

Structured visual and somatosensory stimuli evoke modality-invariant positional and modality specific velocity dynamics during standing

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Abstract

Standing postural control is adaptable to environmental constraints. Center of pressure velocity during support surface translations shows the postural control system utilizes feedforward and feedback control mechanisms to adapt to different environmental structures. It is not clear whether the postural response to structured support surface stimuli is modality specific. This study investigated postural responses to support surface translations and visual surround rotations structured to mimic white, pink, or red noise. Positional entrainment was analyzed using cross correlation and cross sample entropy, and velocity responses were analyzed using mean velocity and detrended fluctuation analysis. Entrainment was strongest for red noise and weakest for white noise. Pink noise was similar to white noise for the support surface translations and red noise for the visual surround rotations. Short-term persistence of the postural response was weakened for support surface translations and strengthened for visual surround rotations, it was also affected by the persistence of the stimulus, with stronger response persistence associated with stronger temporal correlation. Long-term anti-persistence became stronger only in the support surface translations and average velocity increased in both modalities. These data indicate differential effects due to the modality of stimulus, but similar effects due to the structure of the stimulus.

Introduction

Standing posture is a complex task in which an individual interacts with the environment with the goal of maintaining the body's center of mass within the base of support. This involves a continuous flow of incoming sensory information, integration of that information to determine the body's position, velocity, and acceleration, and motor outputs that apply forces on the environment and alter body configuration to achieve this goal. Maintaining the center of mass within the base of support is primarily a position-based goal. However, it has been demonstrated that the sensorimotor system prefers velocity information when performing this task.¹ Therefore, investigating center of pressure velocity (COP_{vel}) responses give information about how the system is controlling posture for the task, and center of pressure position (COP_{pos}) gives information about how the task is being performed.

Feedback for postural control primarily comes through the visual, vestibular, and somatosensory systems.^{2,3} The visual system is stimulated by optic flow, which informs the central nervous system about the movement of the head in relation to the surrounding environment.⁴ The vestibular system provides information about linear movements of the head from the otoliths, and rotational movements of the head from the semi-circular canals.⁵ The vestibular information is with respect to the gravitational vertical. The somatosensory system is made up of several types of receptors, cutaneous mechanoreceptors and joint mechanoreceptors both provide information about posture.^{5,6} As the body sways the cutaneous mechanoreceptors on the plantar surface of the foot provide information about the center of pressure excursion and joint mechanoreceptors provide information about the relationship of

body segments to one another. All this information is integrated in the central nervous system to provide a representation of the body's position and movement.

Manipulating sensory information is a common way to perturb the postural control system or to assess the postural control system's ability to adapt to a changing environment. One method of changing the environment is to manipulate the support surface position, through translations or rotations. Previous research in this area primarily focused on postural responses to periodically moving support surfaces with a variety of postural adaptations noted.⁷⁻⁹ The authors have extended this work by looking at postural responses to support surface translations that contained varying degrees of complexity.^{10,11} This was done by manipulating the strength of persistence of the movement, using uncorrelated white noise movements (no persistence), moderately correlated pink (moderate persistence), and red noise signals (strong persistence), and near perfectly correlated sine wave signals (very strong persistence). It was determined that the persistence of the postural control system trends towards the persistence of support surface movements, indicating that the sensorimotor system can utilize feedback contained in the stimulus to modulate the postural responses.

Another common method of inducing postural responses is the "moving room" paradigm, where a visual perturbation induces sense of postural sway.¹²⁻¹⁴ This sense of postural sway results in postural responses such as swaying in the direction of the visual movement,¹⁵ increasing sway amplitude as visual motion amplitude increases,¹⁶ and a tendency to couple postural sway with the visual patterns.¹⁷ Similar to the support surface translation literature, the majority of work using visual movements to induce postural sway has been performed using sinusoidal translations. Some of the work uses more complex sum of sines manipulations^{17,18} and demonstrates differences between single sine wave inputs and sum of sines, however, these signals still contain inherent periodicities and persistence that allow the system to utilize feedback effectively when modulating postural responses. Thus, the effect of visual stimuli structured according to signal persistence on postural dynamics is unclear.

Another study by the authors has looked at the COP_{vel} responses to support surface translations that contained different strengths of persistence as well as moving at different velocities.¹⁰ It is hypothesized that the short-term persistent region indicates feedforward control mechanisms, while the long-term anti-persistent region indicates feedback control mechanisms.¹⁹ These data showed that the critical point where the system transitioned between persistence and anti-persistence increased as velocity increased and as the strength of persistence of the stimulus increased. This supports the hypothesis that the short-term persistence indicates a feedforward mechanism being dominant. It still needs to be determined if a similar phenomenon exists using different stimulus modalities such as visual stimuli.

Studies have also been conducted where the participant was instructed to sway to a moving target in a tracking task. There are clear differences in how participants track a moving target between a single sine wave stimulus and sum of sines stimulus.^{20,21} When this target tracking task was extrapolated to include not only unpredictable but also a chaotic stimulus it was determined that a higher coherence was found

when tracking the chaotic structure.²² There are potential differences between asking a participant to sway with a target they see on a screen and just putting them in an environment where the visual scene is moving with no instruction. It is still unclear how the postural system responds when the visual surround is manipulated according to different strengths of persistence.

The purpose of this research was to determine the postural responses to a visual stimulus that contains different temporal correlations and compare those to the postural responses of support surface translations. We hypothesized that both support surface and visual stimuli will result in increased sway velocity, weaker short-term persistence, and stronger long-term anti-persistence compared to the no stimuli condition. We also hypothesized that both support surface and visual stimuli will show the weakest entrainment with postural sway for the white noise condition and the strongest entrainment with postural sway in the red noise condition. Finally, it is hypothesized that there will be differential effects of the stimulus modalities, with the support surface translations resulting in stronger effects.

Methods

Subjects

For this study 15 young subjects were collected (12M/3F; age 25 ± 2 years; height 179.1 ± 9.0 cm; mass 89.3 ± 15.7 kg). Participants were recruited through convenience sampling and were students or employees at the University of Nebraska at Omaha. All procedures were approved by the Institutional Review Board at the University of Nebraska Medical Center and conducted in accordance with the relevant guidelines. All participants provided informed consent. Inclusion criteria was between 19 and 35 years of age and able to stand for approximately one hour with breaks as needed. Exclusion criteria was any lower limb dysfunction, peripheral neuropathy, or history of falling in the previous year not due to participation in sports.

Experimental Design

Participants came to the lab for two visits where posture was measured during normal standing and with environmental manipulations on the Neurocom® Balance Manager (Natus Medical Inc. Pleasanton, CA). On one visit the support surface was translated to provide a somatosensory stimulus, and on the other visit the visual surround was rotated to provide a visual stimulus (Fig. 1). During each visit participants stood in a relaxed side-by-side stance with the width between the lateral calcanei standardized based on height (22 cm, 26 cm, or 30 cm width based on heights of 76–140 cm, 141–165 cm, and 166–203 cm respectively) while center of pressure was recorded using the force platform of the Neurocom. An Optotrack Certus (Northern Digital Inc. Waterloo, Ontario, Canada) active marker motion capture system was used to record the positions of the heel, sacrum, upper trunk (~ C7), and the head.

Creation of stimulus signals

The somatosensory and visual stimulus was organized with varying levels of temporal persistence, no temporal correlation (white noise), moderate temporal correlation (pink noise), and strong temporal

correlation (red noise). All the signals used for the somatosensory and visual stimuli were created in Matlab (Mathworks, Natick, MA) using custom functions. The stimuli were based on a 10 Hz signal, which resulted in vectors that were 1200 time points in length for a 2-minute trial. The white noise time series was created using the randn function, and the pink and red noise were created by filtering out the high frequency components to get a $1/f$ and $1/f^2$ power spectrum respectively. All time-series were run through the DFA algorithm with a scaling region of [16, 200], and only accepted if they fell within ± 0.02 of the expected alpha value (0.5 for white noise, 1.0 for pink noise, and 1.5 for red noise). Once the temporal structure of the signal was considered acceptable then it was scaled to result in an average movement velocity of $1.2 \text{ cm}\cdot\text{s}^{-1}$ for the support surface translations and $1.0^\circ\cdot\text{s}^{-1}$ for the visual surround translations. This was repeated enough times that separate white, pink, and red noise time series were created for everyone. These time series were printed to a text file that could be loaded into the Neurocom to drive the position of the support surface or visual surround.

Experimental Conditions

Participants completed four conditions that were two-minutes in length. Condition 1 was always quiet stance, conditions 2–4 were the stimuli randomized (white, pink, red noise). This was done with support surface translations as well as visual rotations.

Laboratory visit

Before participants arrived, the stimuli were loaded into the Neurocom. The Optotrack motion capture system was initialized to match the coordinate system of the Neurocom force plate. During the first visit participants were consented and a short demographics/health history form was completed. Participants were then fitted with the fall harness and placed on the force platform of the Neurocom. Tape was placed on the force platform to create an outline of their feet. This allowed them to move their legs between trials and easily return to the same position for the next trial. The motion capture markers were then affixed, and the participants were instructed to stand in a comfortable fashion with their arms at their sides and keeping their gaze towards the visual surround of the Neurocom. They were also instructed to try and avoid any "fast" movements of the head or arms during the trials.

Data Analysis

This study looked at COP_{pos} and COP_{vel} using linear and nonlinear data analysis. Figure 2 displays example input signals and the resultant COP_{pos} and COP_{vel} signals for each condition. All trials were analyzed using mean COP velocity, and the temporal persistence of COP velocity (both short and long timescales). Trials that had a stimulus present were also analyzed using cross correlation analysis and cross sample entropy. For the support surface translation trials, the AP position of the support surface was compared with the AP COP_{pos} . For the visual rotation trials the degree of rotation in the sagittal plane was compared with an estimated sway rotation in the sagittal plane. This was estimated by calculating the angle from gravitational vertical of the line formed by connecting the heel and sacral marker. Initially the time series from the Neurocom and NDI Optotrack were exported and combined into a Matlab structure. These data were then further analyzed using custom written Matlab scripts.

Mean COP velocity

Mean COP velocity was calculated as the average of the differenced COP position time series.

Temporal correlation of COP velocity

To determine the temporal correlations of the COP velocity time series a modified DFA algorithm was used. This method is the same as DFA up to the point of plotting the log/log plot. The modified method has the user select a cross over region and the short and long timescales, and then continues with the traditional DFA algorithm to determine the alpha value at those regions. Briefly the method is as follows: the time series is integrated and divided into boxes of length n , where n will range from a size of 3 to half of the data length. The boxes are detrended by subtracting a line of best fit and a root mean square (rms) is calculated for all the different boxes. The average rms is determined for each box size and this is plotted on a log/log plot, with box size on the x-axis and rms fluctuation on the y-axis. The user selects the area where the plot transitions from a persistent slope to an anti-persistent slope, then selects the beginning and end of the persistent region and beginning and end of the anti-persistent region. This ensures that only linear regions of the log/log plot are being used for analysis. A line of best fit is determined for the two linear regions and the slope of that line is returned as the alpha value for the respective region resulting in a short-alpha value for the persistent and a long-alpha for the anti-persistent region.

Cross-correlation

Cross correlation measures the Pearson correlation of two time-series at different lag values. A lag of 0 means the time series are correlated in their normal state and lags $\pm N$ mean the time series are offset by N data points before being correlated. This allows correlations to be performed at different time points to allow one system to lead or lag the other system. For this analysis, the maximum absolute value at a range of ± 5 seconds was used. This means the strongest correlation was found regardless of whether it was a positive or negative correlation and whether the participant was leading or lagging the stimulus within a five second window.

Cross sample entropy

Cross sample entropy is a method of determining the probability that patterns within one time series are present in another time series and was implemented according to Richman and Moorman²³. Briefly, two time-series are compared to each other to look for similar patterns. A pattern of length m is taken from one time series and compared to all patterns of length m in the other time series, they are considered a match if the beginning or end point of the pattern fall within a tolerance denoted as r . This is repeated for all patterns of length m within the time series and the total number of matches is counted, denoted as A . Then the same process is repeated for patterns of length $m + 1$ and the total matches are denoted as B . Finally, the calculation of cross sample entropy is $-\ln(A/B)$ and defines the probability that vectors of length m and vectors of length $m + 1$ will be found in the two time-series. Values close to zero indicate

many matches, and higher values indicate fewer matches. For this analysis, the data were first Z-score normalized and the parameters used were $m = 2$ and $r = 0.2 \times \text{standard deviation}$.

Statistical Analysis

Statistics were calculated using GraphPad Prism V6 (GraphPad Software, La Jolla, CA). Separate two-way repeated measures ANOVAs were used to calculate the effect of stimulus mode (support surface or visual surround) and temporal correlation (pink, white, or red noise) for each of the dependent variables. Post-hoc follow up was done using a Tukey test. Significance was set to an alpha level of 0.05.

Results

A two-way repeated measures ANOVA with Tukey post-hoc was calculated for all variables. For the velocity-based measures there were four levels of temporal correlation (no stimulus, white noise, pink noise, and red noise) and for the entrainment measures there were three levels of temporal correlation (white noise, pink noise, and red noise), all measures were compared between stimulus mode (support surface and visual surround).

Average COP velocity showed an effect of stimulus mode ($F(1, 14) = 108.4, p < .0001$; Fig. 3A), temporal correlation ($F(3, 42) = 72.0, p < .0001$; Fig. 3C), and an interaction between temporal correlation and stimulus mode ($F(3, 42) = 52.1, p < .0001$; Fig. 3E). Overall sway velocity was higher when the temporal correlation was stronger, and higher in the support surface condition compared to visual surround. The interaction was seen due to velocity increasing with strength of persistence in the support surface condition while remaining the same across temporal correlation levels in the visual surround condition (Fig. 4A).

Short alpha value showed an effect of stimulus mode ($F(1, 14) = 28.0, p = .0001$; Fig. 3B), temporal correlation ($F(3, 42) = 5.38, p = .0032$; Fig. 3D), and an interaction between temporal correlation and stimulus mode ($F(3, 42) = 25.8, p < .0001$; Fig. 3F). Overall short-term persistence was stronger when the temporal correlation was stronger, and stronger in the visual surround condition compared to the support surface condition, the interaction was seen due to postural persistence increasing with increased temporal correlation in the support surface condition while remaining the same across temporal correlations in the visual surround condition (Fig. 4B).

Long alpha value showed no effect of stimulus mode ($F(1, 14) = 2.37, p = .1462$), an effect of temporal correlation ($F(3, 42) = 8.8, p < .0001$), and no persistence by stimulus mode interaction ($F(3, 42) = 0.35, p = .7897$). There was a strengthening in anti-persistence with movement compared to no movement, but differences were not seen between the different strengths of persistence within the stimuli (Fig. 4C).

Cross sample entropy showed an effect of stimulus mode ($F(1, 14) = 244, p < .0001$; Figure 5A), an effect of temporal correlation ($F(2, 28) = 525, p < .0001$; Fig. 5C), and a persistence by stimulus mode interaction ($F(2, 28) = 6.76, p = .0040$; Fig. 5E). The strength of coupling increased as the strength of persistence increased. The visual surround stimulus had stronger coupling compared to the support

surface stimulus. The interaction occurred because the visual surround stimulus had an increased strength of coupling when moving from white to pink noise, but the support surface stimulus did not exhibit this response (Fig. 6B).

Cross-correlation had an effect of temporal correlation ($F(2, 28) = 64.0, p < .0001$; Fig. 5D), no effect of stimulus mode ($F(1, 14) = 2.3, p = .1512$; Fig. 5B), and a persistence by stimulus mode interaction ($F(2, 28) = 4.9, p = .0152$; Fig. 5F). The strength of correlation increased as the strength of persistence increased in both stimulus modes. However, in the support surface stimulus there was a larger increase in correlation strength during the red noise condition compared to the visual surround stimulus (Fig. 6A).

Discussion

The goal of this research was to determine the postural responses to support surface and visual stimuli that contained different strengths of persistence. The COP_{vel} was analyzed during each stimulus and compared to quiet stance with no stimuli. Then entrainment of the COP_{pos} was analyzed to see how well the output of the postural control system matched the input of the stimuli. It was hypothesized that overall velocity would be increased in movement trials compared to quiet stance. This was partially supported as the average movement velocity was increased for all movement conditions in the SSTs and slightly increased for pink and red noise during the VSRs. It was hypothesized that there would be weaker short-term persistence and stronger long-term anti-persistence during movement trials compared to quiet stance. This was partially supported; the short-term persistence was weakened, and long-term anti-persistence was strengthened in the SSTs but not in the VSRs. When looking at position-based measures it was hypothesized that both modalities would demonstrate a stronger entrainment with the stimuli which had stronger persistence. This hypothesis was supported overall with the red noise stimuli resulting in the strongest entrainment. Finally, it was hypothesized that the SSTs would result in a stronger response compared to the VSRs due to the differences in sensory perception, this was partially supported for velocity-based measures, but not for position-based measures.

Modality specific velocity responses

COP_{vel} responses were analyzed using a modified DFA algorithm to determine the strength of persistence on the short timescale (short alpha) and strength of anti-persistence on the long time-scale (long alpha), as well as average COP_{vel} . The velocity responses were modality specific such that the behavioral response to visual inputs differed from that of somatosensory inputs.

Short alpha value

The short alpha value of a COP_{vel} time series indicates the strength of persistence in the short time scale. It is hypothesized that the presence and size of this region may indicate a reliance on feedforward control.^{10,19} The values during standing with no stimulus resulted in an alpha value just above 1.0, a slightly stronger persistence than a pink noise signal. Support surface stimuli resulted in a weakening of

the persistence, however, the strength of persistence in the COP response increased along with increased persistence of the stimuli. Visual surround stimuli resulted in a strengthening of persistence for the pink and red noise conditions, but white noise was no different from quiet stance. The support surface condition provides a sensory stimulus through the somatosensory system as well as a change to the physical task constraints.⁷ With the visual surround condition, the stimuli are purely sensory, there is no change to the physical constraint of the postural control system. Therefore, the task constraints during support surface conditions may not allow the system to maintain as strong of a persistence, this effect scales with the strength of persistence of the stimuli. In the white noise condition, the feedback from the support surface movements do not provide information about future movements, as the strength of persistence increases the information in the feedback increases, which results in a response that has stronger persistence. In the visual conditions the base of support is not physically changed so the postural control system does not have to adjust to maintain posture. However, there is a strengthening of persistence in the red and pink noise, this may be due to the system constraining its movements as a mechanism to deal with the visual movements. There also may be a ceiling effect in the COP_{vel} short-term persistence. If the system moves too close towards red noise (Brownian motion) then it runs the risk of becoming too constrained and losing flexibility. Therefore, the system may strengthen the short-term persistence enough to cope with the visual stimulus, but not increase beyond a certain level because it would result in decreased flexibility.

Long alpha value

The long alpha value in a COP_{vel} time series indicates the strength of anti-persistence. Because of the time scale where this region exists it is associated with feedback mechanisms.^{10,19,24} Although this region has been associated with feedback mechanisms, not much research has looked at the biological interpretations of the strength of anti-persistence. Basic time series analysis suggests that stronger anti-persistence (lower alpha value) indicates more periodicity in the timing and/or magnitude of the increases and decreases of the anti-persistent region. The white and pink noise stimuli in the support surface condition had stronger anti-persistence than quiet stance, so even though the strength of the persistent region was weaker there was more periodic fluctuation between the increases and decreases in COP_{vel} during these conditions. This reveals an additional strategy for adapting to the stimuli. Increasing the strength of the anti-persistent region may allow the system to maintain control while the persistent region is weakened.

Average COP_{vel}

The average COP_{vel} indicates overall how fast the COP is moving. The COP_{vel} was increased in all movement conditions during support surface translations and slightly increased for pink and red noise stimuli in the visual surround rotations.

Overall, the velocity dynamics of posture demonstrated variance between the two sensory modalities. This indicates differences in the way sensory information is utilized when controlling the velocity of postural sway. In the support surface translation conditions, the postural control system became more

dependent on feedback, which can be seen by a weakening of the short-term persistence.^{10,25} Additionally, as the temporal correlation strengthened in the input signal the short-term persistence increased. In the visual surround rotations, the postural control system was able to maintain feedforward processes, which can be seen by an increase in short-term persistence across all movement trials.

Research looking into the saccades demonstrate that they make an abrupt transition from reactive to predictive behavior at a specific frequency (0.5–0.7 Hz).²⁶ The current research demonstrated that the input and output signals were more tightly coupled when the signal contained more power in the lower frequencies (red noise). Although the trend was similar between modalities this effect was stronger in the visual condition. Additionally, muscle spindles are a large part of the somatosensory system, and they are uniquely tuned to detect velocity information.²⁷ This may contribute to the increases in COP_{vel} during the support surface translations that was not seen in the visual conditions.

Additionally, visual information reaches the cortex quicker due to speed of nerve transmission and distance traveled. Somatosensory information is made up from several different types of receptors (muscle and joint proprioceptors and skin mechanoreceptors) which likely results in additional processing time for this type of information. This may be why the visual system was able to entrain stronger with the pink noise movements when compared to white noise, while the somatosensory system did not.

Modality invariant positional responses

Two measures were used to determine the entrainment between the position of the stimuli and the COP_{pos} . Cross sample entropy analyzes the probability that patterns in one time series are present in the other time series, and cross correlation analyzes the linear dependence between the signals. Entrainment of positional dynamics with different temporal correlations remained invariant between sensory modalities. There were some differences in the strength of entrainment overall but the responses to strengths of temporal correlation remained invariant.

Cross sample entropy

Cross sample entropy measures the probability that patterns in one time series are present in another time series. Low sample entropy means the time series have many similar patterns and higher entropy means less similar patterns (Richman, J. S. & Moorman, J. R., 2000). In the support surface conditions the white and pink stimuli resulted in higher entropy values, but the red noise stimulus had lower entropy. The strength of persistence in the red noise condition allowed the system to match the patterns of the COP_{pos} response to the patterns present in the stimulus. In the visual surround conditions, all the stimuli resulted in different responses, with white having the highest entropy, pink in the middle, and red having the lowest entropy. When the stimulus is random the response of the COP_{pos} does not match as well, and as the strength of temporal correlation increases the COP_{pos} matches better.

Cross correlation

The cross correlation looked at lag values of ± 5 seconds and the absolute value of the strongest correlation was determined. The cross correlation showed similar trends to the cross sample entropy in the support surface conditions, with stronger entrainment to the red noise signal but no difference between white and pink. However, in the visual condition cross correlation did not distinguish between the entrainment to the red or pink signals. The visual stimuli, being a purely sensory task, allows the system to differentiate between the white and pink noise signals. However, when the support surface is being moved the system does not make this distinction.

Limitations

The comparison between modalities is not always clear because the VSR is purely a sensory stimulus where the SST has a sensory and a mechanical component. Because postural control is a multisensory task it is hard to differentiate how much vestibular or somatosensory information helps during a visual entrainment task, or how much vestibular or vision helps during a somatosensory task. However, the goal of this research was to better understand each systems role in adapting to sensory input without delving into the intricacies of multisensory integration.

Conclusions and future directions

Rotations of the visual surround and support surface translations can induce changes in the structure of postural responses. The persistence in the velocity response and the entrainment strengthens as the persistence of the stimulus strengthens. However, there are clear differences between visual and somatosensory stimuli. Furthermore, the frequency of perception for visual and somatosensory stimuli are different which may account for some of the differences in postural responses.

Future research should investigate the multisensory contributions more by perturbing the sensory systems during an entrainment task. By providing a visual stimulus and perturbing the somatosensory system and/or the vestibular system it will be possible to investigate the contributions of these systems to the visual task. Likewise, when providing a somatosensory stimulus and perturbing the visual and/or vestibular systems it will be possible to investigate the sensory contributions of these systems to the somatosensory task.

Declarations

Author Contributions

Study Design – TR, MM

Data Collection and Statistical Analysis – TR

Manuscript writing and submission – TR, MM

Data availability statement

All data is available by written request to Mukul Mukherjee at mmukherjee@unomaha.edu.

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Figures

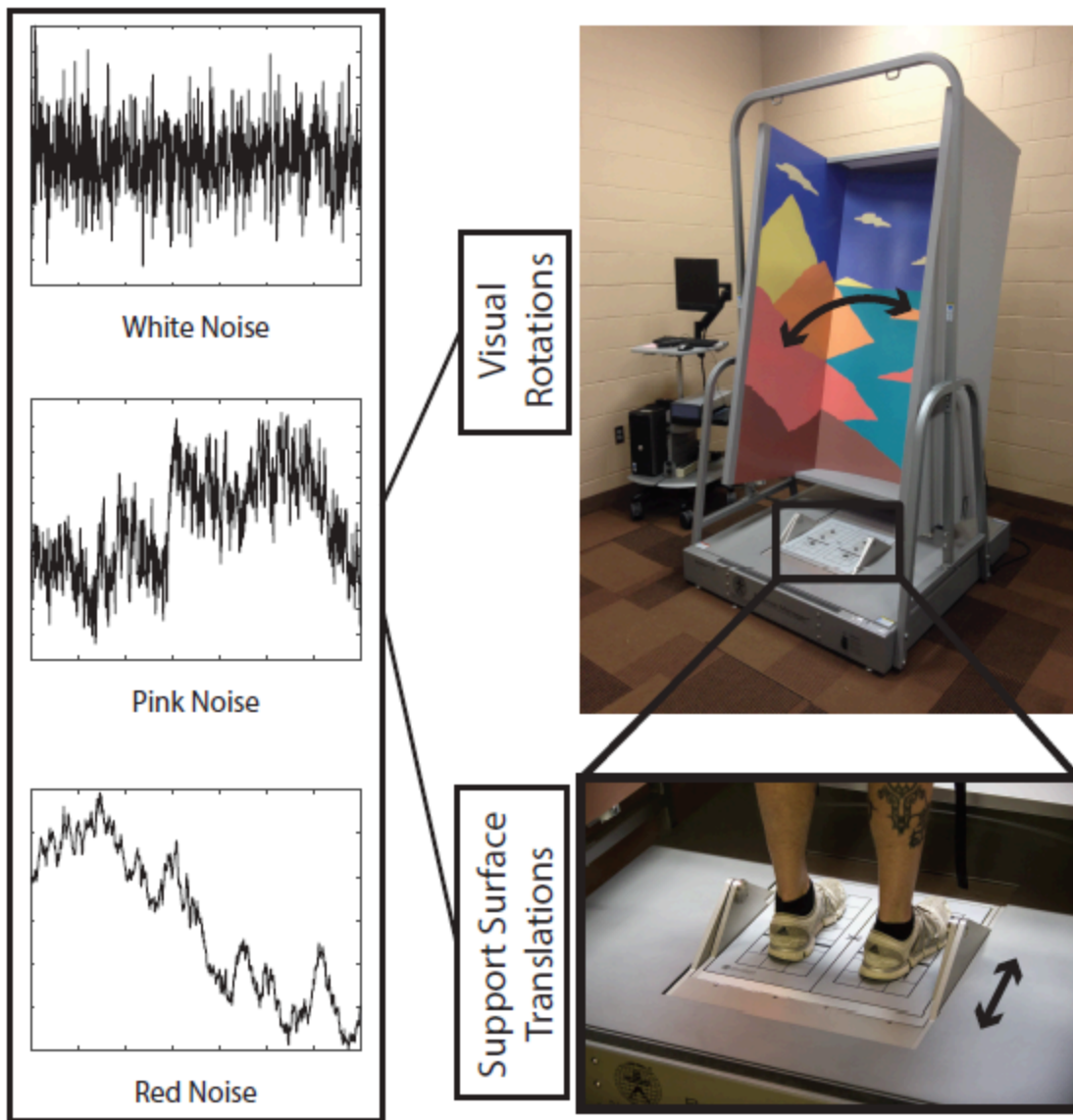


Figure 1

This figure shows the experimental setup. Three signals with different temporal correlations were used to drive the rotations of the visual surround or the anteroposterior translations of the support surface.

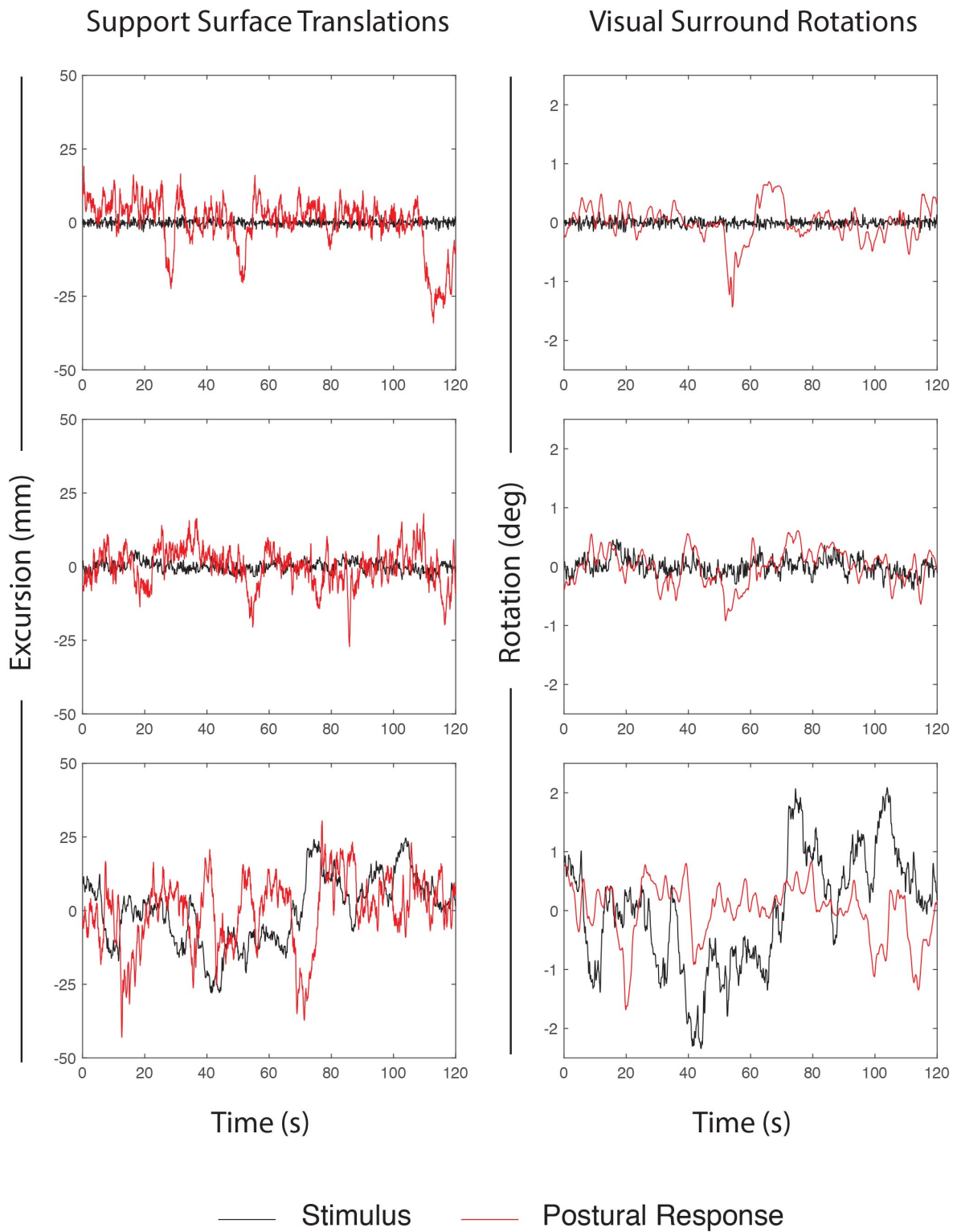


Figure 2

Example of the stimulus signal (black line) and the postural response (red line) for white noise (A,B), pink noise (C, D), and red noise (E, F) in the support surface translation (A, C, E) and visual rotations (B, D, F).

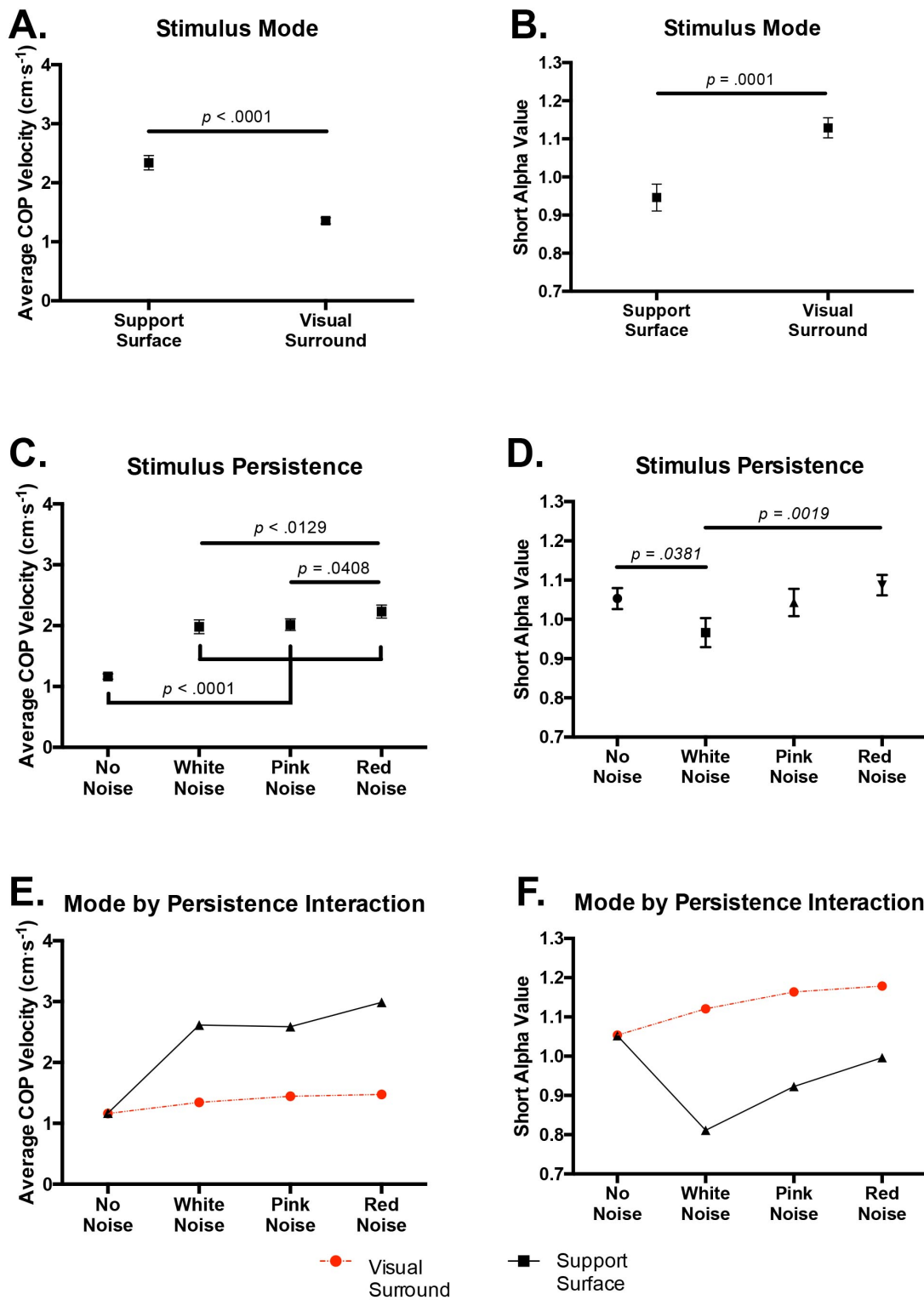


Figure 3

ANOVA results for average COP velocity and short-term persistence.

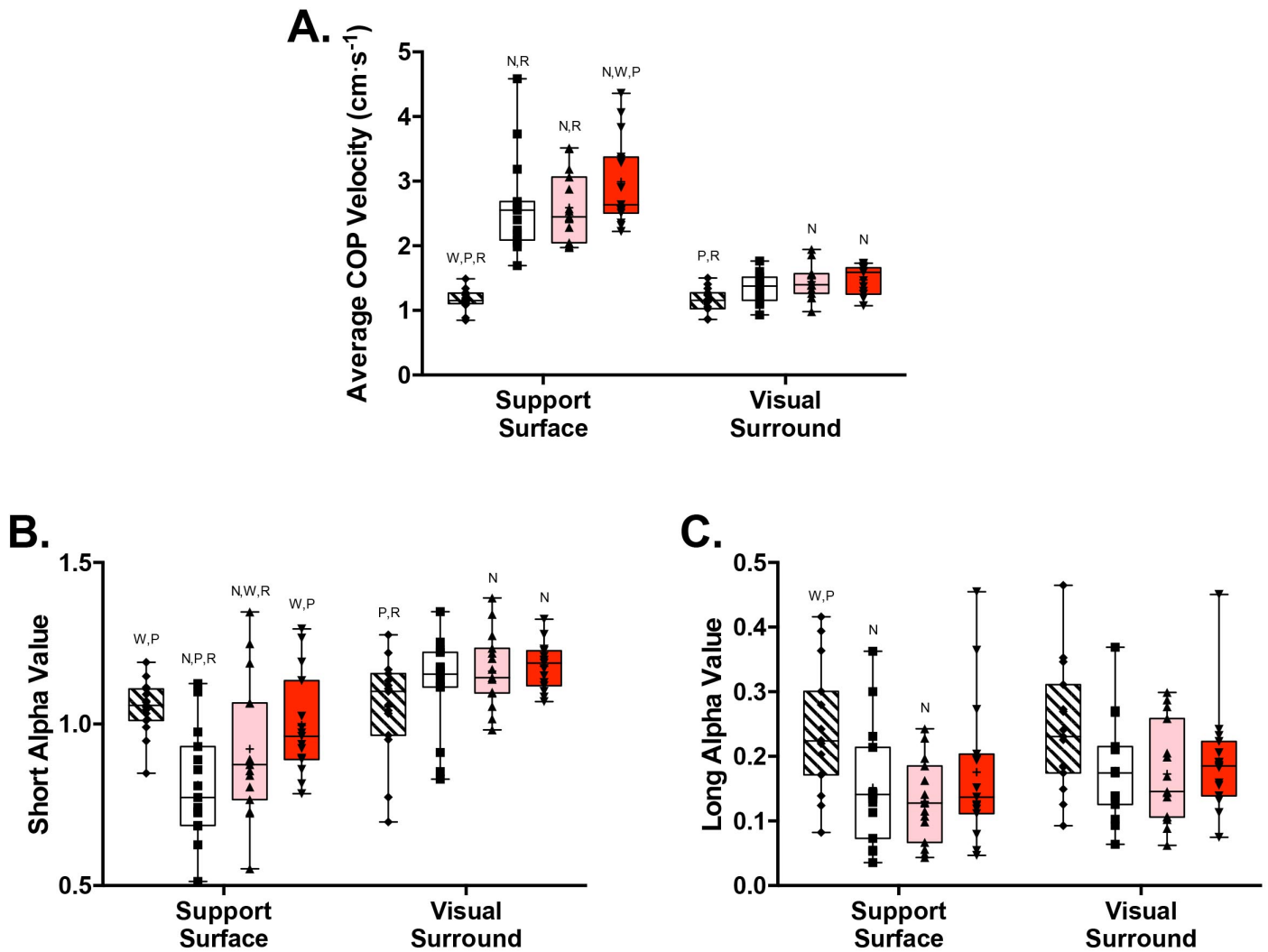


Figure 4

Box and whisker plots of velocity-based measures. The line is the median value, edge of the box is the 25th and 75th percentile, and the error bars go to the minimum and maximum values. Individual values are also shown. Average COP velocity (A) was higher in all three movement conditions for the support surface translations and in the pink and red conditions for the visual surround movements. Short alpha value (B) was reduced in the support surface conditions but increased as the strength of persistence of the input signal increased and increased for pink and red noise inputs in the visual surround condition. Long alpha value (C) was reduced in the white and pink input conditions for the support surface translations but not in the visual surround movements.

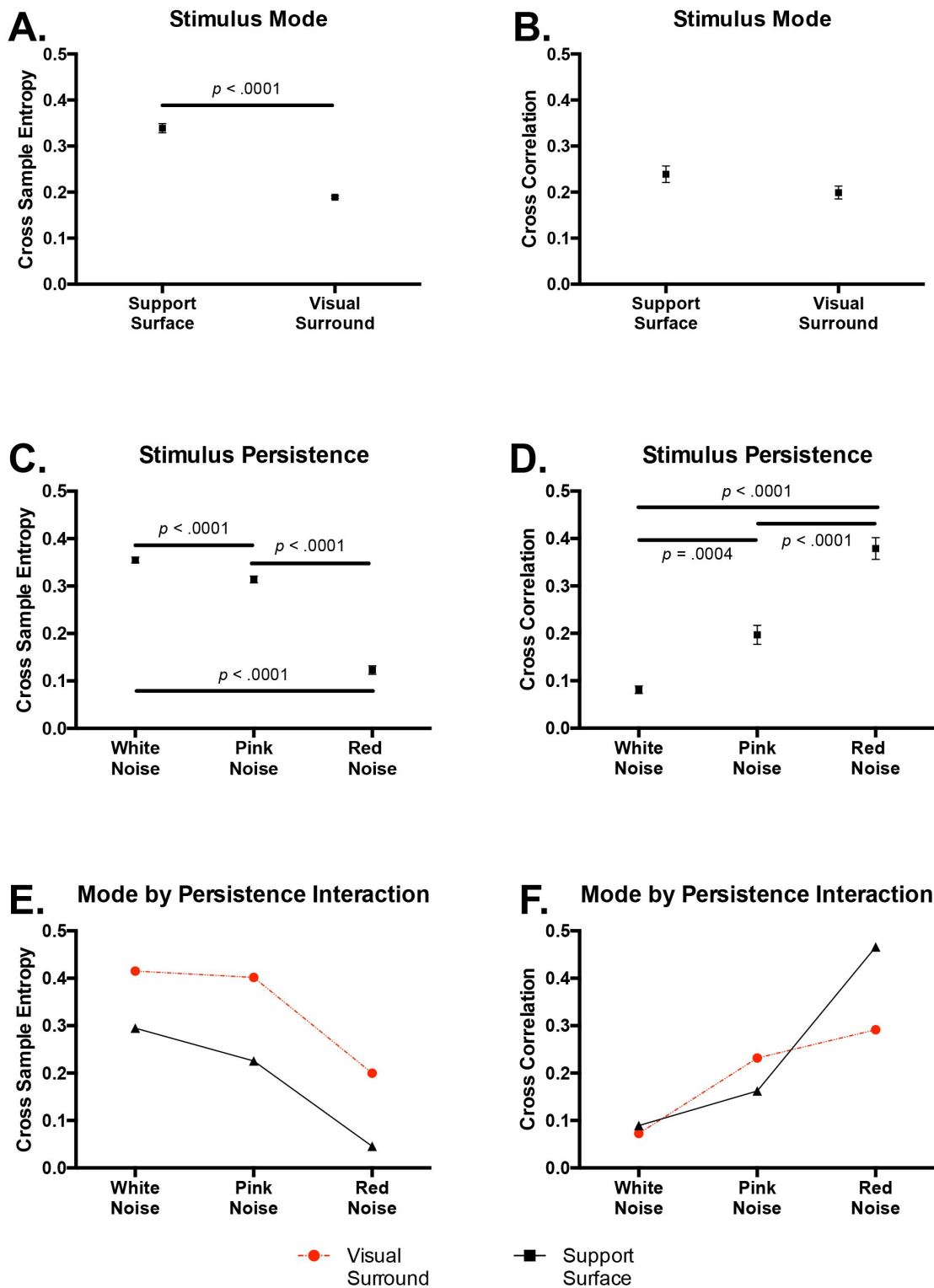


Figure 5

ANOVA results for cross sample entropy and cross correlation.

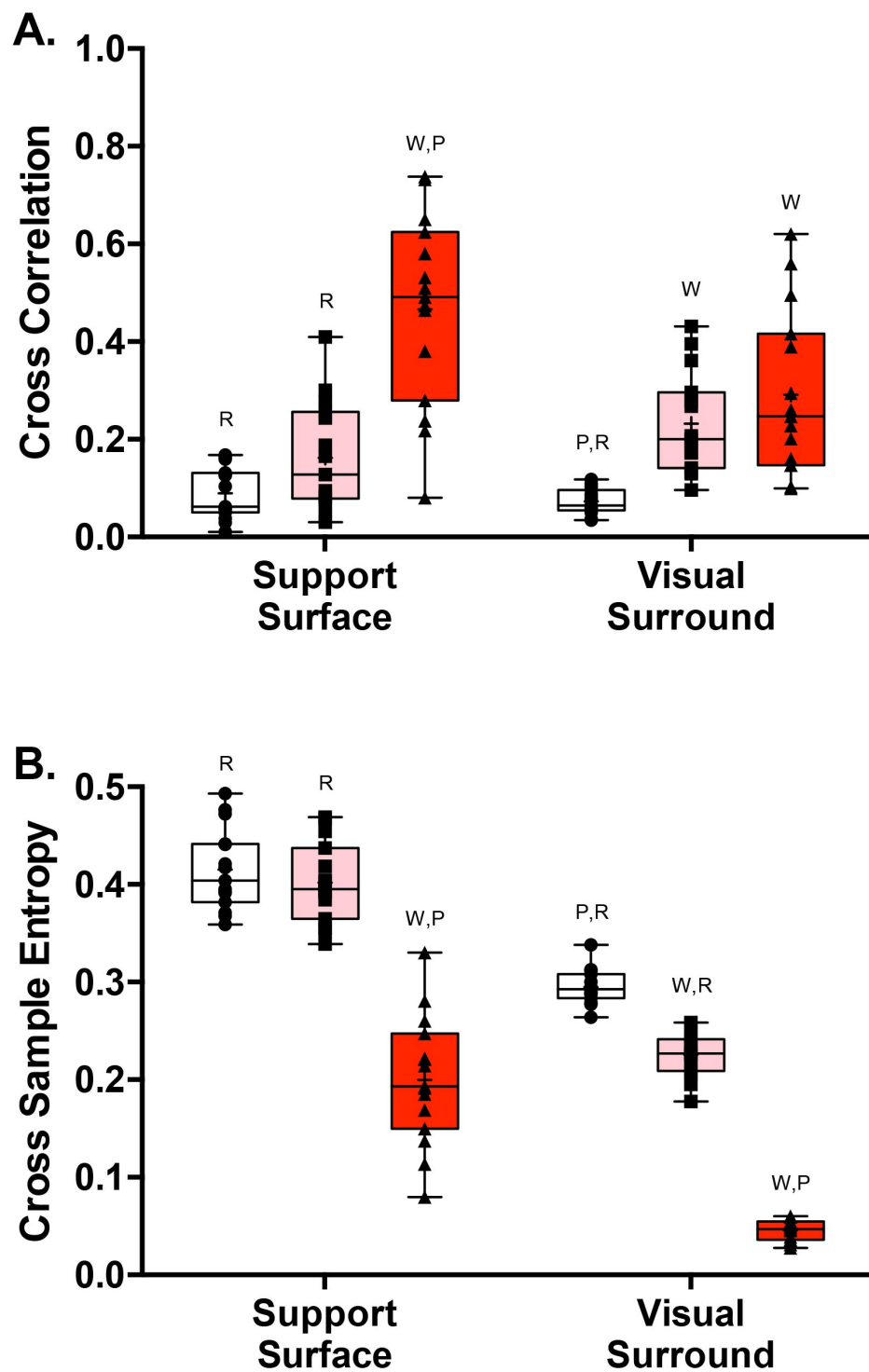


Figure 6

Box and whisker plots of entrainment measures. The line is the median value, edge of the box is the 25th and 75th percentile, and the error bars go to the minimum and maximum values. Individual values are also shown. Cross correlation (A) showed the weakest entrainment during the white noise condition and strongest entrainment in the red noise condition in both modalities. Pink noise showed a stronger entrainment than white in the visual surround condition but not the support surface condition, and red

noise showed a stronger entrainment than pink noise in the support surface condition but not in the visual surround condition. When looking at cross sample entropy (B) the support surface conditions followed the same pattern as cross correlation, however, the visual surround conditions were all different from each other, with white noise being the weakest, pink noise moderate, and red noise the strongest entrainment.