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ISOMETRIC FORCE ENTRAINMENT DEPENDS ON TEMPORAL LOCATION OF VISUAL INFORMATION AND SIGNAL PREDICTABILITY

MOLLY M. MAZICH
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Reviewed and approved* by the following:

Karl M. Newell
Professor of Kinesiology and Biobehavioral Health
Marie Underhill Noll Chair
Head of Department, Kinesiology
Thesis Supervisor

Jinger S. Gottschall
Assistant Professor of Kinesiology
Honors Adviser

* Signatures are on file in the Schreyer Honors College.

Abstract

The purpose of the present study was to investigate the effect of past and/or future information and it's predictability on accurately entraining to a signal in the environment. Participants were asked to produce isometric force via abduction of the right index finger to match 1/f-like waveforms with varying predictability (sine wave, brown/pink, and white noise). The visual condition was manipulated so that only current information, only future information, only past information, or both past and future information about the target waveform was available. For predictable waveforms, subjects entrained locally and thus future information about the target waveform lead to improved performance on local variables such as root mean squared error (RMSE), lead/lag, and correlation coefficient. For unpredictable waveforms, subjects entrained globally so that only the presence of information about the target waveform mattered, and not it's positioning. This was reflected by there being no influence of visual condition on global variables such as Approximate Entropy (ApEn), spectral slope and proportion of power. For target waveforms with some degree of predictability, both local and global entrainment occurred. The emphasis on local or global entrainment was dependent upon the predictability of the isometric force target and its interaction with the information available about the past and/or future properties of the signal.

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Acknowledgments

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Introduction

In everyday life people encounter situations that vary in both predictability and the availability of relevant information. Sometimes behavior is reactive because the environment is characteristically unpredictable or because there is no information about the future provided. While at other times behavior is anticipatory because the future state of the environment is known or can be predicted. Entrainment of movement to continuous environmental signals involves both internal feedback and feedforward mechanisms operating on characteristics, such as predictability, of the environment (Nijhawan, 2008; Sosnoff & Newell, 2005; Sosnoff, Valantine & Newell, 2009). A key question is what placement of information, in the future, past or both, is most beneficial to accurate coordination with, or entrainment to, signals in the environment.

A significant amount of research has been dedicated to studying human entrainment to highly predictable signals (Delignieres, Lemoine, & Torre, 2004; Gilden, 2001; Gilden, Thorton, & Mallon, 1995; Repp 2005; Ward, 2002). Although some aspects of the environment in which people live and interact are predictable, often times they are not. One way to determine the predictability of a signal is to examine the frequencies present in the signal. In the power spectrum, predictable signals tend to have more power at one or two frequencies and thus a steeper spectral slope (>-2), while an unpredictable signal (e.g. white noise) has equal power at all frequencies and thus a spectral slope of 0. Physical and biological processes often times have power spectra between white (random) and black (predictable) noise (Gardner, 1978; Handel & Chung, 1993; Press, 1978; Voss & Clark, 1975, 1978; West, 2006). People typically interact with somewhat unpredictable environments, and therefore it is useful to examine entrainment to less predictable signals with spectral slopes between -3 and 0 (Large, Fink, & Kelso, 2002; Smithson, 1997; Sosnoff et al., 2009; Stephen, Stepp, Dixon, & Turvey, 2008).

Sosnoff et al. (2009) found that humans were capable of producing isometric force signals with spectral slopes between those of highly predictable and random noise. When asked to produce force output signals that matched target waveforms with different 1/f structures, the spectral slope of the participants' force output signal was reflective of the signals' spectral slope when the target waveform had up to 12 Hz fluctuations. The predictability of the participants' force output signal also reflected the degree of predictability of the target waveform, with the force output becoming more predictable (lower ApEn) as the target waveform became more predictable. Thus, humans are capable of producing a range of 1/f behaviors that vary with the goals of the task (Sosnoff et al., 2009).

Pew (1974) had subjects perform arm movements according to a random sequence on a screen. Unbeknownst to the participant, the middle 20 s of the task was the same for each trial (unrepeated) while the beginning and end of the sequence were repeated. After many repetitions, performance improved in terms of the integrated absolute error score for the repeated portion of the pattern but not for the unrepeated portions. Even though the participants were unaware of the repetition in the pattern, it aided their performance. When the repeated pattern was reversed, the participants also performed better, which suggests that the participants ability to entrain to the pattern was more general than specific.

The concept of general versus specific entrainment has been discussed as a difference between global and local entrainment. Furthermore, it has been suggested that entrainment to unpredictable signals depends at least partially on the ability of the participant to pick up on global characteristics of the signal. Rankin, Large, and Fink (2009) investigated how people adapt tapping performance to fluctuating tempi in music performance. The task involved listening to a musical performance and tapping the beat at a ¼ or $^{1}/_{8}$-note level while matching natural tempo changes in the music. Successful completion of the task (adjusting tapping to tempo changes) involved predicting the changes through long range correlations (global characteristics) and fractal scaling. The use of long range correlations to predict tempo changes relies on the existence of persistence whereby changes early in the sequence could be used to predict changes later in the sequence. Participants used fractal scaling, meaning that lower level fluctuations in the metrical structure ($^{1}/_{16}$-note) were used to predict higher level fluctuations in the metrical structure ($^{1}/_{4}$-note) (Rankin et al., 2009).

Synchronization of tapping to an unpredictable (chaotic) metronome signal has been investigated by Stephen et al. (2008). Because the participants' tapping performance had both predictive and reactive aspects, it was hypothesized that they were synchronizing on longer-term time scales rather than short-term ones. Long range fluctuations in the metronome and the tapping behavior were correlated, which also suggested more global synchronization. For unpredictable signals it appears as though synchronization (or entrainment) depends on the ability of the participant to pick up on the long-term time scale (global) characteristics of the signal rather than the short-term time scale (local) characteristics of the stimulus signal.

Research involving entrainment to unpredictable signals has, to date, always involved the participant being able to see the entire waveform of the target signal (Michael & Jones, 1966, Sosnoff et al., 2009). Spectral characteristics of performance around 5 Hz are often attributed to feedback control. Feedback control can also be assessed via looking at the lag between performance and the target signal. As the predictability of the signal decreases, the time lag between performance and signal tends to increase (Michael & Jones, 1966). This suggests that participants need more time to process the available visual information and translate it into movement when the signal is less predictable (Michael & Jones, 1966). Feedforward processes, on the other hand, are thought to operate at frequencies faster than reaction time (100-200 ms) (Miall, Wehr & Stein, 1985; Carlton, 1981). It is not understood as to whether these feedforward processes rely mainly upon future or past information in the signal.

In a recent isometric force production study, Studenka and Newell (2012) investigated the role of visual information about the past and future target signal on a participant's ability to track the waveform. The target signals had different levels of predictability and included sine wave, brown, pink, and white noise structures. The time windows of available information were also manipulated. The time window for past information was 0 ms or the full waveform. The time window for the future waveform was 0, 83, 125, 250 ms, or the full waveform. When past information was present, the future time window had no effect on the accuracy or the structure of the isometric force signal produced by the participant. In the absence of past information, the effect of the future time window depended on the predictability of the target signal. For predictable signals, the root mean square error of the participants' isometric force output signal was lower and there was less error when more future information was present. For unpredictable signals, as the duration of information about the future increased, the irregularity of the force output increased (higher ApEN values), the spectral slope decreased, the proportion of power between 0-4 Hz was lower, and the proportion of power between 4-12 Hz was higher. The duration of future time window only influenced performance when past information was not available, indicating that a greater duration of total information enabled the participant to better replicate the unpredictable signal. For unpredictable signals, the total duration of information mattered, not where it was.

The optimal duration of information used in entrainment appears to be around 2000 ms (Land & Lee, 1994). Wallis, Chatziastros, Tresillian and Toasevic (2006) investigated the role of visual feedback on a steering task during simulated driving in which the goal was to reduce heading error. They found that 417 ms of feedback at the midpoint of the steering task was required to successfully complete the task with the highest amount of accuracy. With 800 ms of feedback information at the midpoint, the most inaccurate participants could produce the correct behavior to complete the task. They also found that the sooner the feedback information was provided, the greater the response (error correction) in the second half of the task was and thus the task was performed with more accuracy. This indicates that visual feedback is used to improve task performance and that most people benefit from between 417 ms and 800 ms of feedback information. The total time window used in the present study was 2000 ms allowing for 1000 ms of past and 1000 ms of future information in the condition with both past and future information.

The present study differs from the work of Studenka and Newell (2012) in a key way. In the present study, the time window of available information was held constant. The time window, no matter what its placement in terms of past or future information, spanned 2000 ms of the target signal. In the previous study, the time window length varied depending on how much information about the signal in the future and past was present. This difference is important because it helps to distinguish how a participant's ability to replicate the target signal was affected by the location, not the duration of information about the target waveform

In entrainment, the relationship between the placement of the time window of visual information (visual condition) and the predictability of the target signal has not been well established. The present experiment investigated whether placement of visual information in the future, past or both is most important for entraining to signals in the environment and how the predictability of the signal affects which placement of visual information is most useful. Participants were asked to track 3 different target waveforms, a sine wave (0.5 Hz), a waveform with noise between brown and pink (brown-pink), and a waveform with white noise. Participants tracked waveforms in 4 different visual conditions, one with 1000 ms of information about the past waveform and 1000 ms of information about the future waveform, one with 2000 ms of information about the waveform in the future, one with 2000 ms of information about the waveform in the past, and one with only current information about the waveform. We were interested in how well participants could entrain to waveforms with different predictability and different placement of visual information.

It was hypothesized that the predictability of the waveform and the visual condition would interact to determine the participants' ability to entrain to the waveform. More specifically, if participants were using local entrainment for target waveforms with some predictability (sine wave and brown-pink), the placement of visual information about the future would be more important for entrainment to the waveform. Here, "local" implies control over short time scales, which means that immediately upcoming information (future) would be useful. This effect was expected in variables that measure how closely performance matched the local characteristics of target waveform such as RMSE, lead/lag and correlation coefficient. We hypothesized that having future information would lead to lower RMSE and lead/lag and higher correlation coefficient over having past-only or only current information.

It was also hypothesized that, as the predictability of the target waveform decreased, more evidence of global entrainment would be observed. For entrainment to the white noise and the brown-pink target waveform it was expected that only the presence of visual information would matter, and therefore the placement of visual information (visual condition) would not influence variables that measure the long-term, more global, structure of the waveform (slope, ApEn, and proportion of power). We predicted that performance with respect to these variables would match the target waveform more closely when visual information about the past, future or both was present compared to when only current information about the target waveform was present.

Methods

Participants. Twelve healthy undergraduate and graduate students (6 females, 6 males) at the Pennsylvania State University voluntarily participated in this study. The mean age of participants was 21.3 (± 2.50) years. All participants were right hand dominant. All participants gave informed consent to the procedures that were approved by the University Institutional Review Board.

Apparatus. Participants were seated at a table with a 14 inch LCD (SyncMaster, 712n, Samsung) monitor positioned in front of them on the table. In front of the LCD monitor, 42 cm from the edge of the table, there was a Entran EL load cell (diameter 1.27cm; Fairfield, NJ,USA) mounted on the right side of a wooden block so that it was normal to the table and on the right hand side of the participant. The participant positioned his/her right hand so that it was pronated, resting to the right of the load cell with only the right index finger coming into contact with the load cell and all other fingers resting in a neutral position on the table. In order to produce a recordable abduction/adduction force using the index finger alone against the load cell, each participant was instructed to position their index finger so that the lateral side of the distal interphalangeal joint was in contact with the load cell. The index finger was not in contact with the table. A Coulbourn (V72-25; Coulbourn Instruments, Whitehall, PA) resistive bridge strain amplifier was used to amplify the output from the load cell. The amplifier had a gain of 100 and an excitation voltage of 10 V. Samples of the force output were taken by the amplifier at a frequency of 100 Hz.

During the trials, the target waveform was represented in red (1 pixel wide) and a larger (4 pixel) red dot represented the instantaneous position of the target waveform. As a participant began to produce force, a white waveform appeared on the monitor, and represented the participants force output. Both the red waveform/dot and the white waveform moved across the monitor in real time during the trial.

Instructions and Procedures. To begin, the participants' maximal voluntary contraction (MVC) was obtained. To obtain the MVC, the participant was instructed to produce a maximal abduction force against the load cell using their right index finger during 3 trials, each 5 s in duration. The MVC was calculated as the average of the maximal forces produced during the 3 trials.

After the MVC was determined, each participant performed 5 practice trials to familiarize him/herself with the task. The practice trials included 3 sine wave targets, 1 brown-pink noise target, and 1 white noise target. The practice trials also included all possible visual conditions (past and future, past only, future only, and current information)

After the practice trials, there were 3 blocks of trials each with a different target waveform and each containing 4 different visual information presentations. The target waveform (red) was centered at 10% of the participants MVC and the waveform scaled from 5 to 15% of MVC. The 4 different visual conditions within each block included past-future (1000 ms of the past and 1000 ms of the future target waveform), future-only (2000 ms of the future waveform), past-only (2000 ms of the past waveform), and current information (only instantaneous position). There were 4 trials of each visual condition per block for a total of 48 trials. Unique waveforms were created for each of the brown-pink and white noise trials. The waveforms that were created were filtered so that they contained fluctuations from 0 to 12 Hz. Each waveform spanned 20 s. The root mean square error (RMSE) was presented to the participant on the monitor at the conclusion of each trial, and indicated the average difference of the participants' force output signal from the target waveform.

For each trial block, the participant was instructed to abduct and adduct the index finger while in contact with the load cell so as to produce a waveform that matched the target waveform on the monitor. Abducting the index finger caused the force output signal to move upward on the screen while adducting the index finger caused the force output signal to move downward on the screen. Each participant was told to try to match the output signal as precisely as possible to the target waveform by replicating as many of the peaks and valleys of the target waveform as possible with their force output signal.

Experimental Design. The experiment was a 3 waveform by 4 visual condition design. The waveforms were a sine wave, noise between brown and pink noise (brown-pink noise) and white noise. The visual conditions were past-future (1000 ms each of future and past target waveform), future-only (2000 ms), past-only (2000 ms), and current information (only instantaneous position). The waveforms were presented in blocks and within each waveform block there were blocks of four trials for each visual condition. The presentation of both the waveform blocks and the visual condition blocks within each waveform block were balanced.

Data Collection. The present design considered dependent variables in the time and frequency domains. Task performance was assessed by calculating the root mean square error (RMSE) for each trial. Smaller RMSE scores indicated that the participant's output signal was closer to the target signal. Approximate entropy (ApEn) was used to evaluate the irregularity of the force output. Smaller values of approximate entropy indicated more regularity and predictability of the signal. Proportions of power between 0 - 4, 4 - 8, and 8 - 12 Hz as well as spectral slope were used to evaluate the frequency characteristics of the force output signal produced by the participant. The spectral slope was assessed from the log log plot of the power versus the frequency characteristics of the signal. Phase lag was assessed by shifting the participants' force output forward and backward in time with respect to the waveform. The lag value indicated the duration of lag between the target and force production when RMSE was minimized. The data analyzed for each trial did not include the first 4 s or the last 1 s of the trial. The significant p-value was less than 0.05 for all statistics.

Results

RMSE

RMSE measured in %MVC as a function of waveform and visual condition is shown in Figure 1. A two-way (waveform x condition) repeated measures ANOVA showed that RMSE decreased as the target waveform became more regular, F (2,22)=5.11, $p<0.05$. A main effect of visual condition, F (3,33)=3.24, $p<0.05$, and a visual condition by waveform interaction were also significant $F(6,66)=8.35$, $p<0.01$.

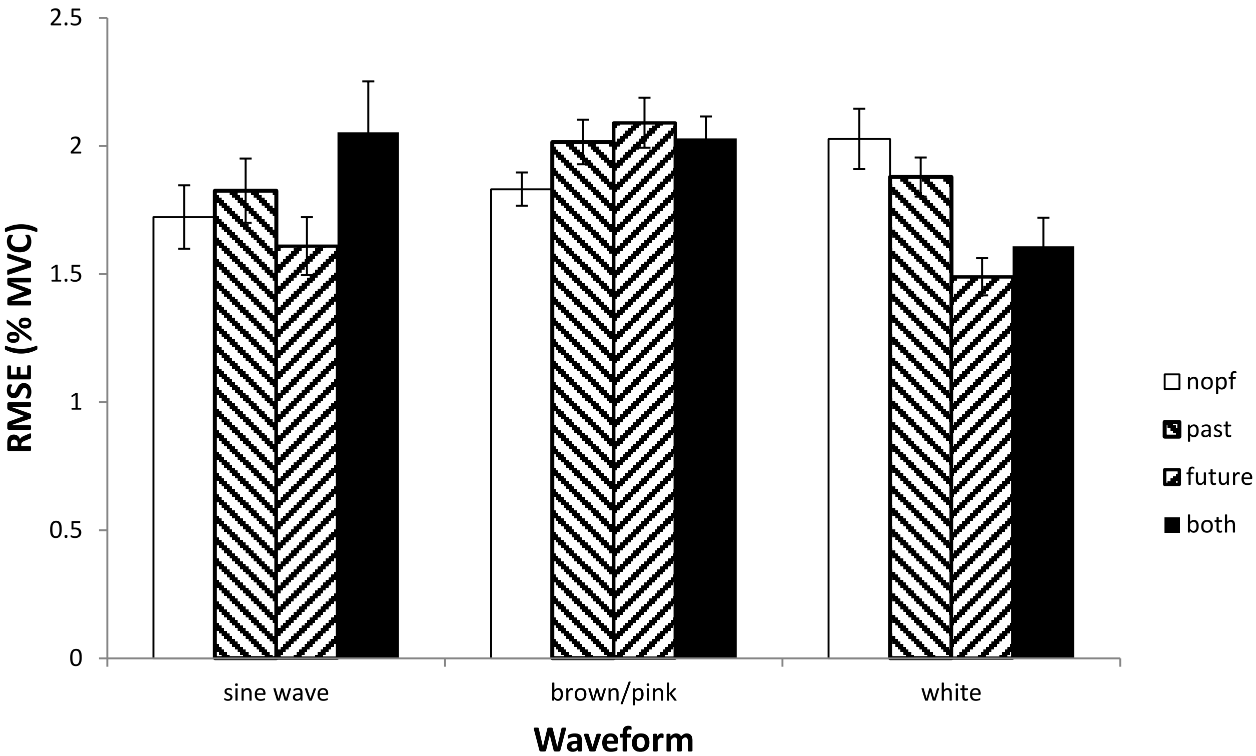

Figure 1. Mean RMSE (%MVC) as a function of target waveform and visual condition

A least significant difference test was performed on the means for target waveform and visual condition. RMSE for the force output to the sine wave (1.8%) was significantly lower ($p<0.05$) than for the white noise target waveform (2.0%) but not the brown-pink noise target waveform (1.8%) ($p=0.569$). RMSE for the force output to the brown-pink noise target waveform (1.8%) was significantly lower ($p<0.01$) than for the white noise target waveform (2.0%).

Within the sine wave target waveform, participants traced the target waveform more accurately (lower RMSE) when only future visual information (1.61%) was available as compared to when both past and future (2.05%) and only past information (1.82%) was available, $F(1,66)= 18.65$, $p<0.05$, $F(1,66)=4.41$, $p<0.05$, indicating that future information helped them trace the signal. Additionally, RMSE was lower when only current information was available (1.72%) than when both past and future (2.05%) information was available, $F(1,66)=10.33$, $p<0.05$. Participants had significantly greater RMSE when both past and future information (2.05%) were available compared with when only past information (1.82%) was available, $F(1,66)= 4.92$, $p<0.05$.

Within the brown-pink noise waveform, subjects were able to trace the target waveform better when they had only future information (1.49%) compared to when they had only current information (2.03%), or only past information (1.88%), $F(1,66)=27.25$, $F(1,66)=14.27$, $p<0.01$. Performance was significantly more accurate when participants had both past and future information (1.61%) than only past (1.88) and only current information (2.03%), $F(1,66)= 6.85$, $p<0.05$, $F(1,66)=16.48$, $p<0.01$. These findings indicate that future information was beneficial to a participants' ability to trace the target waveform.

Within the white noise waveform, participants were able to trace the waveform better when only current information was available (1.83%) as compared to when only future information (2.08%) was available, $F(1,66)=6.31$, $p<0.05$.

ApEn

The irregularity of the force output signal was measured using ApEn (Figure 2). A two-way repeated measures ANOVA showed that the ApEn of the force output increased as the target waveform became less predictable, $F(2,22)=404.34$, $p<0.01$. There was no main effect of visual condition, nor was there an interaction between visual condition and target waveform, $p>0.05$.

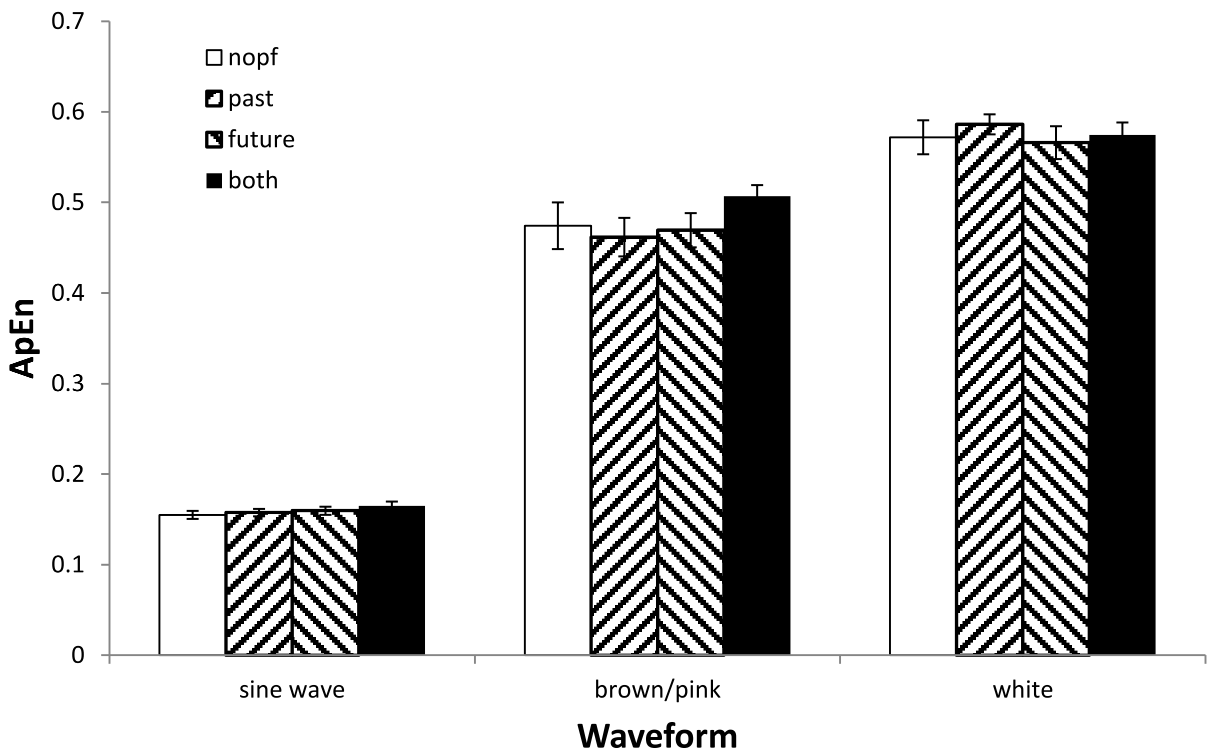

Figure 2. Mean ApEn as a function of target waveform and visual condition

A least significant difference test was performed on the means for target waveform and visual condition. ApEn of the force output for the white noise waveform (0.575) was significantly higher ($p<0.01$) than for the brown-pink noise waveform (0.478) and the sine wave (0.159). ApEn of the force output for the brown-pink noise waveform (0.478) was significantly higher ($p<0.01$) than for the sine wave (0.159).

There was no significant effect of visual condition on ApEn in the sine wave or white noise target waveform conditions, indicating that the placement of available visual information did not affect the participants' ability to scale the irregularity of their force output with the irregularity of the target sine or white noise signals. In the brown-pink noise target waveform condition, the irregularity of the force output signal was greater when past and future information was available (0.51) than when only current information (0.47), only past information (0.46) and only future information (0.47) was available, $F(1,66) = 5.20$, $p < 0.05$, $F(1,66) = 9.95$, $p < 0.01$, $F(1,66) = 6.90$, $p < 0.05$.

1/f Slope

Spectral slope as a function of target waveform and visual condition is shown in Figure 3. The spectral slope of the produced force output became more shallow as the predictability of the target waveform decreased, $F(2,22) = 121.53$, $p < 0.01$. There was no main effect of visual condition, nor was there a significant interaction between visual condition and target waveform, $p > 0.05$.

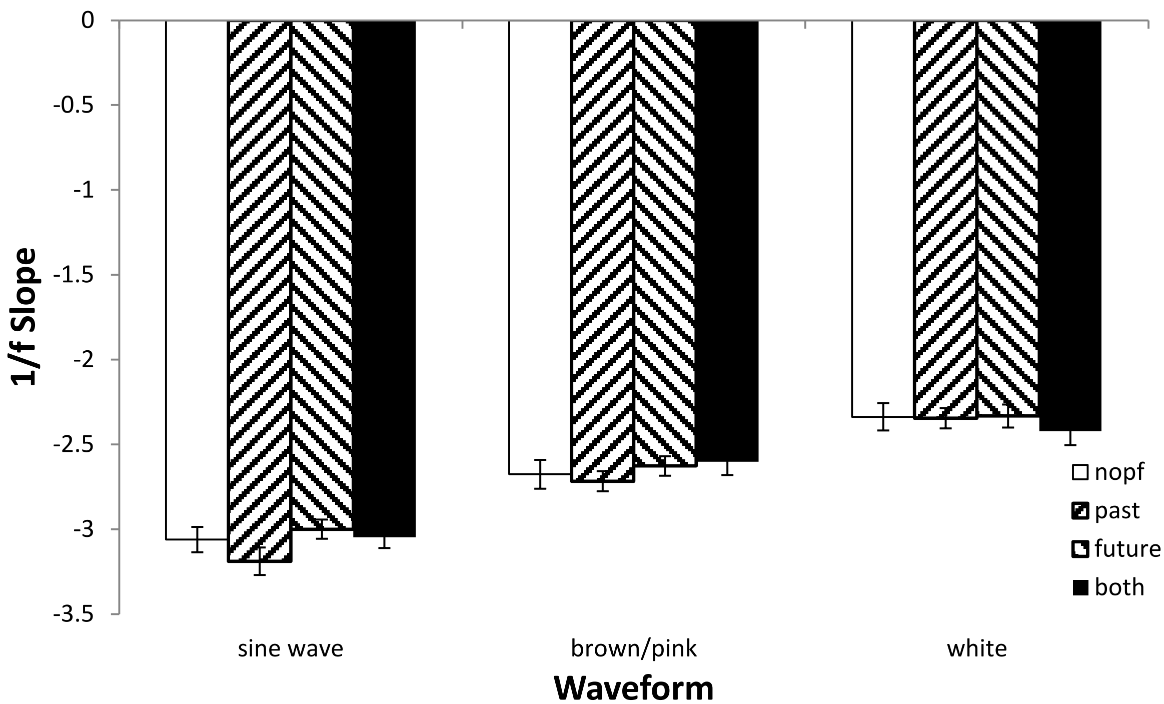

Figure 3. Mean spectral slope as a function of target waveform and visual condition

A least significant difference test was performed on the means for target waveform and visual condition. Spectral slope of the force output for the sine wave target waveform (-3.074) was significantly steeper (p<0.01) than for the brown-pink noise target waveform (-2.656) and the white noise target waveform (-2.360). Spectral slope of the force output for the brown-pink noise target waveform (-2.656) was significantly steeper (p<0.01) than for the white noise target waveform (-2.360).

Within the sine wave target condition, participants produced signals with significantly steeper spectral slopes (characteristic of the sine wave), suggesting that they were entraining with more accuracy, in the past-only visual condition (-3.19) compared to the current information (-3.06), past-future (-3.05) and future-only (-3.00) visual conditions, $F(1,66)=5.26$, $F(1,66)= 6.40$, $F(1,66)=11.55$, p<0.05, p<0.01. In the brown-pink and white noise target waveform conditions there was no significant effect of visual condition on spectral slope indicating that the placement of visual information had no affect on the participants' ability to scale the slope of their force output with the slopes' of the target waveforms.

Proportion of Power

Proportion of power from 0-4, 4-8 and 8-12 Hz as a function of target waveform and visual condition can be seen in Figures 4, 5 and 6, respectively. An arcsine transformation was performed on the data before the ANOVA's were run because the proportion of power represented in the signal was originally collected as a percentage value. As the target waveform became less predictable, the proportion of power between 0-4 Hz was lower, $F(2,22)=59.59$, $p<0.01$. Proportion of power was higher between 4-8Hz and 8-12Hz as the target waveform became less regular, $F(2,22)=57.61$, $p<0.01$, $F(2,22)=92.58$, $p<0.01$, respectively. There was no main effect ($p>0.05$) of visual condition on proportion of power from 0-4, 4-8 and 8-12 Hz, $F(3,33)=1.06$, $F(3,33)=1.04$, $F(3,33)=2.09$, $p>0.05$, respectively. The influence of visual condition did not differ significantly as a function of the target waveform for proportion of power from 0-4, 4-8, or 8-12 Hz, $F(6,66)=1.19$, $F(6,66)=1.18$, $F(6,66)=1.11$, $p>0.05$, respectively.

A least significant difference test was performed on the means for target waveform and visual condition. Figure 4 shows proportion of power between 0-4 Hz as a function of target waveform and visual information condition. Proportion of power between 0-4Hz was significantly ($p<0.01$) greater for the sine wave target waveform (0.996) than for the brown-pink noise target waveform (0.890) and the white noise target waveform (0.703). Additionally, proportion of power between 0-4 Hz was significantly ($p<0.01$) greater for the brown-pink noise target waveform (0.890) than the white noise target waveform (0.703).

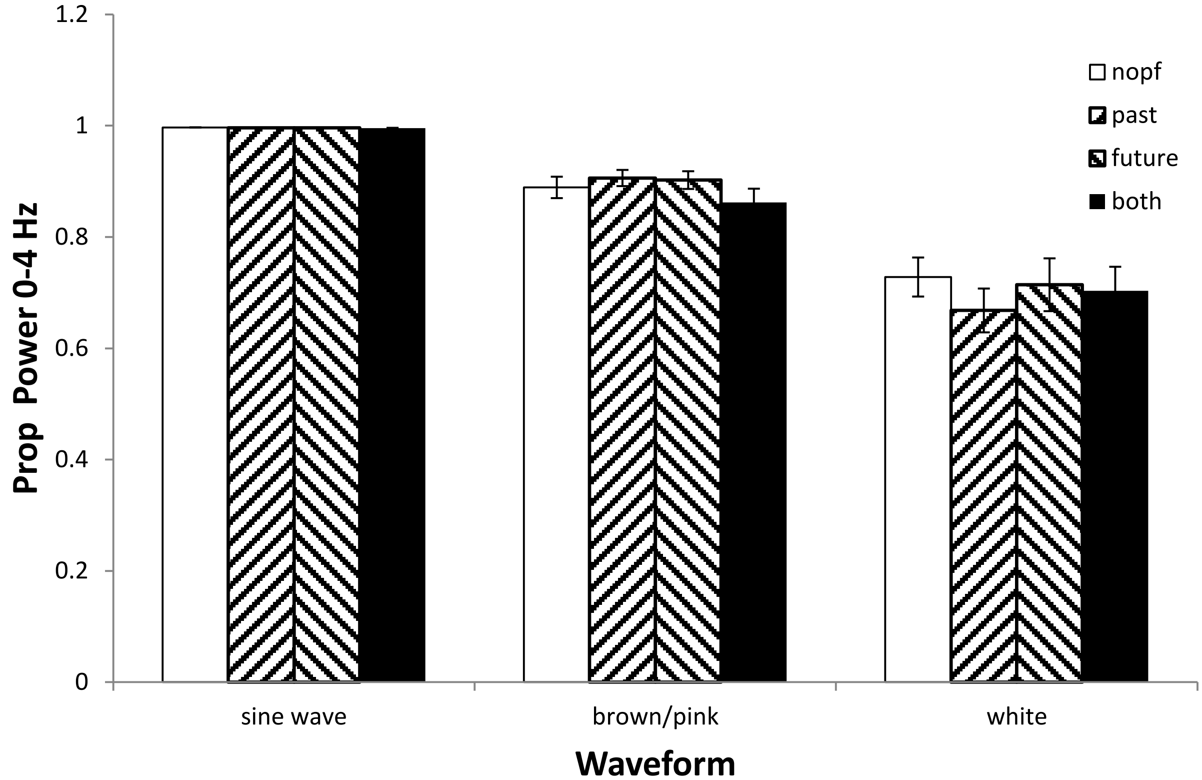

Figure 4. Mean proportion of power from 0-4 Hz as a function of target waveform and visual condition

Figure 5 shows proportion of power between 4-8 Hz as a function of target waveform and visual information condition. Proportion of power between 4-8 Hz was significantly ($p<0.01$) greater for the white noise target waveform (0.290) than for the brown-pink noise target waveform (0.106) or the sine wave target waveform (0.003). It was also significantly ($p<0.01$) greater for the brown-pink noise target waveform (0.106) than for the sine wave target waveform (0.003).

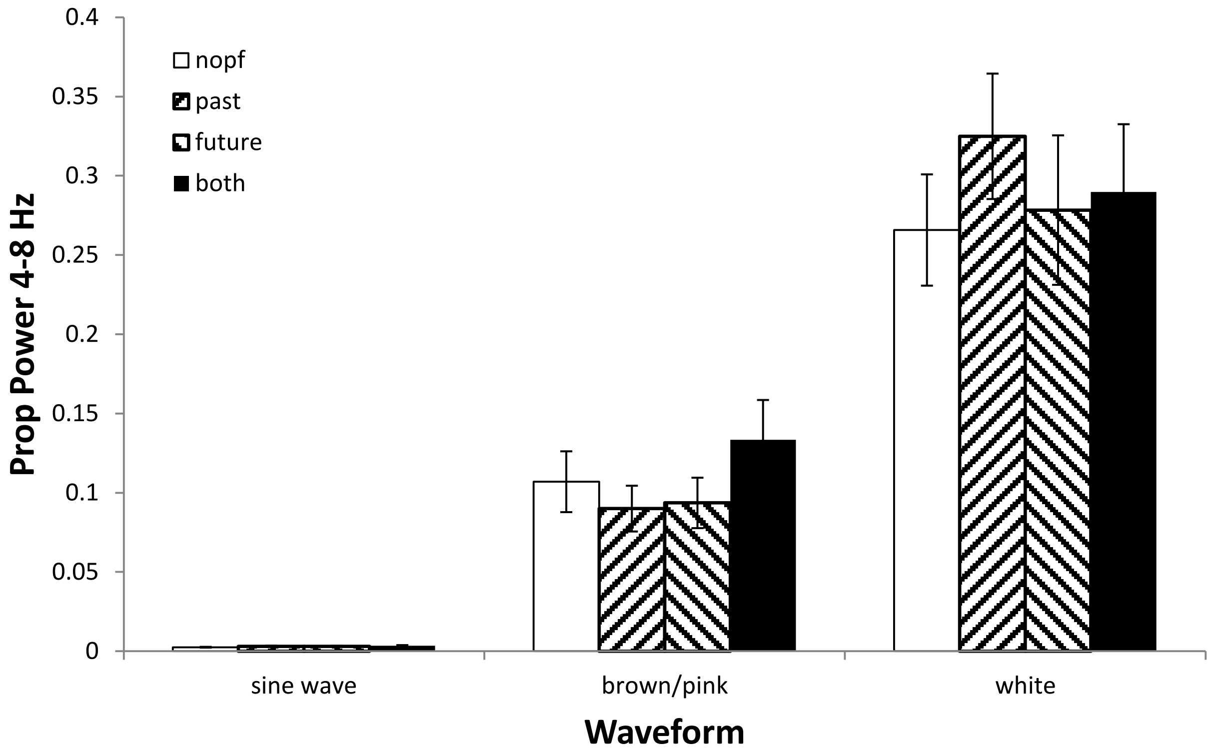

Figure 5. Mean proportion of power from 4-8 Hz as a function of target waveform and visual condition

Figure 6 shows proportion of power between 8-12 Hz as a function of target waveform and visual information condition. Proportion of power between 8-12 Hz was significantly ($p<0.01$) greater for the white noise target waveform (0.007) than for the brown-pink noise target waveform (0.004) or the sine wave target waveform (0.001). It was also significantly ($p<0.01$) greater for the brown-pink noise target waveform (0.004) than for the sine wave target waveform (0.001).

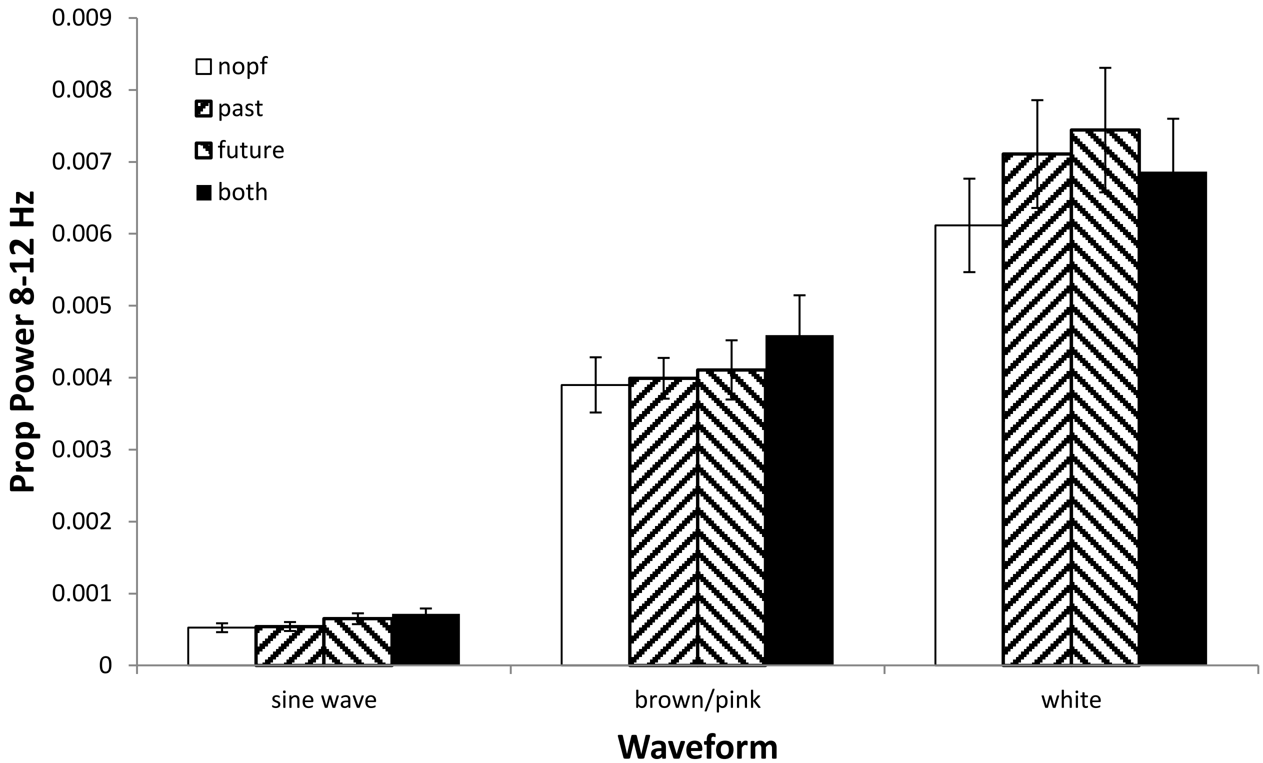

Figure 6. Mean proportion of power from 8-12Hz as a function of target waveform and visual condition

There was no significant effect of visual condition on proportion of power from 0-4, 4-8, or 8-12 Hz in the sine wave or brown-pink noise target waveform conditions indicating that the placement of visual information about the target signal did not affect the participants' ability to produce force output with more power at lower frequencies. In the white noise target waveform condition, having past information only compared to only current information helped the participants entrain more accurately as indicated by less power from 0-4 Hz and more power from 4-12 Hz. The proportion of power from 0-4 Hz was significantly lower in the past-only visual condition (0.67) than in the current information visual condition (0.73), $F(1,66)=5.37$, $p<0.05$. The proportion of power from 4-8 Hz was significantly higher in the past-only visual condition (0.32) than in the current information visual condition (0.27), $F(1,66)=5.25$, $p<0.05$. The proportion of power from 8-12 Hz was significantly higher ($p<0.05$) in the past-only

(0.0071) and in the future-only (.0074) visual conditions than in the current information visual condition (0.0061), $F(1,66)=4.97$, $p<0.05$, $F(1,66)=8.87$, $p<.01$.

Lead/Lag

Lead/Lag values as a function of target waveform and visual condition are shown in Figure 7. Lag values of the force output differed significantly for the three target waveforms, with force output to the sine wave target waveform (-412 ms) leading and force output to the brown-pink target waveform (370 ms) and white noise target waveform (78 ms) lagging, $F(2,22)=74.41$, $p<0.01$. The influence of visual condition differed as a function of the target waveform, $F(6,66)=4.69$, $p<0.01$.

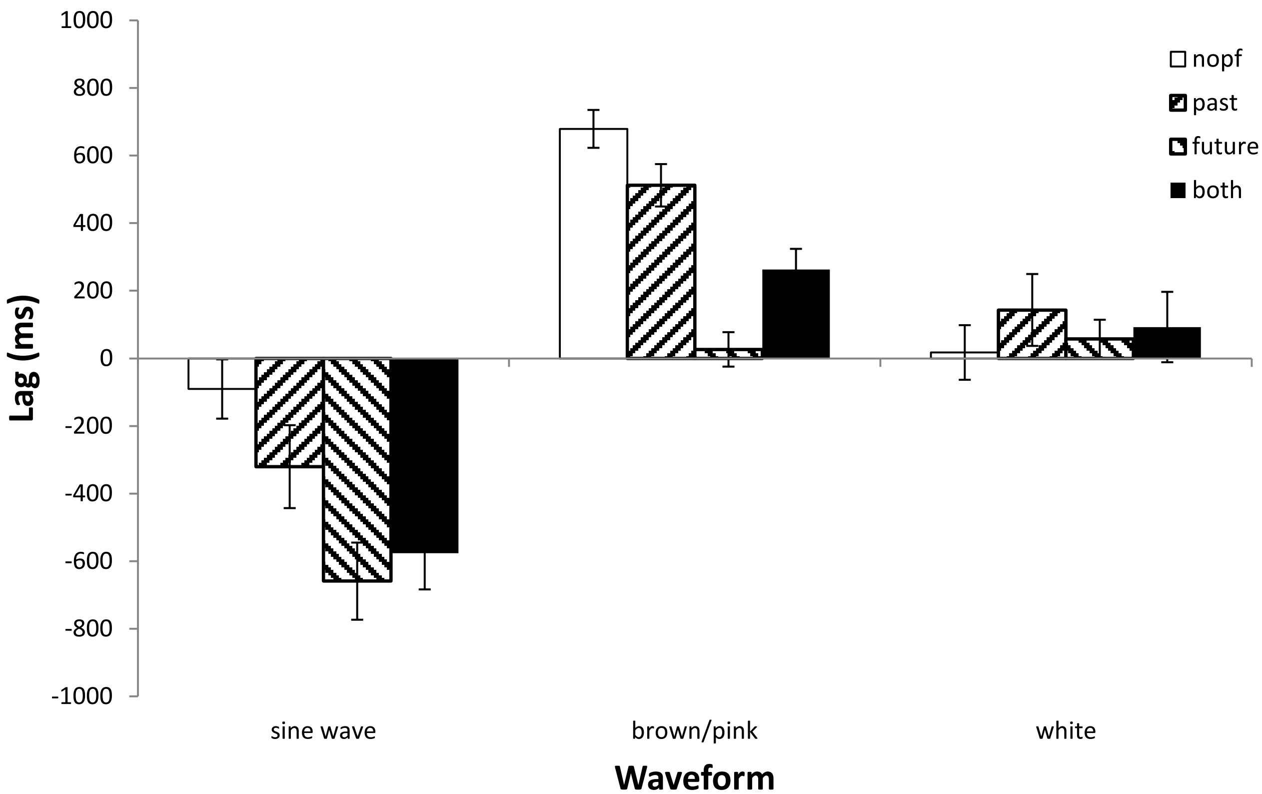

Figure 7. Mean lag as a function of target waveform and visual condition. A negative value indicates participants were leading the waveform, a positive value indicates participants were lagging behind the waveform.

A least significant difference test was performed on the means for target waveform and visual condition. Force output to the brown-pink noise target waveform (370 ms) lagged significantly (p<0.01) more than force output to the white noise target waveform (78 ms). Lag values also differed significantly (p<0.01) as a function of the visual condition.

In the sine wave target condition, the participants lead with respect to the target signal more when there was only future (-659 ms), or past and future (-576 ms) visual information compared to when there was only current visual information (-91 ms) or only past (-321 ms) visual information, $F(1,66)=26.88$, $p<0.01$, $F(1,66)=19.58$, $p<0.01$, $F(1,66)=9.55$, $p<0.05$, $F(1,66)=5.43$, $p<0.05$. This indicated that having future information enabled them to better predict the target waveform. In the brown-pink noise target waveform condition, participants lagged less when there was only future information (26 ms) and past and future information (263 ms) than when there was only current information (679 ms) or only past information (512 ms), $F(1,66)=14.42$, $p<0.01$, $F(1,66)=35.40$, $p<0.01$, $F(1,66)=19.60$, $p<0.01$, $F(1,66)=5.17$, $p<0.05$. Participants' lagged less when there was only future information (26 ms) compared to when there was past and future information (263 ms), $F(1,66)=0.0350$, $p<0.05$. These results indicate that having future information helped the participants entrain to the target signal more accurately and having more future information (future-only, 2000 ms) was beneficial compared to having less future information (past-future condition, 1000 ms). In the white noise target waveform condition there was no significant effect of visual condition on lead/lag.

Correlation Coefficient

The similarity of the force output signal and the target waveform was compared using a correlation coefficient. Correlation coefficient as a function of target waveform and visual condition is shown in Figure 8. The correlation coefficient increased as the predictability of the waveform increased, $F(2,22)= 653.93$, $p<0.01$. There was a main effect of visual condition on correlation coefficient $F(3,33)= 18.11$, $p <0.01$. The influence of visual condition differed as a function of the target waveform, $F(6,66)=24.14$, $p<0.01$.

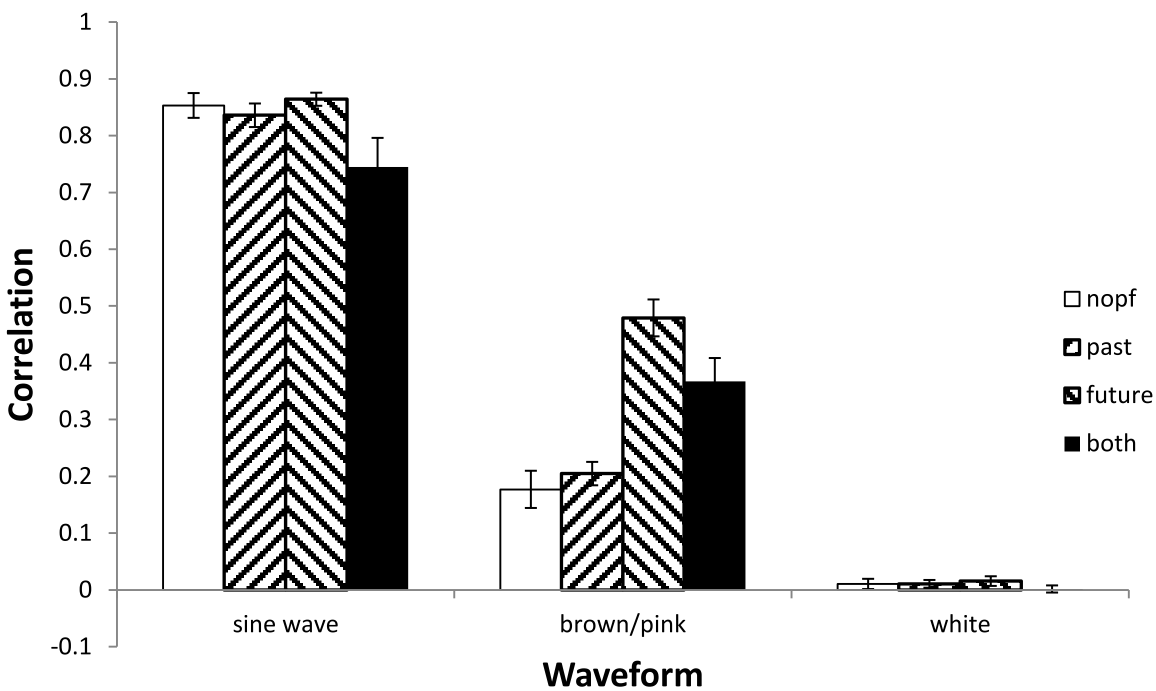

Figure 8. Mean Correlation as a function of target waveform and visual condition

A least significant difference test was performed on the means for target waveform and visual condition. The correlation coefficient was significantly higher ($p<0.01$) for the sine wave target waveform (0.825) than for the brown-pink noise target waveform (0.307) and the white noise target waveform (0.010). The correlation coefficient was also significantly ($p<0.01$) higher for the brown-pink noise target waveform (0.307) than for the white noise target waveform (0.010).

In the sine wave target waveform condition, the correlation coefficient was significantly higher for the future-only (0.86), the past-only (0.84), and current information (0.85) visual conditions than for the past-future visual condition (0.74), $F(1,66)= 21.68$, $F(1,66)=40.23$,

$F(1,66)=55.17$, $p<0.01$. In the brown-pink noise target waveform condition, the correlation coefficient was highest in the future-only visual condition(0.48) compared to the current information (0.18), past-only (0.20), and past-future (0.37) visual conditions, $F(1,66)=139.28$, $F(1,66)=114.84$, $F(1,66)=19.13$, $p<0.01$, respectively. Correlation coefficient was significantly higher for the past-future visual condition (0.37) than the current information (0.18) and past-only (0.20) visual conditions, $F(1,66)=55.17$, $F(1,66)=40.23$, $p<0.01$. These results indicate that for the brown-pink noise target waveform, having information about the future helped the participants to entrain to the target signal more accurately. In the white noise target waveform condition there was no significant effect of visual condition on correlation coefficient.

Discussion

The focus of the present study was to investigate how the location of visual information (future, past, or both), was utilized during motor entrainment to visual signals, and how the utilization of visual information depended upon the predictability of the target signal. The first hypothesis, that the presence of future information would lead to the most accurate entrainment to target waveforms with some predictability, was supported. Entrainment performance with respect to RMSE, lead/lag, and correlation coefficient improved within the more predictable sine wave and brown-pink target waveform conditions. These measures reflect how closely entrainment performance matched the local characteristics of the target waveform.

For entrainment to the sine wave and the brown-pink target waveform, RMSE was lowest in the future-only information condition. This indicates that having only future information enabled the participants to more accurately match the local characteristics of the sine wave and brown-pink target waveforms. For the brown-pink noise waveform, RMSE was also significantly lower in the past-future visual information condition (1000 ms future information) than in the past-only condition, indicating that even a shorter duration of future information can improve the participants' accuracy in matching the local characteristics of the waveform. Goolsby (1994) found that a skilled sight-reader fixates on a point ahead of the performance to see what is happening next in the melody and then returns to the current point of performance. They were more accurate in rhythm and pitch than the less skilled sight-reader who tended to perform note by note rather than looking ahead. This supports our findings that future information can improve performance in terms of accuracy.

Participants' force output led with respect to the sine wave waveform and this anticipatory control was greatest in the future-only visual condition compared to the past-only and current information conditions. Lead for the past-future visual information condition (1000 ms of future information) was significantly greater than for the past-only condition. This indicates that even visual information up to 1000 ms facilitated prediction of the target waveform, which reflected a better mapping of its local characteristics. Lag of force output to the brown-pink noise waveform was shorter in the future-only visual condition suggesting that the participant was better able to track the waveform. Lag for the past-future visual condition was shorter than for the past-only condition which suggests that, similar to the results for the sine wave target waveform, even a shorter duration of future information allowed the participant to better track the brown-pink target waveform. These findings support those of Michael and Jones (1966) who found that participants were able to track unpredictable signals but not without some delay. A greater duration of information about the future state of the waveform as well as the predictability of the sine wave and brown-pink target waveform provided participants with information that allowed prediction (sine wave) and reduced lag (brown-pink). The value of lag for the brown-pink noise waveform with future information was less than 200 ms (minimal time for reaction to a stimulus)(Carlton, 1981) indicating that, although performance lagged the signal, subjects were predicting the upcoming target.

The correlation coefficient was highest in the future-only visual condition for both sine wave and brown-pink noise indicating that participants were better able to replicate the waveform when future information was available. Having the highest correlation coefficient in the future-only visual condition suggests that having future information helped participants entrain more accurately to the local characteristics of the target waveform. Correlation for the past-future visual information condition was significantly greater than for past-only and current information in both the sine wave and brown-pink target waveform conditions. This suggests that even 1000 ms of future information aided the participants in matching the local characteristics of the target with their output.

Local entrainment to predictable waveforms relied strongly on the presence of future information; performance in terms of local variables (RMSE, lead/lag, correlation of coefficient) was best in the future-only visual condition (2000 ms) and declined in the past-future visual condition (1000 ms of future information). The finding that performance was poorer when future information and past information were both available may reflect the different duration of future information that was available. For the past-future visual condition, only 1000 ms of future information was available, whereas, for the future-only condition, 2000 ms was available. During a steering task, Land and Lee (1994) found that drivers visually fixated on a point in a turn 1000-2000 ms before they reached it, helping them to predict how they needed to maneuver the car around the bend. This finding suggests that future information up to 2000 ms is used to aid prediction, and that local entrainment depends on the amount of future information available at least up to 2000 ms.

Our prediction of local entrainment to highly predictable waveforms (sine wave) was also supported by the absence of significant visual condition effects for global variables in the sine wave condition. Participants' performance did not change with respect to variables indicating global entrainment with the exception of spectral slope. In the sine wave condition, slope of the force output was significantly steeper in the past-only visual condition than in the no information, future-only, and past-future visual conditions. The reasons for this are unknown.

Our second hypothesis, that only the presence of visual information, regardless of its location, would improve entrainment to less predictable waveforms, was supported by a lack of improved entrainment with respect to global variables under different visual conditions. Within the white and the brown-pink noise target waveform conditions, better entrainment was only present for some visual information compared with only current visual information. Better entrainment was classified as a closer match of force production to the waveform with respect to variables that measure global characteristics of the waveform (slope, ApEn, and proportion of power). The finding that spectral slope and ApEn did not differ between only current information and some information about the past, future or both, suggests that a participant's ability to pick up on global characteristics particularly pertaining to frequencies in the waveform (slope) and the complexity of the waveform (ApEn) relies more on motor rather than visual perception of the waveform. Interestingly, for the brown-pink noise target waveform, ApEn was significantly higher in the past-future visual condition than in the past-only and future-only visual conditions. The complexity of force production increased as a result of having both past and future information, suggesting that each makes a unique contribution to waveform complexity.

Unpredictable waveforms have more power at higher frequencies than predictable waveforms making the expected slopes for unpredictable waveforms less steep (Gardner et al., 1978). The finding that proportion of power decreased at lower frequencies and increased at higher frequencies when more visual information was available compared to when only current visual information was available indicates that a participant's ability to include higher frequencies of movement into force production depends on being able to see the waveform. Within the brown-pink target waveform condition, only the presence of visual information about the past and/or future as opposed to its absence (only current information) improved entrainment with respect to proportion of power.

Our findings support those of Rankin et al. (2009), who found improved performance in entrainment to an unpredictable musical signal when information about lower and higher levels of the signal was present. Participants picked up on long range correlations and persistence in the signal as well as fractal scaling (global characteristics) to predict changes later in the signal as indicated by improved accuracy and precision in tapping the fluctuating beat of an expressive musical piece. Stephen et al. (2008) also showed that participants entraining to an unpredictable metronome signal could approximate the long-range, global characteristics of the signal. Pew (1974) showed similar findings. During performance of an unpredictable arm movement sequence that had a repeated component (undetected by participants) and an unrepeated component, performance improved with practice on the repeated but not the unrepeated component. Performance improvement with respect to the repeated sequence was also seen in a transfer task when the sequence was reversed. This ability to transfer the task to a signal with different local characteristics suggested that participants had an understanding of the global characteristics of the signal.

Measures of performance to the white noise waveform were consistent with other studies (Sosnoff et al., 2009; Studenka & Newell, 2012). In the current study, the predictability (global structure) of the participants' force output reflected the degree of predictability (global structure) of the target waveform. ApEn increased significantly as the predictability of the target waveform decreased, consistent with the findings of Sosnoff et al. (2009). The proportion of power from 0-4 Hz was less when the target waveform was less predictable, and the proportion of power from 4-12 Hz was greater when the predictability of the target waveform was less.

This too was seen in Sosnoff et al. (2009) and Studenka and Newell (2012) indicating that, as signal predictability decreased, participants incorporated higher frequencies into force production.

In summary, the findings of the present study show that participants tend to locally entrain to predictable waveforms and globally entrain to unpredictable waveforms. This was revealed by manipulating the placement of visual information about the waveform. Providing participants with information about the future waveform improved entrainment to the sine and brown-pink noise waveforms (both characterized by some degree of predictability) indicating that participants entrained locally, depending on upcoming information. For white and brown-pink noise (waveforms with less predictability), improved entrainment in terms of global characteristics of the waveform was present when some information about the past and/or future was available compared to only current information, indicating global entrainment dependent upon long-term waveform characteristics. For the brown-pink noise waveform participants globally and locally entrained indicating that the type of entrainment is not mutually exclusive, both can occur simultaneously. In general, past and future information about a signal can be useful for entrainment to it depending on the predictability of the signal. The predictability of the signal also affects the entrainment strategy (local or global) employed by the subject.

One possible limitation of the present study is that the correlation coefficient for the force output signals produced by subjects in the white noise waveform condition was less than 0.1. This suggests that the subjects may have ignored the task goal of trying to replicate the specific signal being presented and instead attempted to replicate the fast fluctuations of the signal in general. It is possible that 12 Hz is too fast for subjects to capture all of the fluctuations and the correlation may have been higher if up to 8 Hz were included rather than up to 12. Another possible limitation of this study is that the signal moved up and down on the monitor while the subject was expected to try and replicate that motion with side to side motion of their finger. Possible errors in translating the up down motion to a side to side one could be eliminated in a future study by having the signal on the monitor run vertically rather than horizontally. In addition, future studies could involve manipulation of the duration of the time window as well as its placement.

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ACADEMIC VITA of Molly M. Mazich

Molly M. Mazich
30 Ridge Drive
Fleetwood, PA 19522
mmm5484@psu.edu

Education: Bachelor of Science Degree in Kinesiology, Penn State University, Fall 2012
Honors in Kinesiology
Thesis Title: Isometric force entrainment depends on temporal location of visual information and signal predictability
Thesis Supervisor: Karl M. Newell

Related Experience:

Undergraduate Research Assistant- Motor Behavior Lab
Penn State University; University Park, PA
Supervisor: Dr. Karl M. Newell
Fall 2010-Spring 2011

Awards:

Dean's List
National Society of Collegiate Scholars

Presentations/Activities:

Board member of Penn State Strength and Fitness Advisory Board
Physical Therapy Intern, University Health Services
Physical Therapy Volunteer, Mount Nittany Hospital