Impacts of changing frequency on learning of unstable coordination patterns

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Abstract

Coordinated movement of limbs typify stable behavioral patterns that are easily performed and adaptable to a variety of circumstances. Such stable coordination patterns are naturally present under normal circumstances and do not require learning to achieve. These patterns have been studied alone and between two or more individuals, with emphasis on rehabilitation and athletics. Learning a novel coordination pattern often requires overcoming the intrinsic tendency to coordinate in stable modes such as moving limbs in synchronous cycles (in-phase; e.g. jumping) or opposing cycles (anti-phase; e.g. walking). It has been shown that individuals require a slightly longer period of training to overcome stable coordination patterns. However, the effects of varying the rate of movement (frequencies) of novel coordination patterns during learning have not been well studied. The purpose of this study is to examine the effects of changing frequencies as an amplification of error method for learning an inherently unstable coordination pattern. Error amplification has previously been shown to increase learning. Individuals were tasked with tracing a circle using a vertical and a horizontal movement knob to control an on-screen cursor, similarly to the familiar Etch-a-Sketch toy, by following a target moving continually along the circumference of the circle. Successfully following the target required moving the knobs in an unstable ‘quarter-cycle’ coordination pattern. The movement rate of the target varied between trials for two of the experimental conditions. Error was computed as the Euclidean distance between participant cursor and a moving target. The error difference between pre- and post-trial tests was compared across three experimental conditions (no rate change, gradual rate change, and random rate change). Findings are discussed within a learning optimization framework specific to motor control tasks such as athletic performance and rehabilitation training.

Introduction

Coordination of an individual's limbs in specific ways is essential to the performance of many daily activities, such as walking, running, and cooking. Such actions produced by a single individual are referred to as intrapersonal coordination. Previous research has indicated that there are two naturally occurring stable patterns of intrapersonal coordination. These are referred to as in-phase (same motion of both limbs, e.g., jumping) and anti-phase (opposite movement of both limbs, e.g., walking). Despite the inherent stability of these two patterns, individuals can produce unstable coordination patterns with only several minutes of practice when provided with visual (Kovacs et al., 2020) or haptic (Patton et al., 2006) feedback.

While many take these abilities for granted, there are several important groups which are acutely aware of the complexity involved in such coordination patterns. One such group consists of individuals with certain types of motor disabilities due to issues arising from stroke and other neurophysiological issues (Wolf et al., 2006). The other such group consists of athletes (e.g., jugglers or golfers) (Milanese et al., 2016; Yamamoto et al., 2020). Both groups have considerable interest in the study of best practices for motor learning and/or rehabilitation.

A recent study in Nature found that a "difference in attractor stability might affect adaptability to new constraints" (Yamamoto et al., 2020). Previous research has shown that frequency has a significant effect on coordination dynamics (Amazeen, Schmidt, & Turvey, 1995; Haken Kelso, & Bunz, 1985). This happens because of interference with previously established stable attractors. However, Annand & Grover (2019) did not find an effect of frequency on learning in their recent study. They suggested that the lack of findings regarding frequency may have been because they did not use high enough frequencies to cause a noticeable effect. The goal of this experiment, therefore, was to test increases in both the frequency and variability of frequency during learning of the same Etch-a-Sketch task used in their study. We hypothesized that increases in frequency would decrease intrinsic attractor strength and improve performance and learning.

A secondary hypothesis was that the type of block structure used in learning of the Etch-a-Sketch task would also affect performance and learning. Specifically, we hypothesized that participants in the randomized frequency changes condition would show greater pre/post-test differences than participants in the no frequency change condition due to amplification of error learning (Abdollahi et al., 2013; Patton, Kovic, & Mussa-Ivaldi, 2006; Milanese et al., 2008). However, some research suggests that this might be more important for retention than for initial learning (Shea & Kohl, 1990).

Method

The same device used by Annand & Grover (2019) was used (see Fig. 1 & Appendix A).

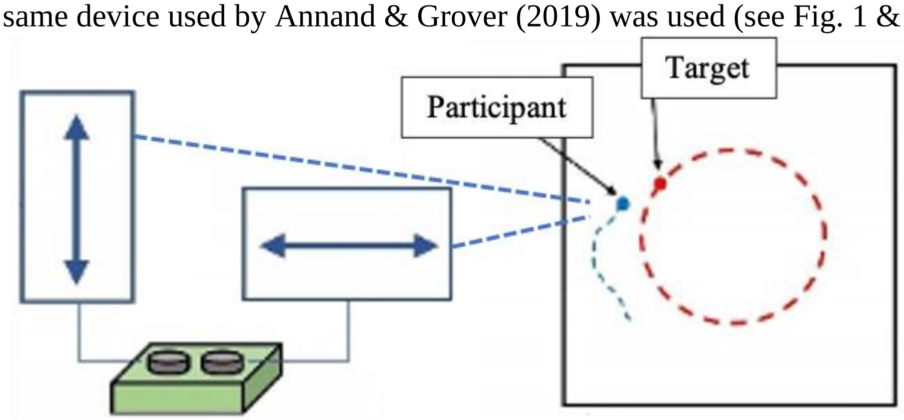

Figure 1. Experimental apparatus. Each hand-turned dial controlled the position of the participant cursor along a respective axis (X and Y). A target cursor oscillated at fixed amplitude and frequency to trace the shape of a circle of fixed size. Perfect performance would be indicated by zero difference in the positions of the participant and target cursor over time. Participants were instructed to try and match the position of the blue dot to the position of the black dot on screen (shown here in red).

RStudio was used to develop an extraction code for the data, which is attached as Appendix B. Prior to extraction, the same pre-processing steps were applied as in the original Etch-a-Sketch experiment (Annand & Grover, 2019), and included the following: (a) cleaning, i.e., removal of values with the same timestamp, or doubled values; (b) truncation of each trial to exactly 60 seconds (or 120 seconds for pre/post trials) from the middle of each trial[1]; (c) resampling of data to ensure each timestep was of equal size, at an average rate of 34 Hz; and (d) rescaling so that the circle radius was equal to 1[2].

Participants & Conditions

32 participants from the University of Cincinnati participated in exchange for course credit. Participants were randomly assigned to one of three conditions: condition 1 (control) with constant frequency (0.38 Hz), condition 2 (collated) with linearly increasing frequency (0.19 – 1.9 Hz in increments of 0.19 Hz), or condition 3 (randomized) with randomized frequency changes (permutation of condition 2). Each of the frequency rates in condition 3 occurred once per block. Conditions 2 and 3 were exposed to a range of frequencies in different orders, while condition 1 served as the control. Participants completed 23 trials with a total time of 26 minutes as follows: (a) a 2 minute pre-test; (b) 20 1-minute trials in their respective condition; (c) a 2-minute post-test at the same rate as the pre-test; (d) a 2-minute post-test at the fastest rate.

Results

No significant differences were found between the 3 conditions, $F(2, 29) = 1.676$, $p = 0.205$. Descriptive statistics for each condition are shown below in Table 1.

Table 1. Descriptive Statistics by Condition

Condition	**Mean**	**SD**	**N**
Control	0.812	0.443	12
Collated	1.090	0.381	10
Randomized	0.844	0.282	10

Both condition 1 and condition 3 appear to have lower differences in error than condition 2 between the pre- and post-tests. This could suggest that those two conditions led to greater learning, although it was not statistically significant over the length of time used in this experiment. Post-hoc comparisons of trial number showed significant differences only for the pre-trial compared to others. These results are similar to those of Annand & Grover (2019), suggesting that unstable pattern learning takes place early and rapidly.

[1] Trials were programmed to record for either 63 or 123 seconds.
[2] The on-screen circle was half the diameter of the screen size, or 512 pixels out of 1024 total. The rescaling was done by subtracting 512 and dividing by 256, which returns a circle radius value of 1.

Within the early learning block (Trials 1-10) condition 2 exhibited a trend of increasing error while condition 3 exhibited a trend of decreasing error (Figure 2). This could suggest that error amplification (condition 3) did improve performance, while conversely the 'easier' condition 2 actually decreased performance. This provides some support for the hypothesis that error amplification via increasing and randomized frequency changes improves initial learning.

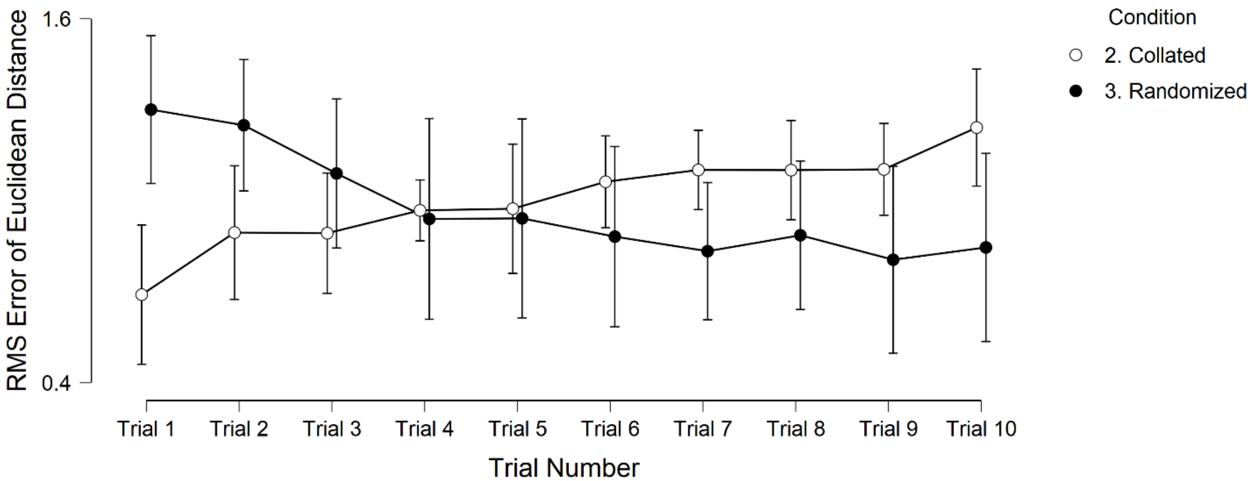

Figure 2. Error trends increased over the first 10 trials for condition 2 and decreased for condition 3, error bars are standard error of mean.

When asked post-experiment if they had any thoughts on the task, many participants observed that the medium to fast frequencies were easier because if they thought too hard about the task, it became much more difficult. For example: "It's harder at slower speeds because you have to think about it more", "Thinking about it makes it harder, just got to get into the zone or rhythm", or "When not thinking about it too much it goes better". Participants who had acquired the desired coordination pattern often took the first 5-15 seconds of a new trial adjusting to the new frequency (including during the post-tests), especially in the random frequency changes condition. This likely increased the calculated Euclidean error during the first portion of trials for that condition. Many participants were also observed to be consistently lagging or leading the target cursor, albeit at the correct frequency with otherwise good accuracy.

Most participants were unable to maintain position with the target cursor for more than 5-10 seconds at 1.71 & 1.9 Hz (the highest frequencies used), although they had usually acquired the desired coordination pattern. Only two participants seemed completely at ease during the two highest frequencies, and likely could have succeeded at higher frequencies. Some participants could acquire the desired coordination pattern required for drawing circles but had considerable difficulty in doing this while matching the target cursor. This was true even if their frequency largely matched that given for the trial, which increased their computed error. A few participants were observed performing either in-phase or anti-phase coordination patterns (diagonal lines up or down in either direction) during the learning phase, which is unsurprising given the previously established inherent stability of these patterns.

Discussion

The lack of significant results was surprising, considering that previous literature has shown significant effects of frequency on coordination dynamics. For example, Kelso reported that “abrupt phase transitions…occur between two hands in humans when the movement cycling frequency is continuously increased” (Kelso, 1984). While the range of frequencies used here was much greater than that used by Annand & Grover (2019), it is possible that the frequency required to cause a phase transition which would significantly affect learning was not reached. Kelso found that the mean preferred frequencies for unresisted experiments (in which external pressure was not applied to participants limbs, such as the present study) was 1.81 Hz, which is slightly between the penultimate and highest speeds used in this experiment. However, the mean transition frequency (the frequency at which participants will shift from one type of coordination, such as in-phase, to another, such as anti-phase) for a 1:1 coordination movement (equal movement required of both limbs, as opposed to 2:1 or other frequency ratio in which one limb moves a certain amount more than the other per cycle) was found to be 2.34 Hz, while the highest frequency used in the present experiment was 1.9 Hz.

Despite the lack of significant results in the current study, error amplification has been shown to provide a small but significant benefit to individuals with chronic hemiparesis (Abdollahi et al., 2013). However, visual error augmentation was combined with haptic error augmentation in that study, which should be considered for future research of this kind and could be a reason for the lack of significant results here. A large study of constraint induced therapy for patients with predominantly ischemic stroke, involving haptic constraint (a different form of error amplification) of the less-affected hand, showed statistically significant improvements in arm motor function lasting through a follow-up period of one year (Wolf et al., 2006). As previous research has shown error amplification benefit for motor rehabilitation, there may still exist some benefit for this kind of task as well, although it was not discovered here.

A possible explanation for most participants inability to consistently match higher frequencies in the present experiment is that for this type of bimanual coordination the ceiling had been reached, and further increases in frequency would not generally yield better results. Future studies should consider increasing frequencies past 2.34 Hz to elucidate this point. Further research should also consider adding a warm-up period like that used by Floyer-Lea & Matthews to prevent increased error during the initial portion of each trial or block, depending on experimental structure.

Research into the functional neuroanatomical changes related to motor learning could provide further insights into possible strategies for improved recovery after brain injury leading to motor disability. For example, Floyer-Lea & Matthews found in a study using fMRI of a similar task to that used in the present study that the initial stage of learning was associated with greatest activity in widely distributed cortical regions, including prefrontal, bilateral sensorimotor, and parietal cortices. As performance improved, activity in these regions decreased simultaneous with an increase in subcortical motor regions including the cerebellar dentate, thalamus, and putamen. They discuss the relation of task automaticity to these functional changes and suggest that further research using similar methods may allow “functional ‘dissection’ of pathologies of motor control and their responses to treatments.” This would be of great value to both athletes and those suffering from various motor control disorders and is recommended for future research.

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