Working Memory, Memory for Musical Rhythms, and Rhythm Perception

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Abstract

This study investigated the relation between auditory working memory, rhythmic timing performance, and memory for musical rhythms. Thirty-six participants were asked to perform each of a digit span task, a finger tapping task and a rhythm memory task. A moderate positive correlation was found between auditory working memory capacity – as measured by the digit span task – and memory capacity for musical rhythms. However, rhythmic timing performance and memory capacity correlated only weakly. Furthermore, the influence of memory capacity on rhythmic timing performance showed no interaction with the interval length of the sequences to which participants synchronized. This suggests that working memory capacity does not play an integral role in rhythm production.

Keywords: working memory, rhythm perception, sensorimotor synchronization, time perception.

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Introduction

Time perception can be characterized as the tracking and experience of perceptual events over time. Such a view emphasizes the connection between time perception and memory, as a coherent memory trace of past events appears to be a requirement for perceiving time. It has even been suggested (e.g., by Lewis & Miall, 2006) that time perception is solely dependent on memory traces in working memory.

One aspect of time perception is rhythm perception: the experience of temporal patterns. While both time and rhythm perception are supramodal processes – auditory, visual, and tactile stimuli can all result in time percepts (Hanson, Heron, & Whitaker, 2008) – auditory stimuli tend to dominate over other type of stimuli in the temporal domain (Ortega, Guzman-Martinez, Grabowecky, & Suzuki, 2014). This proves true for rhythm perception, where auditory stimuli take precedence over visual stimuli, and for sensorimotor synchronization where participants are better at synchronizing rhythmic responses to auditory stimuli (Barakat, Seitz, & Shams, 2015; Glenberg, Mann, Altman, Forman, & Procise, 1989; Repp & Penel, 2002). Here, *sensorimotor synchronization* refers to rhythmic coordination of perception and action, where the prototypical sensorimotor synchronization task involves synchronizing finger taps to the beat of a metronome sequence (Repp, 2005).

Given the seeming reliance of time perception on a memory component, and the dominance of auditory stimuli in rhythm perception, *auditory working memory* is a potentially relevant component of rhythm perception. One of the most influential models of working memory is found in A. D. Baddeley and Hitch (1974). It describes working memory as a multi-component system; the component that implements auditory working memory is the called the *phonological loop*. Auditory working memory capacity is commonly measured using a *digit span* task (A. Baddeley, 2000; Hester, Kinsella, & Ong, 2004), in which participants listen to sequences of digits and try to correctly recall as long sequences as possible. Musicians have been shown to have a larger working memory capacity than non-musicians (George & Coch, 2011) and there is a positive correlation between working memory capacity and musical ability (Hansen, Wallentin, & Vuust, 2012). Saito (2001) also found a moderate positive correlation between auditory working memory capacity and performance in a combined rhythm memory and rhythm reproduction task[1] .

Auditory working memory and rhythm perception both have temporal limitations. In Baddeley and Hitch's model of working memory, the phonological loop is assumed to hold acoustic information for up to two seconds (A. Baddeley, 2000). Pöppel (2004) has argued for a two to three second window for temporal integration: events that fall within this window can be united into one percept without effort. Rhythm perception requires the integration of sound events over time and temporal limits of rhythm perception have been modeled as temporal limits in short term memory (Gilden & Marusich, 2009; Grondin, Laflamme, & Mioni, 2015). The proposed limits of rhythm perception range from a little over one second to a couple of seconds. Grondin (2012) notes that when the interstimulus interval (ISI) between consecutive metronome sounds becomes longer than around 1.3 seconds, participants become significantly worse at representing and reproducing the rhythm. The experienced difficulty of synchronizing to a metronome also increases significantly as the ISI of the pacing sequence approaches two seconds (Bååth & Madison, 2012). The temporal limit of *subjective rhythmization* – the subjective grouping of monotone metronome sequences – is in the vicinity of a two-second ISI (Bolton, 1894; Bååth, 2015b). Participants' synchronization to a metronome rhythm becomes more variable as the tempo gets slower, but there is no evidence for a "slower limit" of sensorimotor synchronization beyond which point participants are unable to synchronize (Repp, 2006). However, when asked to tap a self-paced regular rhythm as slowly as possible, participants tend to tap at an interval of around 2.5 seconds (McAuley, Jones, Holub, Johnston, & Miller, 2006). This is sometimes called the *slow motor tempo task* and has been employed both as a measure of the a slower limit of rhythm perception (McAuley et al., 2006) and as a measure of auditory working memory capacity (Drake & El Heni, 2003).

The current study investigates the relation between auditory working memory, sensorimotor synchronization performance, and memory for rhythms. The capacity to memorize rhythms is measured using a novel rhythm span task taken from (Schaal, Banissy, & Lange, 2014). The literature on rhythm perception and memory capacity allows a number of predictions to be made. A first prediction – also made by (Schaal et al., 2014) – is that

[1]Note that this task is presented as a rhythm memory task. However, the rhythms that the participants were required to remember were of low complexity. The task score was based on how well participants could reproduce the rhythms by tapping on a computer keyboard. In my opinion, this makes the task more akin to a sensorimotor synchronization task than a rhythm memory task.

auditory working memory capacity and the capacity to memorize rhythms are positively correlated, possibly as the result of a common underlying mechanism. Second, both a larger auditory and a larger rhythm memory capacity should be related to better performance in a sensorimotor synchronization task. Third, the relation between memory capacity and synchronization performance should be stronger when the rhythms to be synchronized to are relatively slower. As synchronization to slow rhythms requires longer time intervals to be retained and reproduced, a longer memory span should be more beneficial when synchronizing to a slower rhythm. Similarly, there might be a positive correlation between slow motor tempo – as a measure of a slower limit of rhythm production – and memory span.

Method

Participants

Thirty-six participants were recruited through public advertizing (17 women, mean age: 29 years, age SD: 13 years). Twenty-three reported having experience playing a musical instrument where the mean number of years of regular practice was 14 (SD = 13).

Material

A session consisted of four subtasks: a rhythm span task, a digit span task, a sensorimotor synchronization task, and a slow motor tempo task with overt counting. Participants were tested individually in a quiet room. The rhythm span task, the digit span task and the sensorimotor synchronization task began the session, where the order of presentation of these tasks was randomized. The session concluded with the slow motor tempo task. A session lasted on average 45 minutes. All tasks were presented on a computer running the Ubuntu operating system. Audio was presented through a pair of closed headphones in the sensorimotor synchronization task, while in in the digit and rhythm span tasks audio was presented though a pair of multimedia speakers.

Rhythm span task. Participants were asked to listen to two short rhythm sequences of equal length and judge whether they were identical or different. Depending on participant's performance sequences got longer or shorter. A participant who was able to remember and correctly compare longer sequences received a higher *rhythm span* score. The task was modeled after that described by Schaal et al. (2014), which in turn is modeled after the pitch span task described by Williamson and Stewart (2010). The task used identical auditory stimuli and the only difference with respect to Schaal et al. was slight changes in the visual presentation.

The sequences ranged from two to ten beats where one to three notes were played each beat. They were played at 60 beats per minute using 70 ms long triangle wave sounds with a frequency of 440 Hz. Figure 1 shows an example of a pair of four beat sequences where the rhythm differs.

In each trial, the participant was presented with a pair of sequences, in turn, where it was randomized whether the rhythms were to be identical or different. They were separated by a two second pause. The participant was then asked to indicate whether the sequences were identical or different by pressing the right or the left Control key on a computer keyboard. The length of sequences followed a two-up, one-down staircase procedure: The length of the sequences increased after two correct responses and decreased after one incorrect response. The task ended after the sequence length had reversed direction eight times. The final rhythm span score was calculated by taking the mean of the sequence length on the last six trials where the sequence length reversed direction.

Digit span task. This task was identical to the forward digit span task described in the Wechsler Adult Intelligence Scale IV (Wechsler, 2008), with the one difference: the sequences of digits were pre-recorded and played back to the participants using a computer instead of being read by the experimenter. Participants were asked to listen to sequences of digits and repeat them back, in the same order. The first sequence was two digits long and two sequences were presented at each sequence length level. The task terminated when the participant could not remember either of the sequences at the current length level correctly or after two sequences of length nine had been presented. Sequences consisted of the digits "one" to "nine", with no digit being repeated, and were read at a rate of one digit per second. The final digit span score was calculated as the number of correctly recalled sequences; the maximum attainable score was sixteen.

Sensorimotor synchronization task. In this task participants were asked to synchronize finger taps to isochronous metronome sequences. They were instructed to start as soon as a sequence began and to continue to tap until it ended. A custom-built tapping board, consisting of a piezoelectric sensor mounted on a 5 cm^2 piece of corrugated fiberboard, recorded the finger taps (see Bååth, 2011 for details). Participants tapped with their index finger, their hand resting on a foam cushion. The stimuli consisted of isochronous sequences of 440 Hz square wave tones of 20 ms, where each sequence was 31 tones long. They were presented at four tempi, corresponding to tone ISIs of 500, 1000, 2000 and 3000 ms. An Arduino microcontroller was used both for generating the sounds and registring the taps.The task was divided into three blocks of four trials each, one for each ISI level. The order of the trials within each block was randomized. Participants were instructed to tap along to each tone sequence, to start tapping as soon as the sequence began, and to stop tapping when the sequence stopped. Participants were requested not to subdivide the beat in any way, for example, by covert counting or by moving their body.

Slow motor tempo task with overt counting. The same apparatus was used as in the sensorimotor synchronization task with the difference that the finger tapping was self paced. Prior to each trial, participants were instructed to tap a regular beat that was as slow as possible, while still maintaining a regular beat. Participants were asked to refrain from subdividing the taps in any way. To avoid covert subdivision, the participants were instructed to count aloud with each tap, starting from one. These instructions conform to those described by (McAuley et al., 2006), with the addition of the overt counting. The task consisted of three trials of 15 taps each.

Analysis

For the sensorimotor synchronization task, the first four taps in every trial were discarded, so as to use only those taps where the participants had had some time to synchronize to the sequence. For each tap, the tone-to-tap asynchrony was calculated as the time difference between the tone and the tap, where a negative asynchrony indicates that the tap preceded the tone. The asynchrony SD was used as a measure of timing variability and was estimated for each participant and ISI level using the Bayesian hierarchical method described in (Bååth, 2015a). This method was used, instead of the conventional sample SD, as the Bayesian method has been shown to yield more accurate estimates of timing variability when participants synchronize to slow tempo sequences. Timing variability is here used as the measure of performance in the sensorimotor synchronization task where a low timing variability is taken to mean high synchronization performance.

A technical fault with the tapping board meant that data from four participants in the sensorimotor-synchronization task was lost, as well as that from one participant in the slow motor tempo task. Data from both tapping tasks was excluded for one participant who, after the experiment, admitted to having subdivided the beat covertly. Data was excluded from two participants in the sensorimotor synchronization task as analysis suggested that, in many of the trials, they tapped on the off-beat: the time points in between the tones. However, the exclusion or inclusion of this data does not change the result of the experiment as neither estimates, confidence intervals, nor p-values differ substantially depending on whether this data is excluded or retained.

The slow motor tempo for each participant was estimated by first calculating the median intertap interval for each trial, then taking the mean of the three trial medians. The median was used rather than the mean because some participants were found to produce a small number of inter-tap intervals deviating greatly from the norm.

Statistical analysis was performed using the statistical computing environment *R* (R Core Team, 2012). Relationships between the main measures were assesssed using Pearson product-moment correlation, except in the case of timing variability. As timing variability was measured at four different ISIs for each participant, a linear mixed-effects model was used to assess how timing variability changed as a function of the other measures. Mixed-effects model analyzes were performed using the package *lme4* (Bates, Mächler, Bolker, & Walker, 2014).

Results

The following measures were calculated for each participant: A digit span score, a rhythm span score, a slow motor tempo and a timing variability at the four ISI levels. Slow motor tempo was calculated as the average intertap interval and timing variability as the asynchrony SD.

Summary statistics for these measures are presented in Table 1. The distributions of these measures were found to be positively skewed and were therefore log-transformed in the subsequent statistical analysis. Both the median rhythm span and median digit span scores conformed to median scores reported in other studies on similar populations (Salthouse & Saklofske, 2010; Schaal et al., 2014).

A positive correlation was found between the rhythm span and digit span scores ($r(34) = 0.48$, 95% CI: [0.18, 0.70], $p = 0.003$). Figure 2 shows the relation between these measures, including marginal distributions.

The relationship between timing variability and rhythm span score was investigated using a linear mixed-effects model with log asynchrony SD as the outcome variable and ISI, log rhythm span score, and the interaction between ISI and rhythm span score as the predictor variables. The rhythm span score and ISI variables were standardized prior to the regression analysis. As each participant contributes four data points – one for each ISI level – the intercept and ISI effect were treated as random effects by participant. Table 2 shows the estimated regression coefficients. There was a statistically significant effect of ISI and rhythm span score, where participants with a large rhythm span score tended to have lower timing variability. However, no substantial interaction effect was found between ISI and rhythm span score.

Figure 3 shows the effect of ISI and rhythmspan score. The two regression lines were obtained from the coefficients in Table 2 by plugging in the 25% and 75% quantiles of the rhythm span score. The results show a strong effect of ISI, a small constant effect of rhythm span score, but no substantial interaction effect: i.e., the effect of rhythm span score does not change significantly between ISI levels.

The relationship between timing variability and digit span score was investigated again using a linear mixed-effects model, identical to the one described above but with digit span score as the predictor variable. As with the analysis of the rhythm span score, digit span score shows a small but statistically significant effect on timing variability, where participants with a high digit span score tend to have lower timing variability. No substantial interaction effect was found between ISI and digit span score. Table 3 shows the estimated regression coefficients. Figure 4 – made made in the same way as Figure 3 – shows the effect of ISI and digit-span score.

Slow motor tempo showed close to no correlation with digit span score ($r(33) = 0.034$, 95% CI: [-0.30, 0.36], p = .84) and a weak positive correlation with rhythm span score ($r(33) = 0.35$, 95% CI: [-0.018, 0.59], $p = 0.063$). Figure 5 shows the distribution of participants' slow motor tempo. A linear mixed-effects model found no statistically significant effect of slow motor tempo on timing variability.

Discussion

The current study examined the relationship between auditory working memory, sensorimotor synchronization performance, and memory capacity for rhythms. Auditory working memory was measured using a standard digit span task (Wechsler, 2008), sensorimotor synchronization performance was measured as the timing variability in a finger tapping task, and memory capacity for rhythms was measured using the rhythm span task described in (Schaal et al., 2014). Participants were also given a novel slow motor tempo task with overt counting, which aims at measuring a slower limit of rhythm perception. A number of predictions were made regarding the relationship between these measures, based on the current literature on rhythm perception and working memory.

A first prediction was that there would be a positive correlation between auditory working memory capacity and capacity to memorize rhythms. A correlation of 0.48 was found: what is generally considered a moderate positive correlation (Taylor, 1990). To put this in perspective, compare this result with the difference in median rhythm span score between musicians and non-musicians in the study by (Schaal et al., 2014): 4.5 and 3.8 respectively. In this study, the median rhythm span score for the group with a digit span score equal to or above the median was 4.9; that for the group with a digit span score below the median was 3.8. Compared to the difference between musicians and non-musicians (0.67), the difference between the high and low digit span groups is considerably larger (1.1). This suggests that working memory capacity is as strong a predictor of memory capacity for rhythms as being an active musician. That result could be considered surprising, given that musicians spend much of their time practicing rhythms.

A second prediction was that both a larger auditory and a larger rhythm memory capacity should correlate with lower timing variability in a sensorimotor synchronization task. While the effect of rhythm span score on timing variability *was* statistically significant, the effect was not strong. The asynchrony SD and rhythm span score variables were log transformed prior to being entered into the regression analysis, making it difficult to interpret the resulting coefficients (shown in Table 2) directly. However, because the predictors were standardized, it is possible to compare the magnitude of the coefficients. One SD increase in ISI, corresponding here to an increase of 1109 ms, is predicted to increase the log asynchrony SD by 0.83. The effect of rhythm span score is comparably much smaller: a one SD increase in log rhythm span score is predicted to decrease the log asynchrony SD by 0.088. the same decrease in timing variability that would be predicted by decreasing the ISI by 117bms. For example, at an ISI of 1000 ms the predicted asynchrony SD for the group having a below median rhythm span score is 45 ms, for the group having an above median score it is 39 ms. The difference is only 6 ms, which could be a considered a small decrease in timing variability.

The effect of auditory working memory on timing variability was very similar to the effect of rhythm memory capacity, namely, a small but statistically significant effect of digit span score on asynchrony SD, with a larger digit span score predicting a smaller asynchrony SD. Given that sensorimotor synchronization performance is positively correlated with other capacities such as fluid intelligence (Madison, Forsman, Blom, Karabanov, & Ullén, 2009) and simple reaction time (Holm, Ullén, & Madison, 2011), this small effect of memory capacity on sensorimotor synchronization performance weighs against the idea that auditory working memory is an integral part of rhythm perception. Rather, given that working memory is also related to fluid intelligence (Engle, Tuholski, Laughlin, & Conway, 1999), the relation between sensorimotor synchronization and memory capacity can be explained, in part, by that they both correlate with other capabilities.

A third prediction was that the relation between memory capacity and synchronization performance would be stronger when synchronizing to slower sequences. This prediction was based on that synchronization to slow sequences requires longer time intervals to be retained and reproduced, and that a long auditory working memory span would be advantageous for retention of long intervals. The temporal span of working memory has been suggested to be between two and three seconds (A. Baddeley, 2000; Pöppel, 2004), with large individual differences in working memory capacity (Just & Carpenter, 1992); therefore, the effect of working memory span was expected to be especially pronounced for the sequences with an ISI of 2000 and 3000 ms. No such interaction effect was found. As Figure 4 shows, the estimated advantage of having a large working memory span was constant over all ISI levels, this was also the case for rhythm span. Again, the results do not support the view that working memory is integral to sensorimotor synchronization.

The results of the slow motor tempo task showed no substantial correlation with the other measures. One reason might be that the instructions for the slow motor tempo task were open to interpretation, leaving participants free to approach the task in many different ways. A participant might choose to focus on tapping at a very slow tempo, resulting in a more variable response, or on responding consistently, requiring the participant to tap at faster tempo. While slow motor tempo did not show any substantial correlation with working memory capacity, the majority of participants had slow motor tempi in the range of 2000 to 3000 ms, which is also the temporal region of a suggested temporal span of working memory (A. Baddeley, 2000; Pöppel, 2004).

In conclusion, the results suggest that auditory working memory – as measured by a forward digit span task – and memory capacity for rhythms are related. Indeed, a high working memory capacity is as strong a predictor of rhythm memory capacity as extensive musical experience, if not stronger. Auditory working memory and memory capacity for rhythms are also related to sensorimotor synchronization performance, albeit weakly. The influence of memory capacity on synchronization performance shows no interaction with sequence tempo, suggesting that auditory memory capacity does not play an integral role in rhythm production. This is in line with models of rhythm perception, such as that of (Large, 2010), according to which rhythm perception does not depend on an explicit memory component.

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Summary statistics for the main measures.

Measure	Median	25% quantile	75% quantile	SD
Rhythm span score	4.6	3.5	5.2	1.2
Digit span score	10	8	11	2.0
Slow motor tempo	2719 ms	2124 ms	3207 ms	1046ms
Asynchrony SD				
ISI 500 ms	25 ms	23 ms	30 ms	6.1 ms
ISI 1000 ms	39 ms	34 ms	44 ms	19 ms
ISI 2000 ms	112 ms	87 ms	137 ms	32 ms
ISI 3000 ms	216 ms	204 ms	236 ms	44 ms

Table 1

Estimated coefficients for the linear mixed-effects model with rhythm span score as predictor.

Coefficient	Estimate	95% CI	*p*
Intercept	4.26	[4.20, 4.33]	-
ISI	0.83	[0.80, 0.87]	< .001
log(rhythm span score)	-0.088	[-0.15, -0.024]	.011
ISI × log(rhythm span score)	0.0050	[-0.029, 0.039]	.77

Table 2

Estimated coefficients for the linear mixed-effects model with digit span score as predictor.

Coefficient	Estimate	95% CI	*p*
Intercept	4.26	[4.20, 4.33]	-
ISI	0.83	[0.80, 0.87]	$< .001$
log(Digit span score)	-0.077	[-0.14, -0.012]	.027
ISI × log(Digit span score)	-0.0026	[-0.037, 0.031]	.88

Table 3

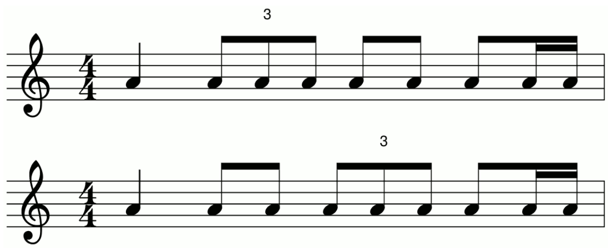

Figure 1. An example of a pair of rhythm sequences from the rhythm span task. In this example the correct reponse would be to indicate that the sequences are different.

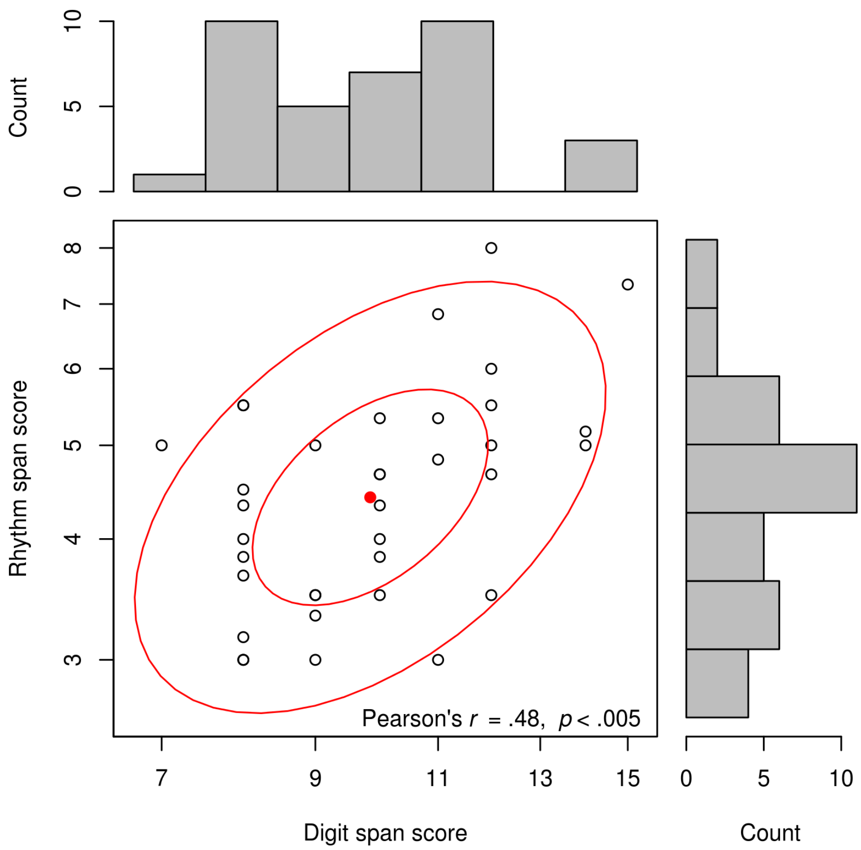

Figure 2. The relation between digit span score and rhythm span score. The ellipses reflect the correlation one and two SD out from the mean, here shown as the filled circle.

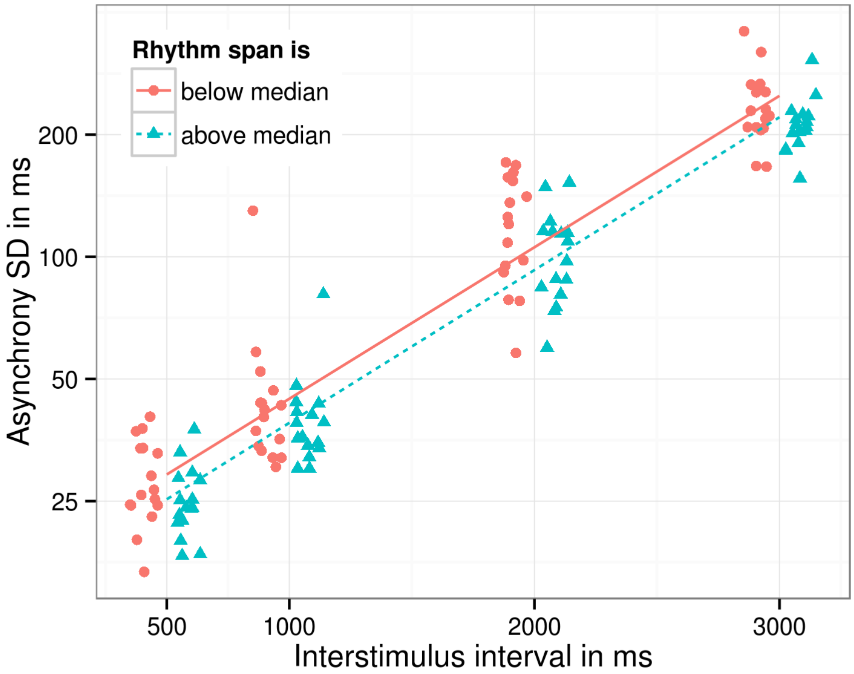

Figure 3. Effect of ISI and rhythm span score on asynchrony SD as estimated using a linear mixed-effects model.

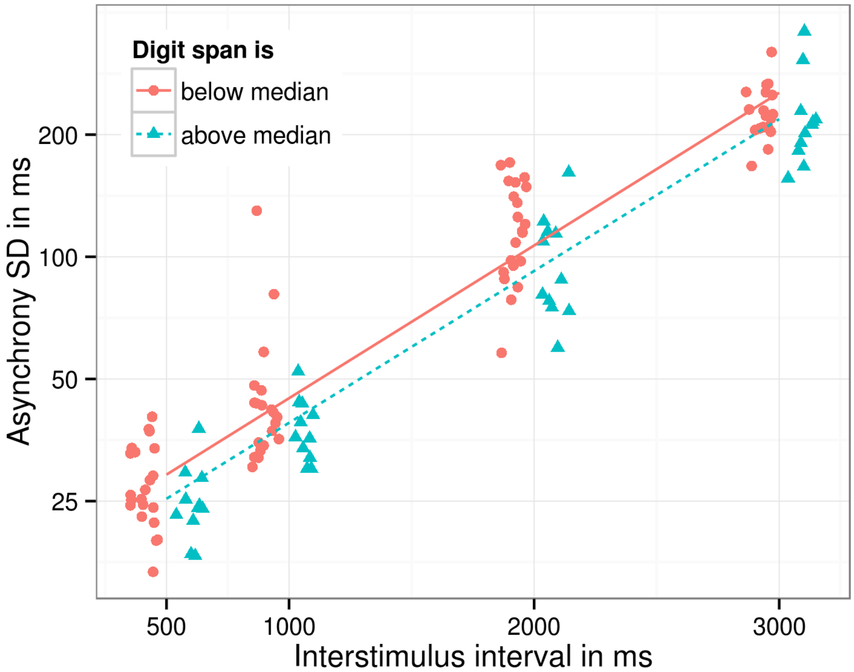

Figure 4. Effect of ISI and digit span score on asynchrony SD as estimated using a linear mixed-effects model.

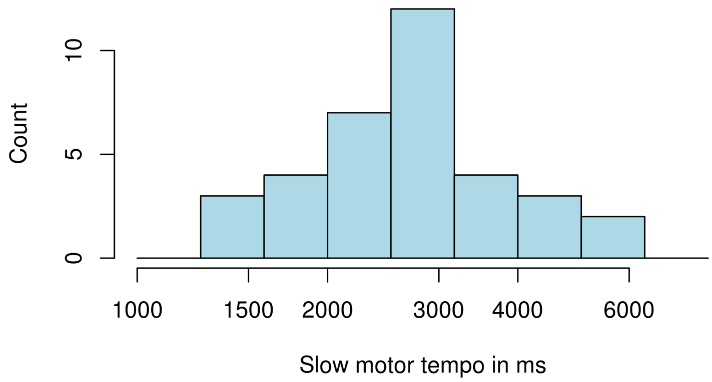

Figure 5. Distribution of participants' slow motor tempo.