Asterisks denote the highly significant main correlational effect of the trial phase on SMS consistency (*SD*). Error bars represent the standard error of the mean. SMS = sensorimotor synchronization. See the online article for the color version of this figure.
** $p < .01$.

was higher (Figure 3). To further examine the effect of auditory imagery control in synchronization and continuation phases, separate correlation analyses revealed a significant negative relationship between BAIS-C scores and consistency during the continuation phase, $r(21) = -.557$, $p < .01$, but not during the synchronization phase, $r(21) = -.309$, $p = .152$.

Significant Autocorrelations in Synchronization and Continuation Phases

Our partial autocorrelation structures for synchronization and continuation phases display consistent patterns between participants, suggesting shared mechanisms underlying SMS in each phase (Figure 4). The only significant negative autocorrelation mean for the synchronization phase was for AC-1 (-0.111, $SD = 0.124$). For the continuation phase, there were significantly positive autocorrelation means for AC-2 (0.132, $SD = 0.090$), AC-3 (0.124, $SD = 0.082$), and AC-4 (0.091, $SD = 0.058$). As expected, a significant positive AC-3 in the continuation phase suggests the presence of a strategy involving imaging of the three-beat visual pattern presented during the synchronization phase.

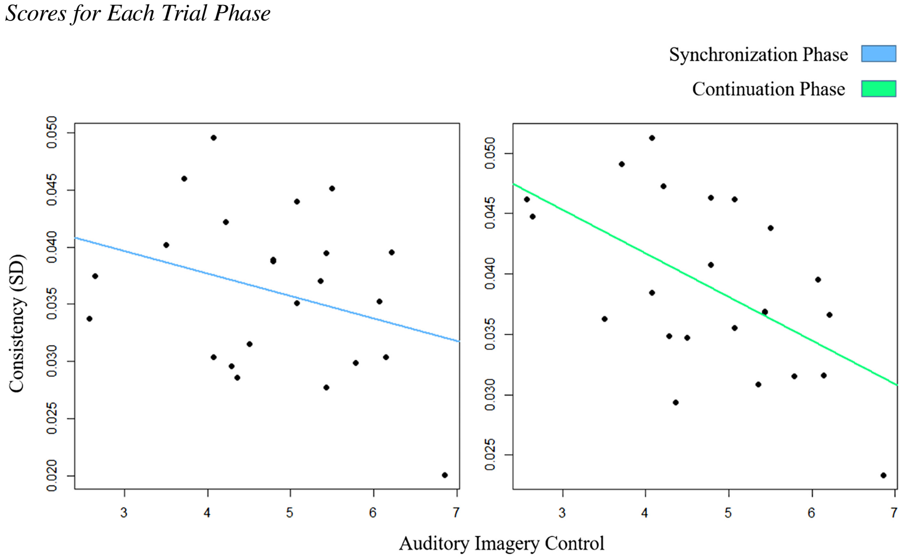
There was no correlation between auditory imagery control (BAIS-C) scores and the significant negative AC-1 in the synchronization phase, $r(21) = -1.447$, $p = .126$. However, there was a significantly negative correlation between auditory imagery vividness (BAIS-V) scores and the AC-1, $r(21) = -2.739$, $p = .012$, suggesting that the more vivid one's self-reported auditory imagery, the stronger their use of an autocorrective synchronization strategy. Bonferroni corrected post hoc tests for the association between BAIS-C and significant continuation phase lags revealed no significant correlations (uncorrected $ps > .046$), and the same was true when the associations between BAIS-V scores and significant continuation phase lags were tested ($ps > .064$).

Visual Rhythm Perception Accuracy Was Correlated With SMS Consistency During the Synchronization Phase

Consistent with our hypothesis that one's SMS would be more consistent with better visual rhythm perception, a positive

Figure 3

Scatter Plots of Sensorimotor Synchronization Performance and Auditory Imagery Questionnaire Scores for Each Trial Phase



Note. Consistency (*SD*) is plotted on the *y* axis, against auditory imagery control (BAIS-C) scores on the *x* axis, with a line of best fit for each trial phase. The lower on the *y* axis, the better SMS consistency. The higher on the *x* axis, the better one's self-reported auditory imagery control. BAIS-C = Bucknell Auditory Imagery Control Scale; SMS = sensorimotor synchronization. See the online article for the color version of this figure.

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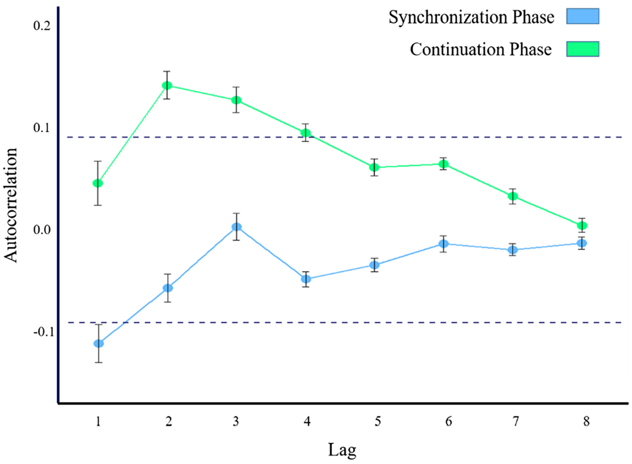
Figure 4
Partial Autocorrelation Function of Tapping Time Series for the Synchronization and Continuation Phases



Note. Autocorrelations above the top dashed line (representing the upper bound of 95% confidence interval: 0.086) or below the bottom dashed line (representing the lower bound of 95% confidence interval: −0.086) are significant. Significant autocorrelation at any lag (1–8) represents a potential grouping pattern corresponding to the lag number. Error bars represent the standard error of the mean. See the online article for the color version of this figure.

correlation between rhythm perception threshold and SMS consistency (*SD*) was significant in the synchronization phase $r(21) = .447$, $p < .05$. However, rhythm perception threshold and SMS consistency (*SD*) were not significantly correlated in the continuation phase, $r(21) = .374$, $p = .079$.

In examining a possible direct relationship between individual differences in rhythm perception threshold and self-reported auditory imagery control, there was no significant correlation, $r(21) = .064$, $p = .773$. Similarly, significant correlations were observed between the visual rhythm perception threshold and neither self-reported Gold-MSI musical general sophistication, $r(21) = -.214$, $p = .328$, nor the individual component of musical perceptual ability, $r(21) = -.258$, $p = .237$.

SMT Did Not Differ From Experimental Tempo or Predict SMS Consistency

The average of participants' SMT (602.0 ms, $SD = 113.13$ ms) was not significantly different from the experimental tempo of 600 ms, $t(22) = 0.083$, $p = .935$. Each participant's intrinsic rhythmicity (consistency of SMT) was significantly correlated with SMS consistency in neither the synchronization phase, $r(21) = .221$, $p = .31$, nor the continuation phase, $r(21) = .297$, $p = .297$.

Discussion

In the present study, we examined the influence of auditory imagery on visual SMS performance in a sample of the general population. Using a finger-tapping synchronization–continuation paradigm and a flashing visual stimulus that included apparent motion, we quantified participants' SMS consistency in both synchronization (with visual cues) and continuation (without visual cues) phases of the trials. In addition, participants completed imagery and musicality questionnaires and performed a visual rhythm perception task that assessed their ability to detect rhythm perturbations.

SMS Consistency Was Influenced by the Trial Phase and Self-Reported Auditory Imagery Control

Participants performed SMS more consistently during synchronization (while the guiding visual stimulus was present) than in the continuation phase, suggesting that the external visual stimulus was an important component of our participants' mechanism of entrainment. Their reliance on additional cues, such as the sensation of finger taps that would have reduced the difference in SMS consistency between the two phases, therefore, was limited. One example of an internal mechanism is posited by the action simulation for auditory prediction (ASAP) hypothesis (Patel & Iversen, 2014), whereby entrainment occurs independently from the external rhythm and its presence (absence) has little influence on SMS performance. Musicians are more likely to rely on ASAP that is untethered to an external stimulus due to their enhanced functional coupling of auditory and motor areas (Patel & Iversen, 2014). In contrast, our results suggest that the external visual stimulus is primarily relied upon by the less specialized general population (nonmusicians).

Furthermore, our results suggest a beneficial influence of self-reported auditory imagery control on SMS performance during the continuation phase. While there were many possible imagery-related modes one could use during the continuation phase, none of the other self-reported imagery modalities (IVI, kinesthetic imagery) yielded significant correlations with SMS consistency in the current study. Our results support that auditory imagery might be the main contributor while synchronizing to an imagined stimulus (Halpern, 2015). The auditory imagery control scale asks about various scenarios, but some (e.g., imagining the beginning of the song "Happy Birthday") require a good sense of rhythm to report a high score, and therefore higher scores might be associated with better timing abilities (Colley et al., 2018). Our results suggest that if one has proficient control of an imaginary auditory rhythm, one can use this skill while continuing to synchronize without a guiding visual stimulus.

While we did not find a relationship between self-reported visual imagery vividness and SMS consistency, a participant's use of visual imagery during the continuation phase might be recruited under different circumstances. For example, one might be more likely to utilize visual imagery during SMS continuation if auditory imagery was prevented. Future studies could investigate the contribution of self-reported (or measured) visual imagery while participants' use of auditory imagery is limited by a distractor or secondary task. Furthermore, we cannot exclude the impact of working memory on SMS consistency during the continuation phase, as has been suggested for guided SMS consistency (Colley et al., 2018). Future studies can further investigate the potential relationship between unguided SMS, self-reported imagery, and working memory abilities.

High SMS Accuracy and Significant AC-1 Autocorrelation in the Synchronization Phase

We observed high SMS accuracy to the flashing visual pattern across participants in the synchronization phase, consistent with previous studies that reported precise SMS when implied movement

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was included in the visual stimulus (Gan et al., 2015; Hove et al., 2010; Iversen et al., 2015). Our results support that the addition of spatial information facilitates the entrainment to visual rhythm.

In keeping with other recent research (Gan et al., 2015; Iversen et al., 2015), our results further support the notion that including spatial information in the visual stimulus enhances entrainment. Negative AC-1, commonly indicating autocorrection in SMS tasks with precise entrainment to auditory or tactile rhythm (Ammirante et al., 2016; Guérin et al., 2021), was observed in the synchronization phase. Contrastingly, when stationary stimuli are used, visual SMS typically elicits a positive AC-1 (Hove et al., 2010). Positive AC-1 suggests emergent timing, a distinctly different process from predictive autocorrection (Delignières & Torre, 2011; Guérin et al., 2021), and implies worse entrainment (Hove et al., 2010). Thus, our findings suggest that including spatial information in the visual stimulus engages one's event-based (nonemergent) entrainment.

The significant negative correlation between auditory imagery vividness (BAIS-V) scores and synchronization phase AC-1, suggests that the higher one's auditory imagery vividness, the higher their tendency (a more negative AC-1) to use autocorrection, and the better their entrainment (Iversen et al., 2015). While synchronizing to the external visual stimulus, participants might have employed a simultaneously simulated auditory image that matches important temporal attributes of the visual stimulus. The reliance on auditory imagery abilities during SMS might be impacted by specific characteristics of the visual pattern, such as the speed and complexity of the implied movement. For example, a faster or more complex pattern may limit the use of an imagined auditory rhythm. Future studies could investigate how rhythm characteristics influence the recruitment of auditory imagery to aid SMS consistency.

Significant High-Order Autocorrelations in the Continuation Phase

Our finding of a significant positive AC-2, AC-3, and AC-4 during continuation, without a significant AC-1, suggested a different strategy than during the synchronization phase. We had predicted significance at AC-3 as evidence that imagery was being relied upon, given that the guiding visual stimulus pattern provided during synchronization lasted three beats. Significance at AC-4 could occur as a result of 4 s being the most common unprompted grouping to count in for Western culture (Benjamin, 1984). It is important to note that independent significance at multiple ACs does not necessarily suggest that the synchronizers were counting in 2, 3, and 4 simultaneously (Vorberg & Schulze, 2002). While the synchronizers might have explicitly counted or subvocalized a repeated number of taps throughout the trial, this is not the only explanation for the observed autocorrelation patterns.

Another explanation is that the synchronizer implicitly perceives and responds to underlying patterns of the imagined stimulus from the synchronization phase. While finger-tapping might be synchronized to the visual pattern, a recurring grouping of three beats, the same pattern could also easily be perceived as multiples of two (e.g., six) or four (e.g., 12) beats. While the synchronizer may not be consciously counting or dividing the taps into groups, they might perceive the rhythm as a whole, as suggested by their tapping ACs (Vorberg & Schulze, 2002). In this way, the observed AC structure reflects a stimulus-driven (external) timing mechanism, as posited by the neural resonance theory (Comstock et al., 2018). Neural oscillations can synchronize with the external rhythm and produce rhythmic output patterns that are stable over time and exhibit periodicity at multiple lags, without requiring explicit counting or cognitive control (Henry & Obleser, 2012). Future studies could use electroencephalography (EEG) and electromyography to examine whether neural oscillations are being produced at periodicities corresponding to the pattern of the stimulus, or whether subvocalization of explicit counting is a contributing factor, respectively.

Visual Rhythm Perception Accuracy Correlated With SMS Consistency During the Synchronization Phase

One's accuracy in perceiving rhythm perturbations in the visual pattern positively correlated with SMS consistency during the synchronization phase, suggesting that the better one's rhythm perception, the more consistent their SMS performance. The same relationship did not extend to the continuation phase, further suggesting that a different SMS process took place for each phase. Perceived temporal features of the visual pattern played an important role in the synchronization phase, consistent with previous findings that rhythm perturbation detection is a commonly supportive feature of event-based SMS (Delignières & Torre, 2011; Repp, 2010).

We did not find a relationship between visual rhythm perception and self-reported auditory imagery control, potentially explained by a functional dissociation between their underlying mechanisms. The beneficial influence of rhythm perception on SMS was observed only in the synchronization phase, whereas the beneficial influence of self-reported auditory imagery control was observed only in the continuation phase. Together, our results suggest that while a visual stimulus was present, perception of the stimulus was relied upon, whereas when there was no guiding stimulus, auditory imagery was utilized to assist SMS performance. Therefore, our data support there being two strands of beneficial influence on SMS consistency that are relatively independent.

On the other hand, the strong positive correlation observed between synchronization and continuation performance suggests an interconnection between the two phases. It is plausible that despite the absence of a direct association between visual rhythm perception and self-reported auditory imagery control, the top-down mental imagery of a stimulus could transiently influence subsequent bottom-up perceptual processing (Pearson et al., 2008). Alternatively, the potential overlap in SMS processing with the visual stimulus or imagined auditory stimulus might primarily concern the act of coordinating movements (finger taps) rather than the perception of cues (Silva & Castro, 2016).

Musicality Did Not Correlate With Either SMS Consistency or Rhythm Perception

In the present study, synchronizers' self-reported level of musical general sophistication or musical perceptual abilities (an individual component of the Gold-MSI) did not correlate with SMS consistency in the synchronization–continuation task. This contradicts our previous finding of a significant beneficial effect of self-reported musical general sophistication on SMS consistency with a stationary flashing stimulus (Whitton & Jiang, 2023). However, the relationship was only found in the condition with the highest stimulus rhythmic deviation. The increased task difficulty, therefore, might have resulted in the need for musical aptitude and experience to improve SMS consistency.

Contrary to our prediction, neither musical general sophistication nor musical perceptual abilities components of the self-reported Gold-MSI correlated with rhythm perception of the visual pattern. While our study yielded no relationship, previous studies using auditory tones instead of visual patterns have indicated that individuals with a higher level of self-reported musical experience and aptitude demonstrate enhanced rhythmic error detection skills (Matthews et al., 2016; van Vugt & Tillmann, 2014).

Limitations and Future Directions

One limitation of the current study is the possible confound of finger-tapping sensation in the form of kinesthetic input. Although there exist alternative means of recording finger taps besides utilizing a computer keyboard, it is crucial to recognize that any repetitive movement, regardless of the method of recording, can be sensed and potentially utilized during SMS performance. The tapping sensation can potentially serve as an additional external stimulus. Future studies can use EEG to assess neural entrainment during SMS performance with an imagery stimulus, thereby eliminating the need for explicit tapping.

Our results suggest that individuals with higher self-reported control of auditory imagery abilities are better able to predict the timing and rhythm of the visual pattern and are therefore more consistent in their finger-tapping. It would be interesting to see whether our findings can be replicated when auditory imagery control ability is measured by specific imagery tasks (Hubbard, 2013; Tużnik et al., 2018). Additionally, the present research could be further extended to investigate the impact of training on imagery abilities, and the subsequent influence of improved imagery abilities on SMS performance. Training in auditory imagery might improve SMS performance in tasks that require synchronization with a visual pattern, similar to what has been shown after auditory training (Barakat et al., 2015). However, it remains to be established whether and how control or vividness of auditory imagery can be improved through short-term training.

Conclusion

As is commonly found, individuals performed SMS more consistently when a visual stimulus that included apparent motion was present (synchronization phase) than absent (continuation phase). Further, while synchronizers' self-reported control of auditory imagery significantly correlated with their SMS consistency during the continuation phase, their ability to perceive visual rhythm significantly correlated with SMS consistency during the synchronization phase. No correlation was found between visual rhythm perception and auditory imagery control. Combined, our results suggested relatively independent contributions of auditory imagery control and visual rhythm perception to synchronization with visual rhythm.

Constraints on Generality

The goal of the present study was to test our predictions on a sample from the general population. Hence, we sampled from the greater Reno area, including participants not affiliated with the University of Nevada, Reno and from different cultural backgrounds, in an attempt to test a generally representative sample.

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Appendix A

Auditory, Visual, and Kinesthetic Imagery Questionnaire Results

Participant	BAIS-V	BAIS-C	VMIQ-IVI	VMIQ-KIN
1	5.00	5.43	6.00	5.67
2	5.21	5.43	5.58	5.67
3	5.07	5.36	5.83	5.64
4	5.00	4.21	5.25	5.50
5	5.50	5.79	4.33	4.25
6	5.36	4.36	3.92	3.50
7	4.50	3.71	3.50	3.25
8	5.93	6.21	6.58	3.83
9	3.93	4.07	3.83	4.08
10	5.07	4.79	4.08	3.58
11	5.36	6.07	3.83	3.00
12	5.79	6.14	6.83	6.92
13	5.14	5.07	4.92	5.00
14	5.21	5.50	5.67	5.92
15	3.79	2.64	3.25	2.67
16	4.29	4.29	3.50	3.42
17	4.64	2.57	3.92	5.33
18	3.43	4.07	3.58	3.50
19	5.57	4.79	5.08	5.08
20	4.79	5.07	5.83	4.08
21	6.79	6.86	6.17	6.33
22	4.36	4.50	4.33	2.92
23	3.07	3.50	3.83	1.25

Note. Mean responses to the self-reported questionnaires for each participant. BAIS-V = Bucknell Auditory Imagery Vividness; BAIS-C = Bucknell Auditory Imagery Control; VMIQ-IVI = Internal Visual Movement Imagery; VMIQ-KIN = Kinesthetic Imagery.

(*Appendices continue*)

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Appendix B

Gold-MSI Results

Participant	Active engagement	Perceptual abilities	Music training	Emotions	Singing abilities	General sophistication
1	22	36	15	28	17	46
2	60	49	40	41	29	101
3	49	46	35	31	29	92
4	30	39	12	30	25	61
5	34	51	34	31	31	84
6	26	41	28	36	23	62
7	52	56	44	39	44	112
8	36	47	36	33	35	90
9	55	52	8	39	18	57
10	22	44	21	33	24	60
11	41	57	39	42	42	105
12	33	50	25	37	22	60
13	20	40	19	27	23	52
14	33	44	25	34	31	77
15	31	37	20	25	20	50
16	34	43	24	32	31	75
17	30	39	12	33	37	67
18	31	38	23	26	28	66
19	43	34	7	33	11	42
20	38	43	28	31	32	80
21	51	59	38	41	40	106
22	44	48	30	34	33	84
23	24	44	15	31	29	64

Note. Responses to the 38-item self-reported questionnaire generated a score on each factor for the participant. Gold-MSI = Goldsmiths Musical Sophistication Index.

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