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PHYS 8814: Neurophysics Course

The Effect of Sound-Induced Brain Waves on Visuospatial Information Processing

I. Abstract

The human brain processes visuospatial information to optimize motion toward a target position in space. The effects of different brain waves on the relationship between information processed and movement time, defined by Fitt's Law, were investigated. We observed and analyzed the impact of ambient sounds across different frequencies such as white noise, pink noise, and brown noise before and during motion planning to a target location. Additionally, the effects of meditation prior to performing the movement-to-target exercise were evaluated. The sounds and meditation intended to alter the participant's mental state by modulating brain activity, or brain waves, associated with states such as focus, alertness, and problem solving. Brain waves were recorded throughout the experiment using an electroencephalographic (EEG) device.

II. Introduction

In 1954, Psychologist Paul Morris Fitt's Jr. proposed that the time necessary to move to a target location depended on the distance A between the starting and target locations and the width W of the target location [8]. He posited that distance A could be partitioned into states N computed with *Equation 1*. He derived the logarithmic relationship in *Equation 2* relating an index of difficulty (ID) of information processing and movement to the number of states in order to transform the number of states present to the number of bits of information available, or entropy, across all states. Fitt's Law, *Equation 3*, exhibits the linear relationship between the movement time (T_m) and the ID, where a and b are the respective y-intercept and slope of the regression line fitted to this relationship. The effective ID, ID_e, was also measured using the effective sub-target area that is reached within the target area. Humans' assessment of movement difficulty depends on the degree of information available among the states. This determines the type of motion strategy selected. One may invoke limit cycle dynamics that emphasize proactive planning of the trajectory required to reach the target. Alternatively, an individual may prioritize speed and progressively update the velocity and direction of motion toward a fixed point.

We designed a seven-trial experiment that required a participant to move a cursor on a computer screen between two targets with varying A and W values to change the ID.

$$N = \frac{2*A}{W} \qquad (1)$$

$$ID = \log_2(N) \qquad (2)$$

$$T_m = a + b * \log_2(N) \qquad (3)$$

Given the initial cognitive processing of movement difficulty and motion planning strategies, the human brain performs complex computations to optimize movement toward a target.

For our research, we seek to investigate brain activity in the form of brain waves, or global frequencies of excitation, occurring during movement to a target location and how brain activity influences motion toward a goal. Brain waves are comprised of oscillations in electrical signals transmitted throughout the brain [1]. Fast Fourier Transforms (FFTs) convert the excitation of brain regions across time and space into the frequency domain. Brain wave bands include delta, theta, alpha, beta, and gamma waves. *Table 1* details the frequency ranges and mental states associated with each wave band.

WAVE BAND	FREQUENCY RANGE (HZ)	MENTAL STATES
DELTA	.5 – 4	Deep sleep, non-rapid eye movement (NREM)
THETA	4 – 8	Light daydreaming, meditation, creative thinking, internal focus
ALPHA	8 – 13	Relaxed, calm, alert
BETA	13 – 30	Active, alert, focused, problem-solving, and decision-making
GAMMA	25 – 45	Problem-solving, memorization, learning

Table 1: Information about brain wave bands such as frequency ranges and associated mental states

In our experiment, we actively manipulated the frequencies of our participant's brain waves with the usage of sound and meditation. During three sets of trials, our participant listened to sounds including white noise, pink noise, and brown noise. White noise, akin to white light, is composed of all frequencies audible to the human ear within the range of 20 to 20,000 Hz. A familiar example of white noise is the hum of a cooling fan. A study investigating the effects of white noise on memory and recall demonstrated that participants with attention deficits who listened to white noise attained higher scores on tests evaluating recall of recently learned names for objects. White noise may also enhance motor excitability [6].
Pink and brown noise frequency ranges are equivalent to white noise. However, pink noise is a smoother form of white noise with frequencies that decrease by three decibels per octave [2], yielding a softer tone by accentuating lower frequencies and dissolving higher frequency sounds. The sound of ocean waves is a naturally occurring example of pink noise. Researchers Zhou et al. (2012) revealed that pink noise reduced brain wave complexity in subjects and promoted more stable sleep time [4]. Brown noise emphasizes lower

frequencies to a greater extent compared to pink noise with frequencies that decrease by six decibels per octave. According to the Attention Deficit Disorder Association (ADDA) [5], brown noise may enhance dopamine levels in people with ADHD by counteracting under-stimulation that reduces attention and focus. Optimal arousal theory proposes that low and high levels of arousal hinder attention, so noise such as brown may optimize mental arousal levels and subsequently heighten attention. In addition to investigating the effects of noise on information processing, we also conducted a set of trials that required the participant to meditate. In a study conducted by Stapleton et al. (2020), subjects with limited meditation experience participated in three days of guided meditations with emotionally evocative music. Delta wave band powers decreased by 5%, while theta, alpha, beta, and gamma waves increased by 29%, 16%, 17%, and 11%, respectively [11]. To measure brain activity in our experiment, we recorded the participant's brain frequencies using an electroencephalographic (EEG) device across five sets of the Fitt's Law exercise trials: a control set, three sets in which the participant listened to white, pink, and brown noise, and a meditation set that required the subject to follow a guided meditation prior to completing the task.

We hypothesize that white, pink, and brown noise as well as meditation will increase the information processing rate of the participant during the movement-to-target task. The order may vary, but we predict that pink noise will be the most suitable for increasing attention and information processing. Pink noise is more soothing than white noise, which contains higher decibels for all frequencies. White noise follows with the next highest predicted information processing rate as it can increase motor excitability and improved attention. Meditation, shown to increase band powers at higher frequencies associated with alertness, will have the third highest information processing rate as it may improve focus, but its effects may diminish throughout the trial as its influence is not sustained as with the noise trials. Brown noise is predicted to fall next in line because it has been shown to improve attention, but the lower frequencies could be relatively more distracting. Lastly, we hypothesize that the control set will result in the slowest information processing as we expect the sound and meditation enhancements to improve focus, attention, and processing of information across the states between targets.

III. **Methods**

In this study, our subject performed an exercise to observe the logarithmic relationship proposed by Fitt's Law of the movement time between two targets and the number of states. First, we initialized images of two squares separated by a distance *A* displayed on the computer using MATLAB. We designed six trials varying the square widths *W* and distances starting from low distances and progressively increasing the *A* and *W* across seven trials. *Table 2* details the values for *A* and *W* for each trial, the computed number of states between each target, and the indices of difficulty. An example of the image displayed to the participant is provided in *Figure 1.* Each trial was presented to the participant at random to reduce the effects of expectation and highlight the user's subconscious application of fixed point or limit cycle trajectories. The subject was required to glide a stylus on a Wacom tablet back-and-forth between the two red squares for 30 seconds as rapidly as possible while maintaining accuracy with misses occurring less than 3% of time. They also needed to maintain a fixed body position at midpoint between the targets, and sufficient constant pressure on the tablet throughout the trials. The trajectories of the stylus in the x- and y-directions were recorded using a MATLAB function that tracked the cursor positions on the computer screen.

TRIAL	DISTANCE *A* (PIXELS)	WIDTH *W* (PIXELS)	N (STATES)	ID = LOG2(N) (BITS)
1	300	100	6	2.585
2	400	75	11	3.415
3	500	50	20	4.322
4	600	25	48	5.585
5	700	20	70	6.129
6	750	10	150	7.229
7	775	5	310	8.276

Table 2: Parameters for each experimental trial

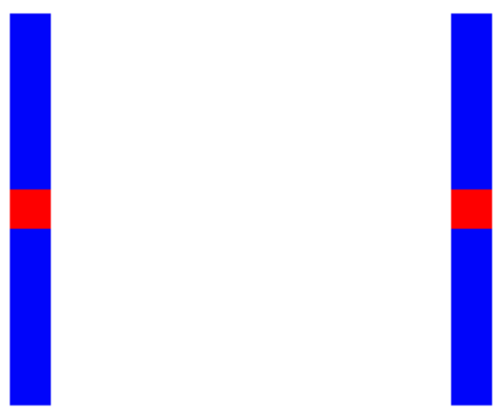

Figure 1: Example of computer image displayed to participant

Five sets of the seven trials were conducted during the experiment, including: (1) a control set in which the subject completed the trials with no additional modifications to the experimental process previously described; (2)-(4) three sets of trials that require the subject to listen to white noise, pink noise, and brown noise, respectively, with headphones for five minutes and follow up with completing the seven trials while simultaneously listening to the sounds; and (5) a set in which the participant followed a 15-minute guided meditation video [12] that promoted deep breathing and relaxation of tense regions of the body with a subsequent completion of the seven trials for the final set. The participant had no prior meditation experience.

During all trial sets of the experiment, the subject's brain activity was measured using an electroencephalographic (EEG) device. The Flex Cap by Emotiv Epoc Flex was fitted to the participant's head, and a conductive gel was inserted into each electrode, making contact with the scalp. Hair was moved away from each electrode with a cotton swab for optimal contact with the scalp. The Epoc Flex Controller was secured into a pouch in the cap and recorded measurements from the electrodes via a wired connection. The EmotivPro application was used to calibrate the cap by ensuring that electric signals were being measured at each electrode. An example of the electrode configuration on the cap is shown in *Figure 2*. Each electrode position lights up in green to indicate that the location has satisfactory conditions for accurate measurement. EEG data, global firing rates presented as brain waves, were recorded as band powers in $\mu V^2/Hz$ using Fast Fourier Transforms (FFT). The data was compared across all sets of trials and indices of difficulty of the Fitt's Law task. An example of the brain wave data provided by the EmotivPro application is shown in *Figure 3*. It covered the theta, alpha, low beta, high beta, and gamma wave bands. To analyze the raw data, we required a license but were unable to obtain one. Instead, we used video recordings of the results for each trial saved with the application. We took screenshots of the bar graph at an interval of every two seconds and estimated their values using the PlotDigitizer program to extract data. The data was graphed over time for each 30-second trial for data analysis. The data was filtered using the Modified Akima Piecewise Cubic Hermite, or 'makima,' interpolation in MATLAB.

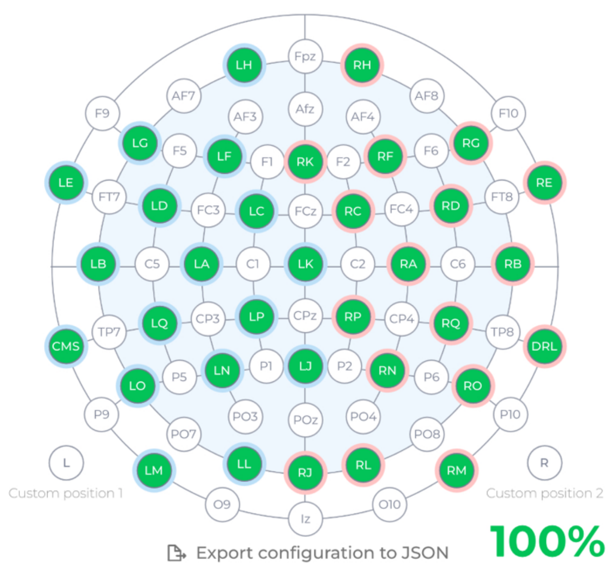

Figure 2: Electrode configuration for the Emotiv Epoc Flex EEG Cap at 100% optimal quality for sensing

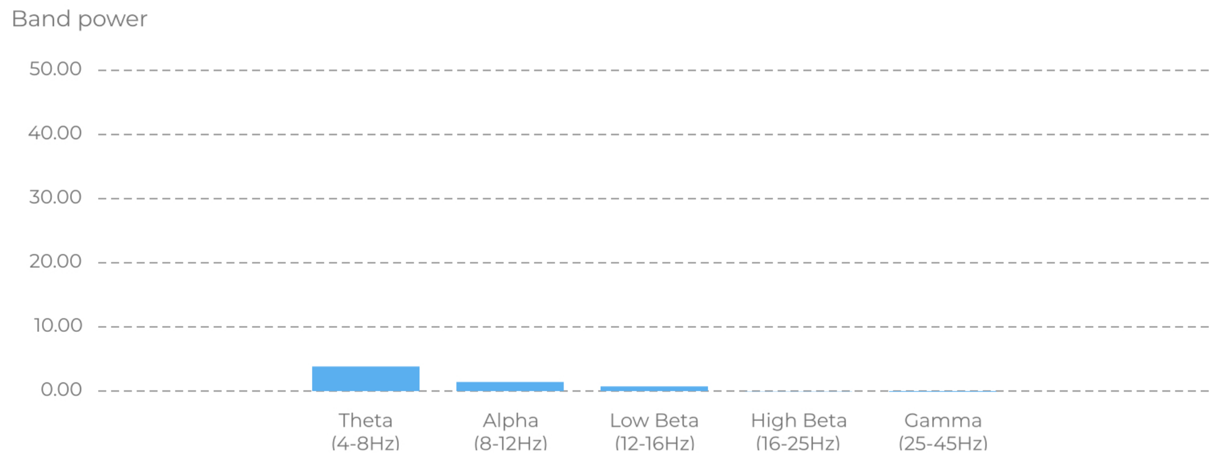

Figure 3: Example of brain wave data from the EmotivPro application.

IV. Results

A. Results demonstrating the Fitt's Law relationship

Figures 4 and *5* show the relationship between movement time and the number of states between targets and the movement time and the ID_e, respectively, for all sets of trials. The subject exhibited an information-rate-limited form of processing, indicated by the logarithmic relationship between the movement time and the number of states in conjunction with the linear relationship between the movement time and the ID_e. The individual plots in *Figure 5* were combined in *Figure 6* to compare the rates of information processing. A comparison plot for *Figure 4* is available in *Figure 20* of the *Appendix*. According to *Figure* 6, the pink noise trial set linear fit achieved the shallowest slope, yielding the fastest information processing rate. The white noise trial set resulted in the slowest information processing rate with a linear fit of the highest slope. The brown noise trial set resulted in information processing very similar to that of meditation. The sets of trials in the order of increasing information processing rates were as follows: white noise, brown noise, meditation, control, and pink noise.

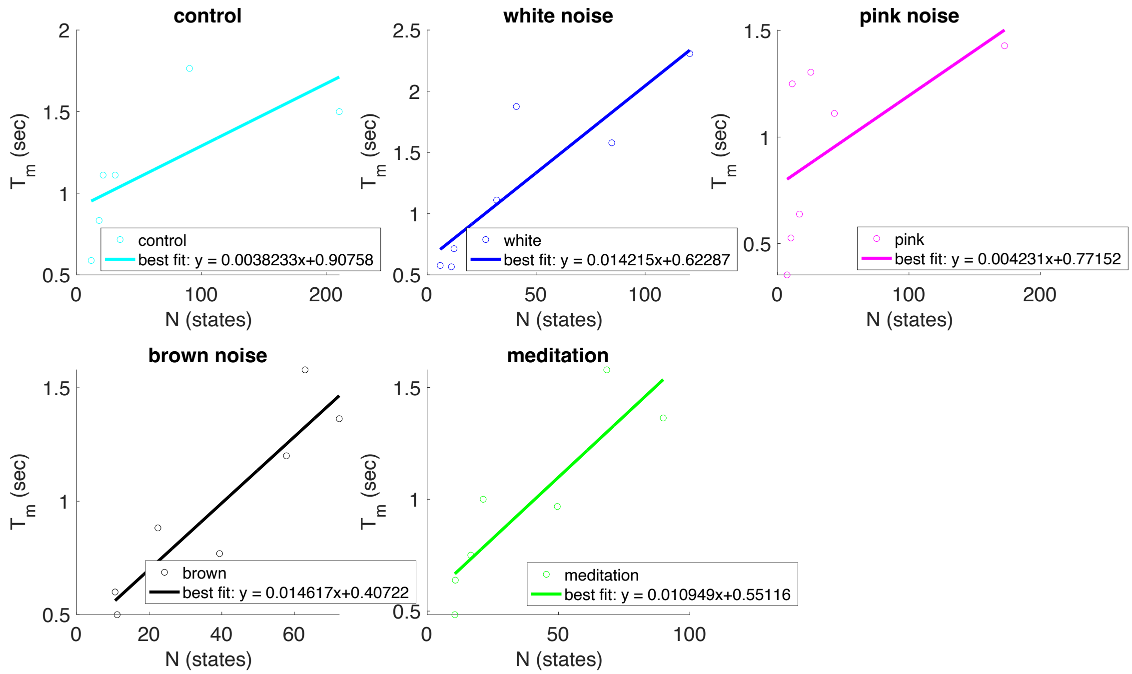

Figure 4: Movement time vs number of states for each set of trials

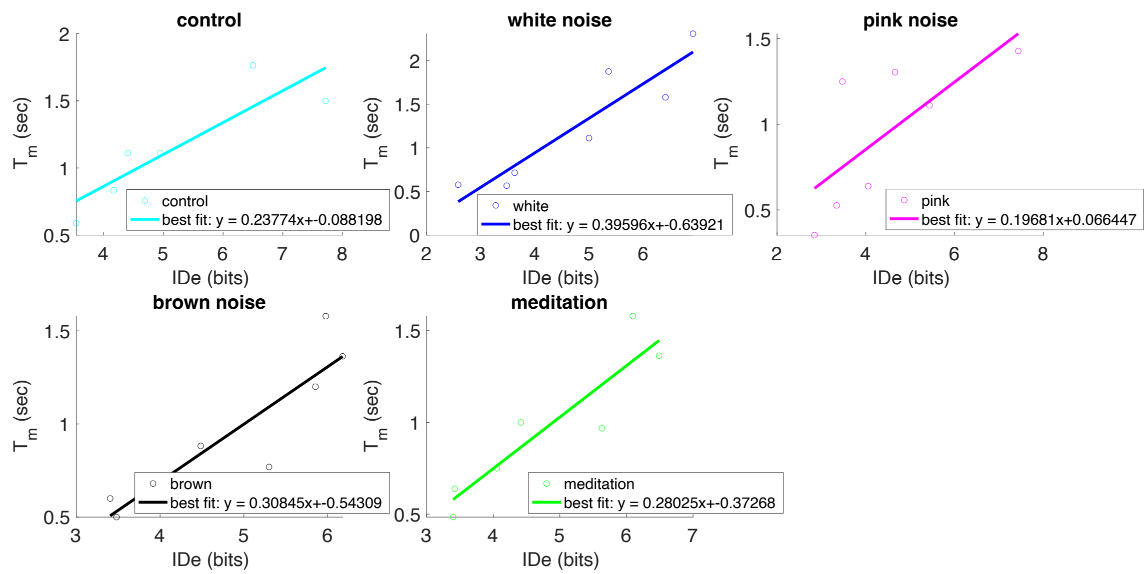

Figure 5: Movement time vs ID_e for each trial

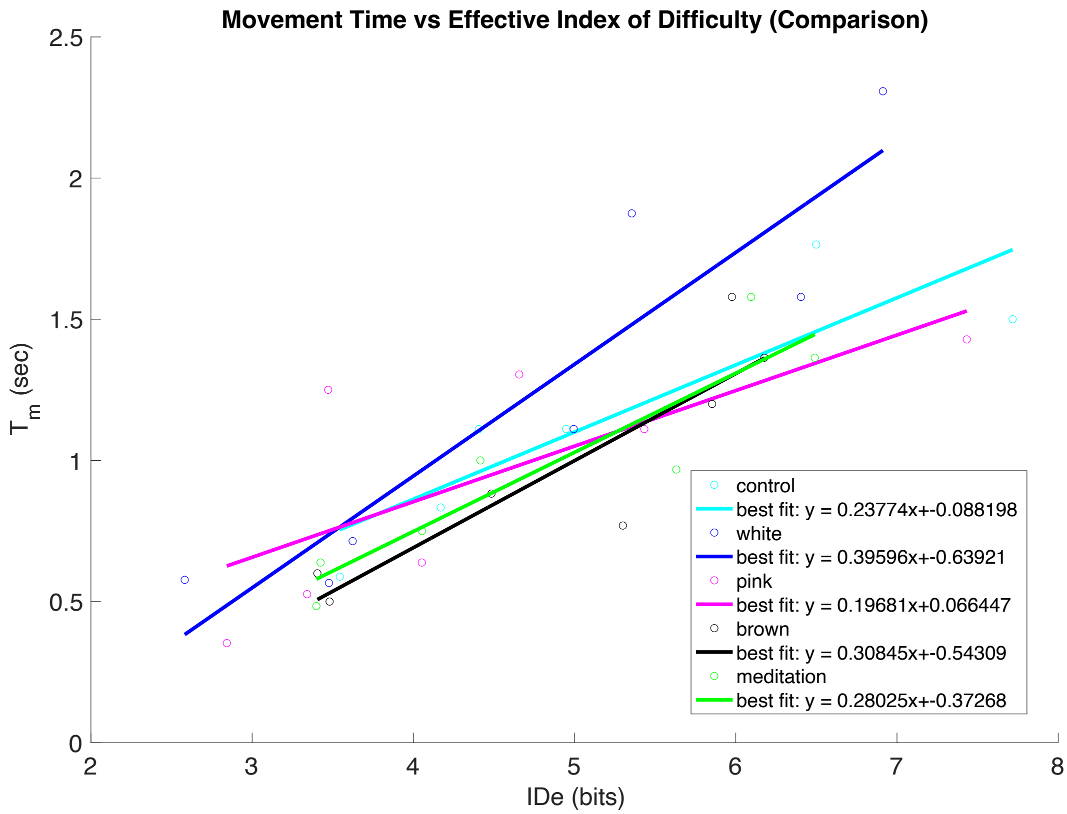

Figure 6: Comparison across sets of trials of movement times vs ID_e

B. Phase-space results at every ID for each trial in all trial sets

The phase-space plots for the different trial sets are shown in *Figures 7-11*. To compare strategies, throughout the control set, the participant utilized fixed point trajectory dynamics as shown by the increasing velocity up to a horizontal position *x* close to the target and an abrupt deceleration near the target for higher accuracy. Limit cycle dynamics were more apparent in the remainder of trial sets. *Table 3* details ID_e thresholds for transitions from limit cycle to fixed-point dynamics, where the threshold corresponds to the minimum ID_e at which fixed-point dynamics occurred. The lowest thresholds for transition to fixed-point dynamics were found in the pink noise and control sets; as noted, fixed-point dynamics were primarily used during the control set. The highest transitions to fixed-point trajectories occurred during the brown noise and meditation sets.

With regard to movement velocity, for all sets maximum velocities decreased as ID_e increased. Velocities were lowest for all trials during the control and meditation sets and highest during the pink noise set. After the control set, movement velocities increased when the participant listened to white noise but decreased after the pink noise set when exposed brown noise. Velocities tended to decrease to a greater extent when the subject transitioned to fixed-point trajectories.

TRIAL SET	ID_E CYCLE DYNAMICS TRANSITION THRESHOLD (BITS)
CONTROL	3.544 *possible limit cycle at ID_e of 4.4065 bits
WHITE NOISE	4.9944
PINK NOISE	3.4716 *possible limit cycle at ID_e of 4.0527 bits
BROWN NOISE	5.8532
MEDITATION	5.6312

Table 3: Transition thresholds from limit cycle to fixed-point dynamics for each trial set

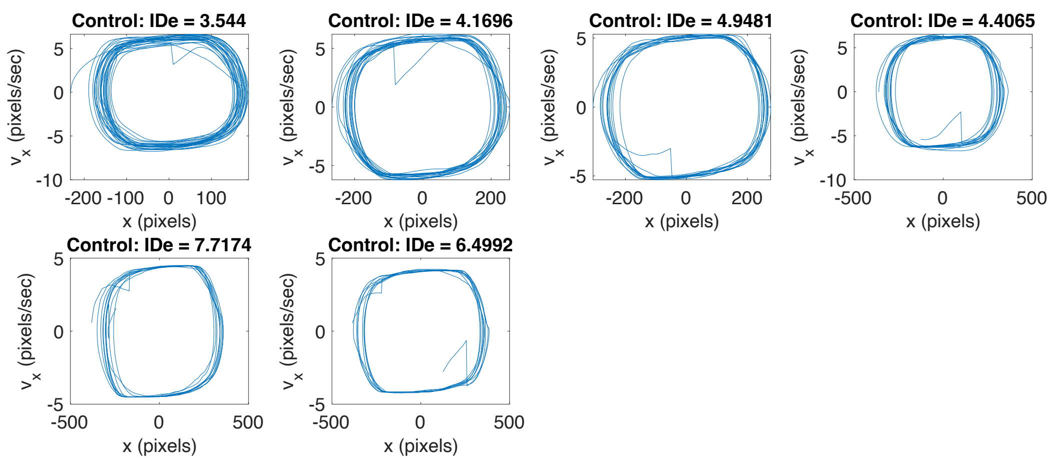

Figure 7: Phase-space plot of velocity in the x-direction vs x position of the participant's path during the exercise for the control set across ID_e's given in bits of information; note: error was found in path for trial 2, so the trial was omitted from the results

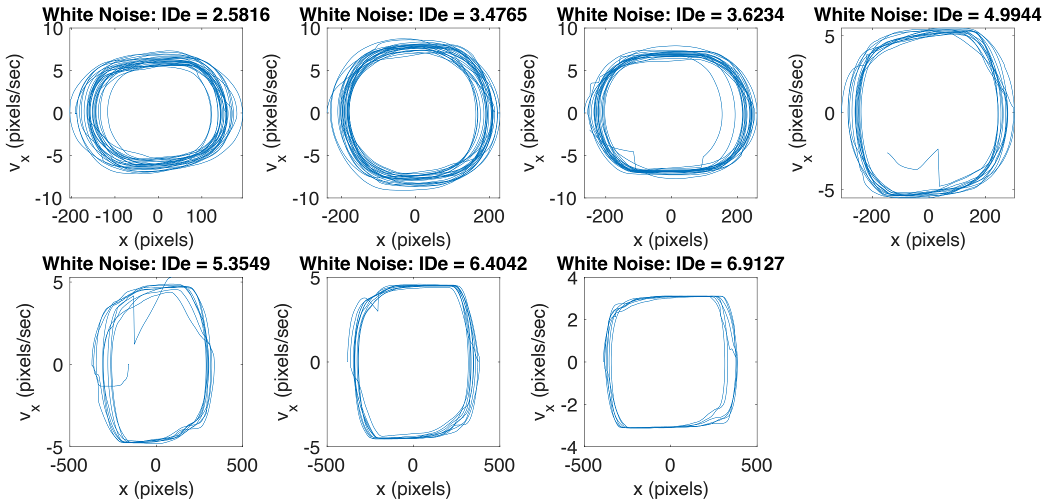

Figure 8: Phase-space plot of velocity in the x-direction vs x position of the participant's path during the exercise for the white noise set

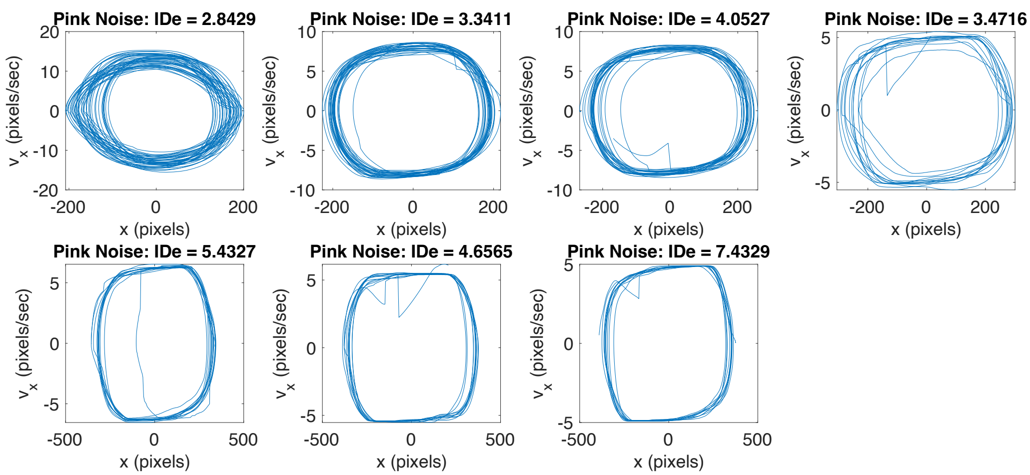

Figure 9: Phase-space plot of velocity in the x-direction vs x position of the participant's path during the exercise for the pink noise set across ID_e's, given in bits of information

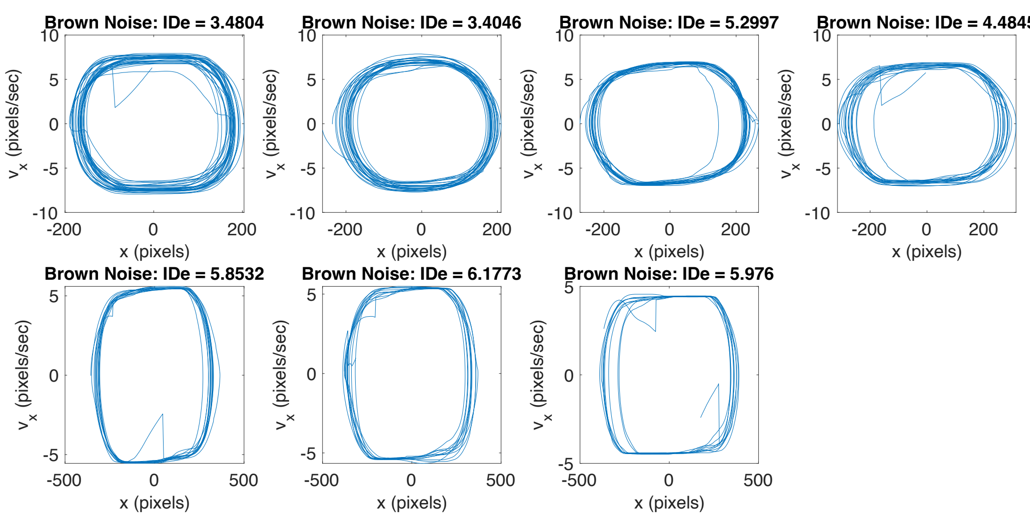

Figure 10: Phase-space plot of velocity in the x-direction vs x position of the participant's path during the exercise for the brown noise set across ID_e's, given in bits of information

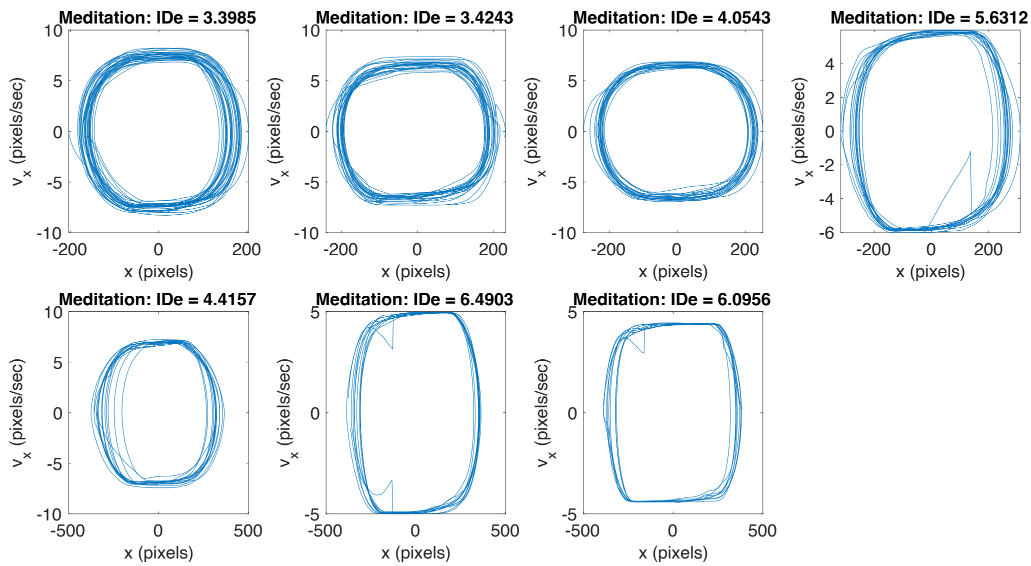

Figure 11: Phase-space plot of velocity in the x-direction vs x position of the participant's path during the exercise for the meditation set across ID_e's, given in bits of information

C. *Comparison of trial sets for each wave band across varying IDs*

Figures 12-14 depict the wave band power recorded for each wave band, comparing the trial sets for trials one, four, and seven with increasing ID, respectively.

For trial one, with an ID of about 2.585 bits, the control set resulted in production of the highest theta waves in our subject's brain. The white noise set induced the highest alpha, low beta, high beta, and gamma waves; the control set also induced high low beta waves. More brain activity was present at higher frequencies during the white noise set.

At a mid-level ID of about 5.585 bits in trial four, pink noise resulted in the highest band powers for lower frequencies such as theta, alpha, and low beta waves; a higher band power was also observed in the control set for theta, alpha, and low beta waves, but only at the beginning of the trial. Brown noise additionally produced high theta waves during this trial. The control set induced higher wave band powers for high beta and gamma waves, followed by meditation, which also displayed heightened activity in the high beta and gamma wave bands as well as low beta.

Furthermore, at the highest tested ID of about 8.276 bits for trial seven, the control set yielded high wave band powers at low brain wave frequencies, including theta and alpha waves. Low beta wave band brain activity was most prevalent during the meditation trial set. Brain activity across all sets of trials were very similar for high beta and gamma waves bands.

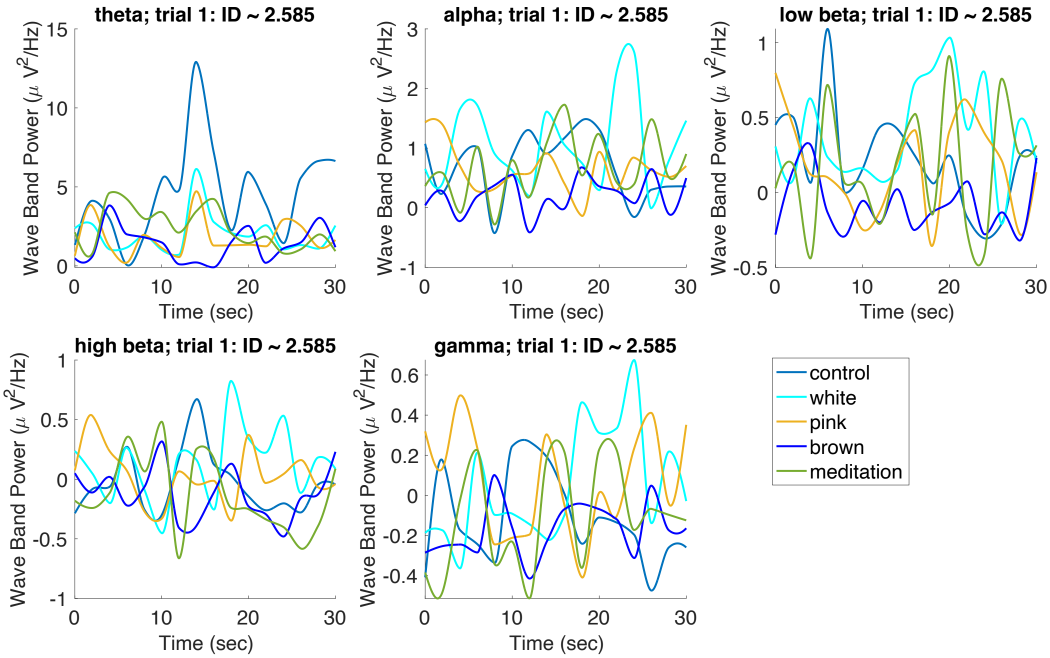

Figure 12: Comparison of trial sets for each wave band for the lowest ID tested, given in bits of information

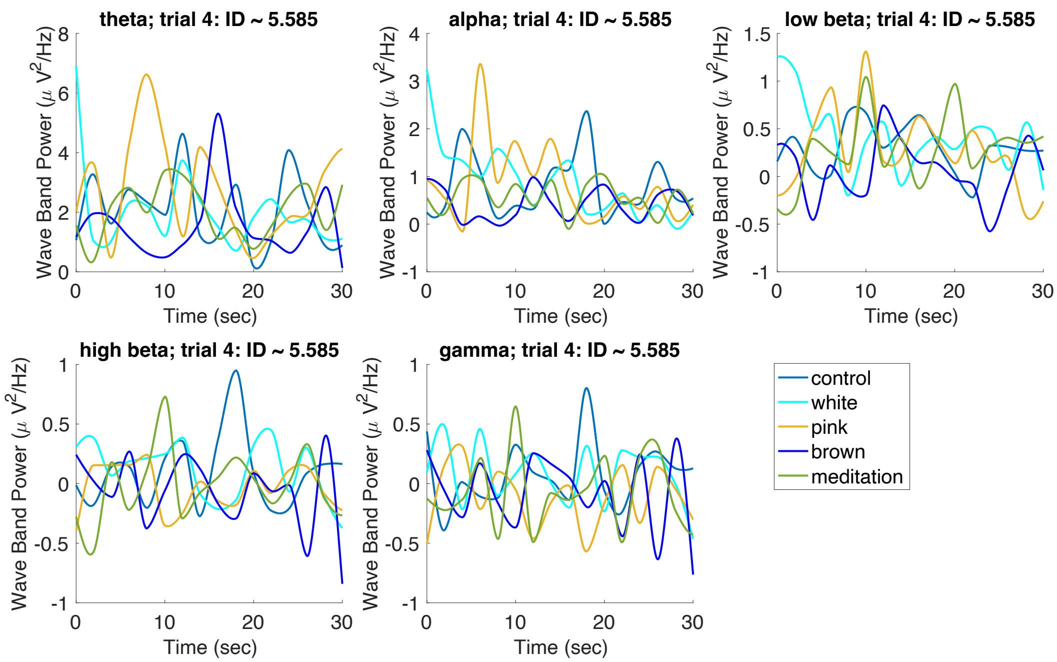

Figure 13: Comparison of trial sets for each wave band for the mid-level ID tested, given in bits of information

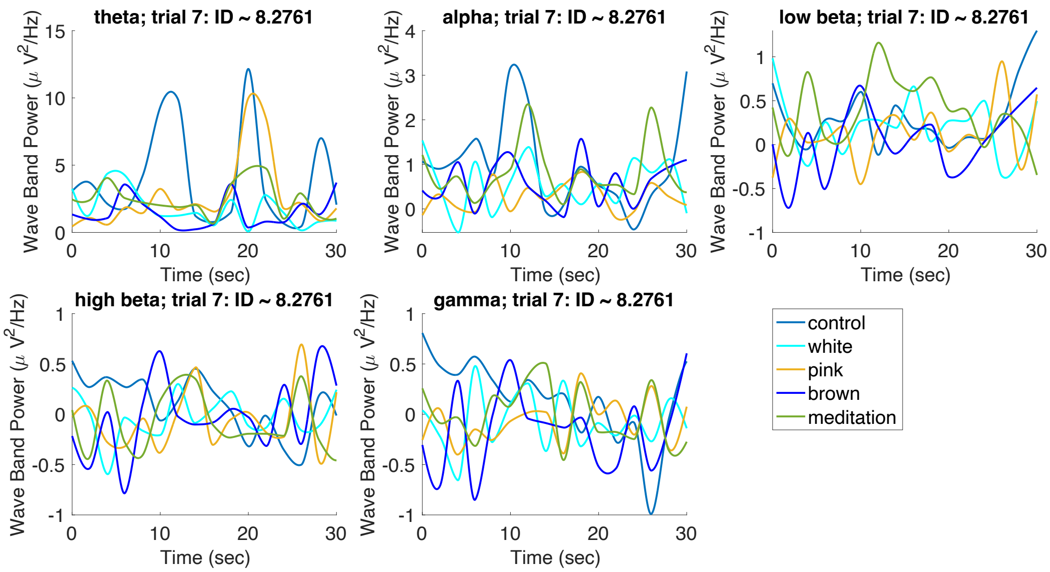

Figure 14: Comparison of trial sets for each wave band for the lowest ID tested, given in bits of information

D. Comparison of wavebands for each trial set across varying IDs

Figures 15-19 compare the brain activity within each wave band for each trial set, respectively, across three trials with increasing ID. In all trial sets and IDs, theta wave activity was the most prominent, followed by alpha waves. The theta waves achieved the highest band powers at low and high IDs during the control set and at a high ID in the pink noise trial set. Their lowest values occurred during the brown noise and meditation trial sets. Pink noise resulted in progressively increasing theta wave band powers and the ID increased. Brown noise and meditation induced the highest band powers for alpha waves. The remaining higher frequency wave bands, such as low beta, high beta, and gamma, displayed low activity in all figures.

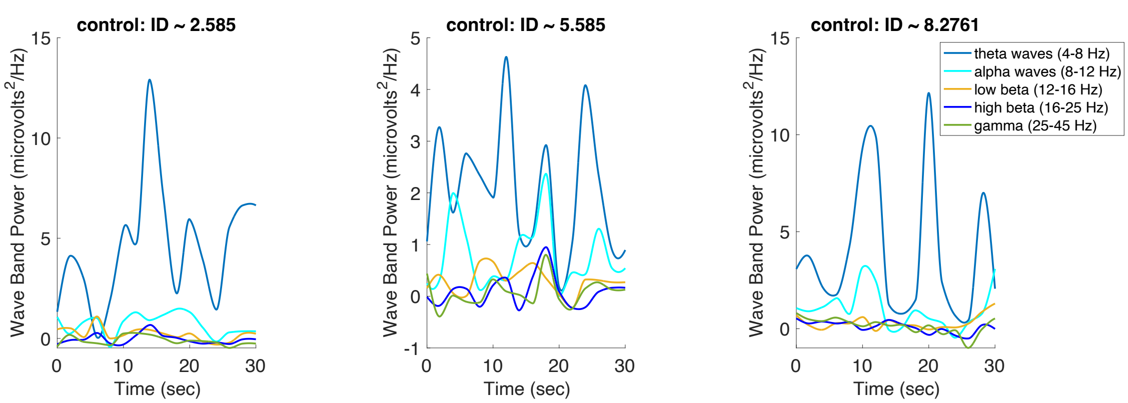

Figure 15: Comparison of wave bands for low (ID ~ 2.585 bits), mid-level (ID ~ 5.585 bits), and high ID (ID ~ 8.2761 bits) values tested in the control set

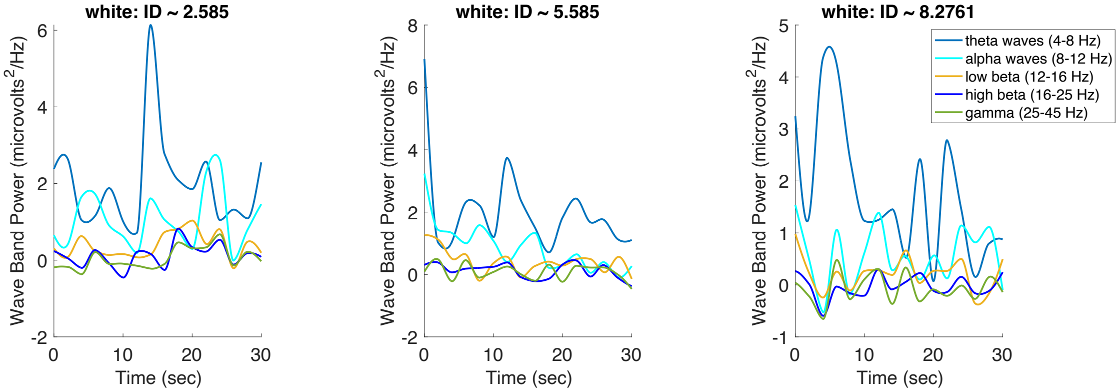

Figure 16: Comparison of wave bands for low (ID ~ 2.585 bits), mid-level (ID ~ 5.585 bits), and high ID (ID ~ 8.2761 bits) values tested in the white noise set

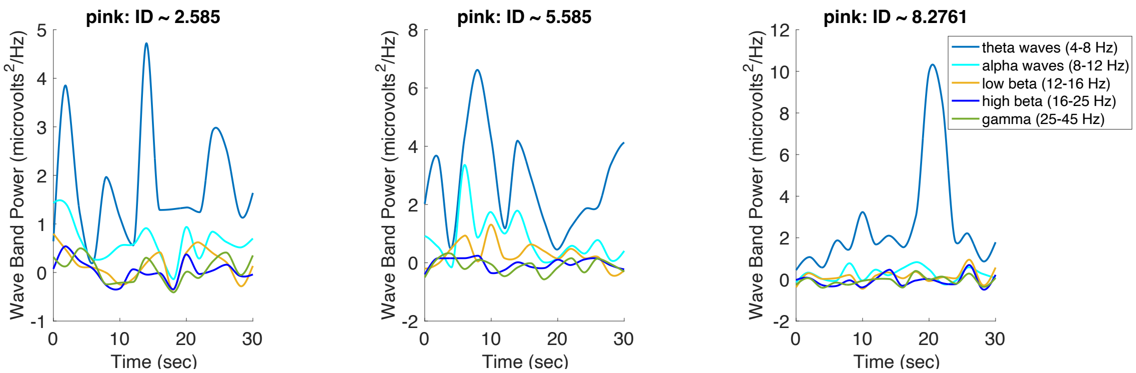

Figure 17: Comparison of wave bands for low (ID ~ 2.585 bits), mid-level (ID ~ 5.585 bits), and high ID (ID ~ 8.2761 bits) values tested in the pink noise set

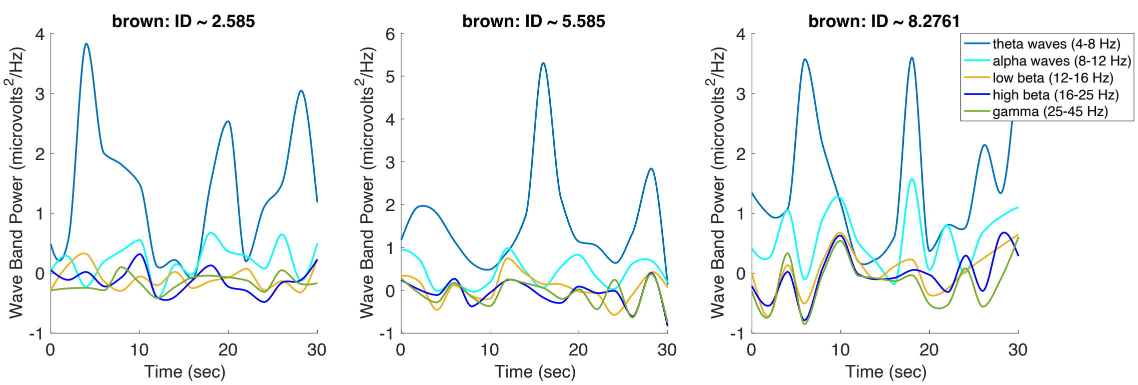

Figure 18: Comparison of wave bands for low (ID ~ 2.585 bits), mid-level (ID ~ 5.585 bits), and high ID (ID ~ 8.2761 bits) values tested in the brown noise set

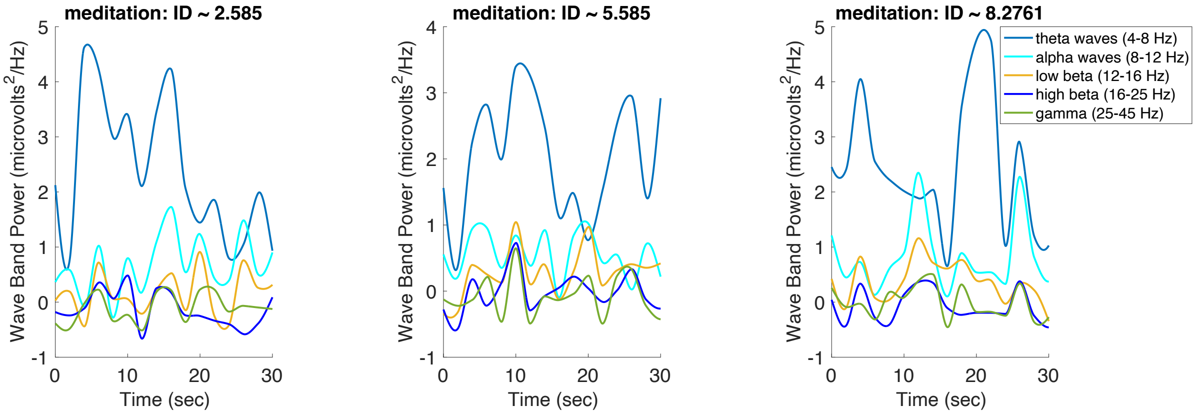

Figure 19: Comparison of wave bands for low (ID ~ 2.585 bits), mid-level (ID ~ 5.585 bits), and high ID (ID ~ 8.2761 bits) values tested in the meditation set

V. Discussion

A. Fitt's Law Task and Information Rate

To reiterate the hypothesis, we predicted that the following sets of trials would result in an information processing rate in increasing order: the control, brown noise, meditation, white noise, and pink noise. The participant carried out the trial sets in consecutive order of white noise, pink noise, brown noise, and lastly, meditation exercises. The experimental results yielded the following order of increasing information processing rate: white noise, brown noise, meditation, control, and pink noise. *Table 4* summarizes this information. As noted, white noise consists of all frequencies audible to the human ear at uniform decibels. Despite the prior research indicating improvement in attention, memory, and motor excitability [6] induced by white noise, the intensity across all the entire audible frequency range could potentially be disruptive. The studies we reviewed discussed the effects of heightened attention on memory and motor skills but did not evaluate white noise' effect on visuospatial information processing. Brown noise may have yielded the second lowest information processing rate due to possible distraction from the higher volume at low frequencies. Moreover, this low range of pitch could have lowered the mental arousal of the participant and reduced their attention and focus. Furthermore, meditation falling next in line below the control was unexpected as meditation has demonstrated positive effects on focus and increased in higher frequency waves associated with problem-solving and alertness. This was the last trial conducted in the sequence, so fatigue may have reduced performance by reducing the information-rate to motion relationship. In addition, unlike the noise trial sets, meditation was performed only prior to the task, so lingering effects were not sustained throughout the entire set of trials. The resulting highest information processing rate with exposure to pink noise supported our hypothesis that the softness and consequent relaxation would promote the highest level of focus and attention for completing the task.

SEQUENCE	1	2	3	4	5
EXPERIMENTAL SET COMPLETION	control	white noise	pink noise	brown noise	meditation

INFORMATION RATE HYPOTHESIZED	control	brown noise	meditation	white noise	pink noise
INFORMATION RATE RESULT	white noise	brown noise	meditation	control	pink noise

Table 4: Details about sequences for completion of experimental sets, information rate order hypothesized (lowest to highest), and information rate order result (lowest to highest)

B. Motion Planning Strategies

Considering the effects of the noise and meditation sets on path planning strategies, we reference the results in *Table 3*. Pink noise yielded the lowest ID_e for transition to a fixed-point trajectory from the limit cycle followed by white noise. We also note that the fixed-point dynamics were employed during all control trials, so the threshold for motion strategy transition may be lower and is unknown. Meditation and brown noise yielded even lower path planning strategy transitions; however, white noise was associated with a higher transition than both mediation and brown noise. There may be a correlation between the engagement of fixed-point dynamics and the type of noise listened to by the subject, but more data is required to conclude the existence of this relationship.

C. EEG Results Comparing Trials Sets for Each Wave Band

The results comparing trial sets among three increasing ID indicate that, for the lowest ID tested, white noise induced the highest alpha, low beta, high beta, and gamma wave band powers. The heightened brain activity across higher frequency wave bands indicates higher alertness to surroundings possibly due to the processing of an expansive range of frequencies at equivalent decibels. The participant's brain may have become overwhelmed by the wide scope of sound during the exercise, leading to reduced information processing rate for a given movement time.

For the mid-level ID trial, pink noise, followed by the control early on in the trial, induced the highest lower-frequency wavebands theta, alpha, and low beta. The subject may have been more relaxed during this trial, which had moderate difficulty. The pink noise may have amplified this state of relaxation, which improved information processing to carry out progressive motion. This supports the result found in by Zhou et al. (2012) [4], which stated that pink noise can reduce brain wave complexity. The control and meditation sets induced the greatest increases in higher-frequency wave band such as high beta and gamma, indicating the high focus, attention, and active alertness were able to be sustained throughout the moderately difficulty trial with ease. This may demonstrate that, without any additional sound, the subject was able to maintain high focus on a task with relatively mid-level difficulty of information to process. This meditation finding also supports the research of Stapleton et al. (2020) [11], who found that meditation increased higher frequency wave band powers. Moreover, meditation may not have significantly altered the participant's natural rest state or increased tiredness after the noise trials.

Lastly, for a high ID, the control resulted in the highest production of low frequency waves such as theta and alpha. All sets were associated with similarly low wave band powers for high frequency wave bands, including high beta and gamma. The high difficulty may have yielded a reduction in attention if it was too difficult, or its high difficulty raised susceptibility to distraction.

D. EEG Results Comparing Wave Bands Across ID's for Each Trial Set

For all low, moderate, and high difficulty trials and all sets of trials, a meditative and internally focused state associated with theta waves were maintained, and their highest band powers occurred at the low and high ID trials of the control set. This may have been due to the naturally relaxed state of the participant even during the control set. Pink noise may have had the most direct influence on the engagement of the theta waves because as ID increases, the theta waves produced, potentially to assist visuospatial information processing, also increased. Brown noise and meditation may have improved a balance of relaxation and alertness, as indicated by the high alpha wave band powers in these trial sets. Low activity across all higher frequency wave bands such as low beta, high beta, and gamma may indicate that these wave bands may not be as influential in visuospatial information processing and motor processing as theta waves.

E. Limitations

The order of increasing information rate-to-motion processing may have been influenced by factors such as volume and intensity of the noise [7]. The white noise may have been listened to at a high volume compared to the other sounds and resulted in lower rates of information processing for a given time of motion. Environmental noise could also impact results [9]. Furthermore, the consecutive execution of each trial set may have caused effects from one trial set to leak into subsequent sets. Finally, the fatigue of the subject can also slow processing rate, which could have skewed results such as the meditation set carried out at the end [10]. More data is necessary to confirm the correlative effects of ambient noise and meditation on information processing and performance during motion planning tasks.

VI. **References**

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VII. **Appendix**

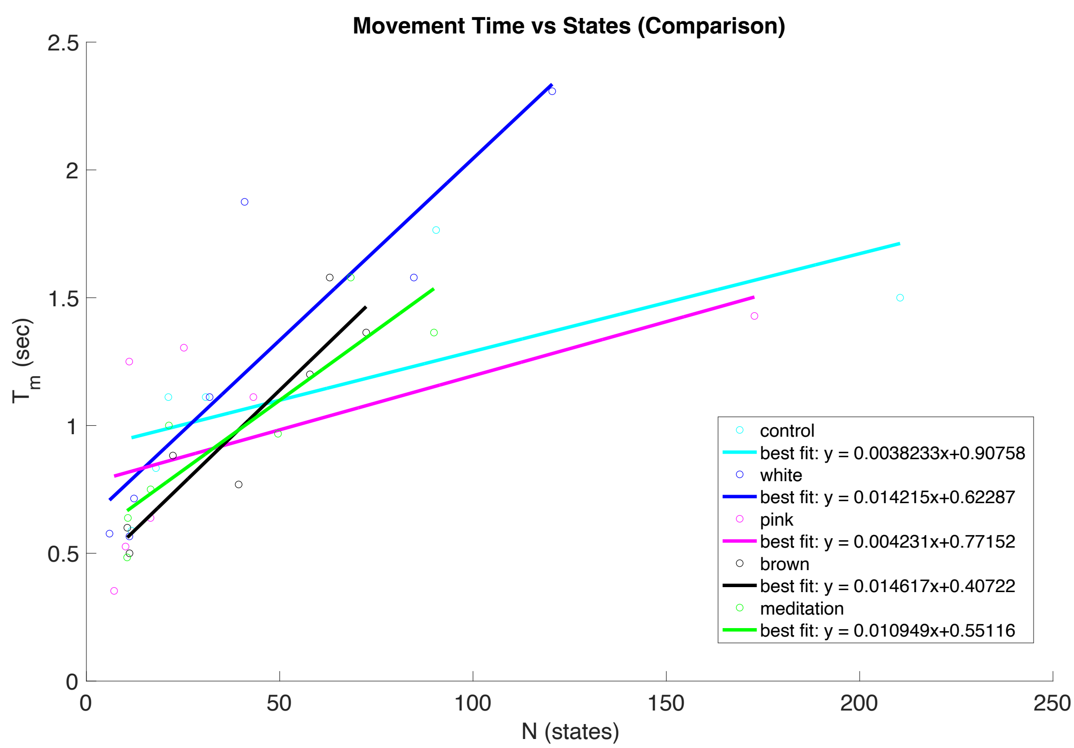

Figure 20: Comparison across sets of trials of movement time vs number of states