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Interaction of Intention and Environmental Constraints on the Fractal Dynamics of Human Performance

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Abstract

The current study investigated whether the influence of available task constraints on power-law scaling might be moderated by a participant's task intention. Participants performed a simple rhythmic movement task with the intention of controlling either movement period or amplitude, either with or without an experimental stimulus designed to constrain period. In the absence of the stimulus, differences in intention did not produce any changes in power-law scaling. When the stimulus was present, however, a shift toward more random fluctuations occurred in the corresponding task dimension, regardless of participants' intentions. More importantly, participants' intentions interacted with available task constraints to produce an even greater shift toward random variation when the task dimension constrained by the stimulus was also the dimension the participant intended to control. Together, the results suggest that intentions serve to more tightly constrain behavior to existing environmental constraints, evidenced by changes in the fractal scaling of task performance.

Keywords

intention; volition; fractals; $1/f$ noise; motor control

Over the past several decades, a substantial amount of research has indicated that human cognitive and motor performances do not produce random variation around a central tendency, but instead are better characterized by power-law scaled fluctuations lacking a stable mean and variance (e.g., Delignieres, Fortes, & Ninot, 2004; Gilden, Thornton, & Mallon, 1995; Van Orden, Holden, & Turvey, 2003). Time series of human performances (e.g., reaction time, memory retrieval, self-esteem evaluations) tend to reveal non-random patterns of variation where the size of deviations (S) scales as a constant power of how often deviations of that size occur (f), $S(f) = 1/f^{\alpha}$. In such power-law behavior, the scaling exponent (α) captures the dynamic patterning in the time series, with human performances typically producing patterns of fluctuation with $\alpha \approx 1$; often termed $1/f$, or pink noise (Van Orden, Kloos, & Wallot, 2011).

Pink noise is ‘fractal’, or statistically self-similar, such that fluctuations in behavior are approximately scale-invariant (see Brown & Liebovitch, 2010). That is, fractal series display nested ‘waves’ of fluctuation, with the same amplitude-frequency relation characterizing the larger and smaller waves of variability in performance (Holden, 2005). Finding such scale-invariant structure is meaningful, as it implies that the causal processes underlying behavior operate across multiple timescales simultaneously and result in ‘persistent’, long-range correlated structure in the time-evolving behavior. These qualities stand in stark contrast to the white noise, random variation traditionally assumed to characterize human behavior, wherein there is no inherent relation in the size and frequency of variation (i.e., $\alpha \approx 0$) and successive observations are independent of one another.

Previous researchers have suggested that pink noise might be an intrinsic property of localizable cognitive or neural mechanisms (e.g., Delignieres, Lemoine, & Torre, 2004). An alternative model, more consistent with embodied-embedded approaches to human behavior, is that pink noise is a general property of ‘interaction-dominant’ systems (e.g., Holden, Choi, Amazeen, & Van Orden, 2011; Kello, Beltz, Holden, & Van Orden, 2007). The core idea of interaction-dominant dynamics is that the activity of any given behavioral unit (e.g., neural, motoric, perceptual, or cognitive structures or processes) is functionally dependent on the activity of other units. Hence, the measured behavior of an interaction-dominant system reflects the *coordination* of many componential processes. Theoretically, it is this manner of non-linear, complex system organization that gives rise to pink noise (e.g., Holden, Van Orden, & Turvey, 2009; Stephen & Mirman, 2010).

Although many human behaviors are characterized by pink noise (i.e., $0.5 < \alpha < 1$), there is ample evidence that both experimental manipulations and quasi-experimental conditions yield reliable deviations from this ‘natural’ fractal scaling (e.g., Chen, Ding & Kelso, 2001; Goldberger, Peng, & Lipsitz, 2002; Delignieres, Torre & Lemoine 2009). Van Orden and colleagues proposed a synthesized model to account for these observations that is consistent with interaction-dominant approaches and grounded on the core concepts of *coordination* and *constraint* (Van Orden et al., 2011). This model asserts that the scaling of an observed behavior reflects the degree to which the component processes have been constrained to operate as a single, coordinated system. In its final form, it specifies that the scaling in behavior equates to a balance of *voluntary* sources of control against *involuntary* sources of control (Van Orden et al., 2011). Pink noise therefore results when a balance of strong, rigid task constraints and more flexible, participant-enacted constraints exist to limit the degrees-of-freedom and sustain the task goal. Alternatively, conditions that give rise to greater relative influence of either rigid or flexible constraints result in deviations from pink noise. Conditions that involve a relative increase in rigid constraints, and subsequently result in involuntary behavioral control, consistently lead to ‘overly random’ variation and shifts in the fractal scaling toward white noise (or lower α values) (e.g., Kello et al., 2007). Conversely, conditions demanding greater voluntary control, (i.e., the environment does not provide enough rigid constraint to support successful task performance), constitute a relative increase in the recruitment of additional flexible constraints, lead to ‘overly regular’ variation and shift scaling toward brown noise (or higher α values) (e.g., Chen et al., 2001).

A summary of the proposed theoretical relationship between constraint, control, and fractal scaling from this model can be found in Table 1.

The current study was designed to investigate these aspects of control, constraint, and fractal scaling with respect to how they might be affected by a manipulation of the intention participants assumed during performance of a simple rhythmic coordination task. Specifically, we hoped to define the effect of intending to control one particular aspect of behavior both with and without environmental constraints. Outside the field of research on fractal scaling, there are several well-established effects of intention on the dynamics of behavioral performance. For instance, research on rhythmic movement coordination (see Kelso, 1995; Schmidt & Richardson, 2008 for reviews) has provided evidence that intentional coordination yields ‘absolute’ entrainment (e.g., Kelso, 1995; Schmidt, Carello & Turvey, 1990), whereas unintentional or spontaneous coordination produces ‘relative’ entrainment, wherein coordination is more intermittent and less stable (e.g., Schmidt & O’Brien, 1997; Richardson, Marsh & Schmidt, 2005). Additionally, the manipulation of attention during a bimanual coordination task revealed that when individuals visually attend to their preferred hand, behavioral variability in the movements of that hand is reduced (Amazeen, Amazeen, Treffner, & Turvey, 1997). Interestingly, with respect to the current discussion, many accounts of these findings rely on the idea that the coordination dynamics reflect the nature of the coupling between componential processes (e.g., Coey, Varlet & Richardson, 2012; Kelso, 1995).

In the present experiment, participants performed a rhythmic arm-swinging task while intending to control either the timing or spacing of their behavior. We manipulated the structure of the task environment so that there were either no additional constraints on the participants’ performance or a visual metronome stimulus that constrained the timing/period of the participants’ movements. Based on findings from previous studies, we predicted that the presence of the environmental constraints (i.e., visual stimuli) would lead to a decrease in the fractal scaling (i.e., α shifts toward 0) as compared to the condition with no environmental constraints. However, we also expected that participants’ intention to engage with the stimulus, and control either the timing or the spacing of their movement, might affect the degree to which the environmental constraints shaped the scaling of their behavior. Specifically, we thought that participants with the intention to control the dimension of their behavior that was more consonant with the nature of the metronome stimuli (i.e., timing) would show a larger decrease in fractal scaling.

Method

Participants

Eighteen University of Cincinnati students (18 to 28 years of age) were recruited to participate in this experiment, nine in the ‘spacing’ and nine in the ‘timing’ intention condition. One of the participants in the ‘spacing’ condition was unable to perform the task in accordance with the given instructions, and their data was therefore omitted prior to analysis. The experiment was approved by the University of Cincinnati Institutional Review Board. All participants provided informed consent.

Procedure and Design

Participants were instructed to stand approximately 1 meter in front of a flat screen television. The experimental task consisted of holding one's upper right arm flush with the side of the body and swinging the forearm in an arc about the elbow, while keeping the forearm parallel to the floor. The right hand was to be held in a fist with the first two fingers extended to point toward the screen. Initially, two green dots (5.5 cm in diameter) appeared on the screen, centered vertically and separated by a distance of 57 cm (see Varlet, Coey, Schmidt, & Richardson, 2011 for information on the stimulus methodology).

Eight participants were asked to control the spacing of their movements by traveling the same distance with every arm swing. The other nine participants were asked to control the timing of their movements by maintaining a consistent swing duration each time. All participants completed two six-minute trials. The first trial involved a continuation paradigm¹, with the green dots appearing for the first 10–12 seconds, followed by a blank screen for the duration. This trial was collected as a baseline. The green dots were set to flash in an alternating pattern at a frequency of 1 Hz, (with a dot appearing on one or the other side of the screen every 500 ms) throughout the time they were visible. Participants were instructed to use the dots to help control their designated task dimension, and to do their best to maintain the same movement for the duration of the trial once the dots had disappeared. In the second trial, the flashing dots were displayed for the full six minutes and participants were instructed to use them over the entire trial to help achieve consistency in their designated task dimension. This was the test trial.

The display was generated by an application written using C/C++ and OpenGL. Data was collected using a Polhemus Fastrak (Polhemus Corporation, Colchester, VT), with the motion sensor attached to the outside of the extended fingers of the right hand. Movement data was recorded and displayed at a sampling rate of 60 Hz.

Data Analysis

All data analyzed was taken from the screen coordinate time-series produced by each participant during each trial. Movement time-series were low-pass filtered using a 10 Hz Butterworth filter and the first 5 s of each trial were discarded to remove transients. The time and the location of the endpoints of each arm-swing were determined, and these were used to create a period and amplitude time series, respectively. During pre-processing, outliers greater than three standard deviations from the mean were removed, each series was trimmed to 512 points, and each series was linearly detrended. The pre-processed series were submitted to power spectral density (PSD) analysis to assess the fractal scaling of movement amplitude and period. Briefly, the first step in PSD analysis was to decompose the time series into a set of composite sinusoids with varying power and frequency by Fourier approximation. The power and frequency were then plotted against one another on double-logarithmic axes (several example plots are provided in Figure 1). The inverse of the slope (S) of a regression line fitted to the lower half of frequencies on this spectral plot

¹Several studies have demonstrated that using a continuation paradigm in this manner results in self-similar variability, or pink noise ($\alpha \approx -1$) (e.g., Gilden et al., 1995; Torre, & Delignières, 2008).

served as an estimate of the scaling exponent of the analyzed time series, $\alpha = -S$ (Holden, 2005).

Given that the rhythmic stimulus employed here provided an opportunity for movement entrainment, we were also interested in examining any coordination that might have occurred between stimulus and participant movement. To assess such rhythmic entrainment, we used discrete relative phase (DRP) analysis, which is a standard assessment of coordination between a continuous, rhythmic signal and a discrete, rhythmic signal. The rhythmic phase of the participant movement (i.e., 0° being the corresponding to the beginning of a cycle, and 360° corresponding to the end of a cycle) was determined at the initial time (i.e., onset) of every flash of the stimulus. Next, we determined the proportion of DRP angles falling into each of eighteen bins, labeled by the midpoint of the 20° range of relative phase values they contain (-170° , -150° , -130° , ... -10° , 10° , ... 130° , 150° , 170°) to generate a distribution reflecting the coordination between the participant and stimulus. Here, a phase lead by the participant with respect the stimulus is indicated by positive relative phase values, while a lag results in negative values. Perfect ‘inphase’ coordination, wherein the endpoints of the participant’s movements were always exactly synchronized to stimulus onsets, would result in a DRP distribution concentrated around 0° , with values entirely within the -10° and 10° bins.

Results & Discussion

In order to examine whether differences in intentional and environmental constraints affected the consistency of movement timing and spacing exhibited by participants during the task, separate 2 (intention: timing vs. spacing) $\times 2$ (trial: baseline vs. test) mixed ANOVAs were conducted on the average values for standard deviation of period and amplitude of arm movements. The ANOVA for movement period showed a main effect of intention, $F(1, 15) = 6.08$, $p = .026$, $\eta_p^2 = .29$, a main effect of trial, $F(1, 15) = 7.45$, $p = .016$, $\eta_p^2 = .33$, and an interaction between intention and trial, $F(1, 15) = 5.39$, $p = .035$, $\eta_p^2 = .26$. In the baseline trials, movement period (s) was longer for those intending to control movement spacing than for those intending to control movement timing, while in the test trials, movement period became shorter for those intending to control spacing and stayed roughly the same for those intending to control timing. Values for the means and standard deviations of movement period in each of the experimental conditions can be found in Table 2. The ANOVA for movement amplitude revealed only a main effect of trial, $F(1, 15) = 24.91$, $p < .001$, $\eta_p^2 = .62$. Movement amplitude (cm) was slightly greater for participants intending to control the timing of their movements, but decreased between the baseline and test trials. Amplitude also decreased between the baseline and test trials for those participants intending to control the spacing of their movements. Values for the means and standard deviations of movement amplitude in each of the experimental conditions can also be found in Table 2. Collectively, these results indicate that the presence of the visual stimulus served to constrain both movement period and movement amplitude in the current task.

To examine whether differences in intentional and environmental constraints affected the fractal scaling of movement timing and spacing exhibited by participants during the task,

separate 2 (intention: timing vs. spacing) $\times 2$ (trial: baseline vs. test) mixed ANOVAs were conducted on the scaling exponents (α) of the period and amplitude series. The ANOVA for movement period showed a main effect of intention, $F(1, 15) = 5.57, p = .03, \eta_p^2 = .27$, a main effect of trial, $F(1, 15) = 69.28, p = .001, \eta_p^2 = .82$, and an interaction between intention and trial, $F(1, 15) = 8.84, p = .009, \eta_p^2 = .37$. The ANOVA for movement amplitude revealed only a main effect of trial, $F(1, 15) = 4.97, p = .04, \eta_p^2 = .25$.

As displayed in Figure 2, the interaction effect found in the fractal scaling for the movement period series is driven by a greater decrease in α from the baseline to the test trial for participants in the timing intention than those in the spacing intention. The general decrease in α is consistent with the results of past research on differences in scaling of timing behaviors between continuation and synchronization conditions (e.g., Chen et al., 2001). That is, participants in both intention conditions produced period series in the scaling region associated with pink noise ($\alpha \approx 1$) during the baseline trial, when no environmental constraints were available. During the test condition, when the environmental constraints were present, participants in the timing intention group showed the traditional decrease in α to anti-persistent, blue noise ($\alpha \approx -0.5$). Participants in the spacing intention group, however, produced a decrease only to the level of random, white noise ($\alpha \approx 0$). In contrast, there were no differences between the two intention groups in terms of the fractal scaling of their movement amplitude. The amplitude series consistently revealed persistent, pink noise variation ($\alpha \approx 1$), and only showed a slight overall decrease in α from the baseline to the test trial.

These results suggest that the degree of change in fractal scaling, for the period series, might reflect the degree to which participants coordinated with the rhythmic signal embedded in the environmental constraints. Indeed, the DRP distributions reveal that participants in the timing intention group produced a higher degree of rhythmic entrainment with the stimulus during the test trial. As shown in Figure 3, participants in both intention conditions spent the larger proportion of the test trial at phase angles in the -70° bin. This ‘phase shift’ away from perfect, inphase synchronization (0°) reflects the fact that participants did not coordinate their movements exactly to the onset of the stimulus’ flashes, but instead to the middle of the flashes. Nevertheless, these distributions revealed that participants in the timing intention group showed a significantly greater concentration of phase angles at the -70° bin, $t(15) = -2.18, p = .046$, and were therefore more coordinated with the stimulus than participants in the spacing intention group.

Given that the intention condition affected both the fractal scaling of period and the degree of rhythmic coordination in the test trial, we also tested whether there was a continuous predictive relationship between coordination and fractal scaling. As displayed in Figure 4, there was a strong, negative relationship between the proportion of occurrence in the -70° bin and the scaling exponent for the period series during the test trial, $r(15) = -.66, p = .004$. This finding demonstrates that, across the categorical difference in the intentions to control either the timing or spacing of movements with reference to the environmental constraints, the more strongly entrained a participant was to the stimulus, the lower the scaling exponent of the resulting behavior. Moreover, there was no such relationship between the degree of coordination and the scaling of the amplitude series ($r = .013$) during the test trial, or

between the incidental coordination in the baseline trial and the accompanying scaling of either period or amplitude.

Lastly, careful analysis of the spectral plots revealed another noteworthy relationship concerning the intention conditions, the resulting differences in rhythmic entrainment, and the fractal scaling of the movement period series. The decision to estimate α from the lower half of frequencies on the spectral plot was made primarily with respect to the persistent, pink noise scaling evident in the period series during the baseline trials. Estimating α using different proportions of the lower-end of frequencies revealed interesting changes in the pattern of effects for the experimental manipulations. Specifically, estimating α from anywhere between the lowest 12.5% and the lowest 50% of frequencies consistently revealed persistent scaling (i.e., $\alpha \approx 0.70$) in the baseline period series for both intention groups. Using the lowest 25% of frequencies showed a good fit to the spectral plots, distinguishing the lower-frequency, persistent region from a higher-frequency, random scaling region (see Figure 5).

In contrast, the scaling for movement period evident in the spectral plots for the test trial differed substantially between the spacing and timing intention groups. Specifically, participants in both groups tended to produce a low-frequency, anti-persistent region and a high-frequency, slightly persistent region. What differed between the intention groups was the range of frequencies defining these two respective regions of scaling. As depicted in Figure 6, the spacing intention group only showed the anti-persistent scaling, traditionally found during coordination with a metronome stimulus (e.g., Chen et al., 2001) in the lowest 5 or 6 frequencies on average, whereas the timing group showed anti-persistence across the lowest 18 to 20 frequencies. It is important to note that the scaling exponents taken from this region are very similar between the two intention groups ($\alpha \approx 0.60$). This finding indicates that the difference between the groups in their average scaling exponents for the period series reflects these differences in scaling region. That is, the exponents calculated from the standard lowest 50% of frequencies include more of the higher-frequency, persistent region for the spacing group than for the timing group.

Taken together, these results suggest that the intention to control the timing of behavior leads to a greater degree of entrainment with the rhythmic aspect of the environmental constraint and, in turn, carries the anti-persistent scaling associated with that entrainment into faster and faster frequencies of variation in behavior. Participants in the spacing group did not have an intention consistent with rhythmic entrainment to the stimulus. Nonetheless, they exhibited a moderate degree of spontaneous entrainment to the stimulus, as is evident in the DRP distribution. This moderate entrainment eliminated the low-frequency, long time-scale fluctuations in the movement period that characterize the pink noise pattern of variation in the baseline trial. However, this degree of coordination did not wipe out the nested waves of fluctuation producing the slightly persistent scaling in the higher-frequencies. In contrast, the much stronger form of entrainment exhibited by the participants in the timing group did wipe out the persistent scaling in considerably higher frequencies of variation.

Conclusion

The aim of the current study was to investigate whether the influence of environmental task constraints on power-law scaling of human behavior might be moderated by a participant's task intention. Participants performed a simple rhythmic arm movement task with the intention of controlling either movement period or amplitude, either with or without an experimental stimulus designed to constrain movement period. The results reveal three main findings: 1) in the absence of environmental constraints, behavior along both task dimensions (i.e., movement period and amplitude) exhibit persistent, pink noise regardless of an actor's intention; 2) when environmental constraints are present for a given task dimension, there is a shift in scaling exponents toward the region associated with white noise for that task dimension; and 3) this shift is greater when an actor's intention is to control the same task dimension as that constrained by environmental conditions. Together, these observations indicate that the effect of any 'intentional constraint' on the fractal scaling of behavior is critically dependent on the concurrent existence of external constraints.

Generally, the first two effects observed here are consistent with existing research in that increased task constraint results in a shift toward more random variability (see Table 1). However, the third finding—the interaction between intentional and environmental constraint—has not been emphasized previously and indicates that an actor's intention can modulate the effect of environmental constraints on performance variability. Within the context of Van Orden et al.'s (2011) proposed domain-general model of fractal scaling in human behavior, this suggests that an actor's intention can actually increase the 'involuntary' nature of behavioral control by more tightly coupling an intended aspect of behavioral regulation to external task-relevant constraints. It therefore appears that in the presence of task-relevant constraints, a behavioral intention can reduce rather than increase the 'voluntary' and therefore scale-invariant nature of behavioral performance and that the relationships between constraint, control, and behavioral variability are highly interdependent.

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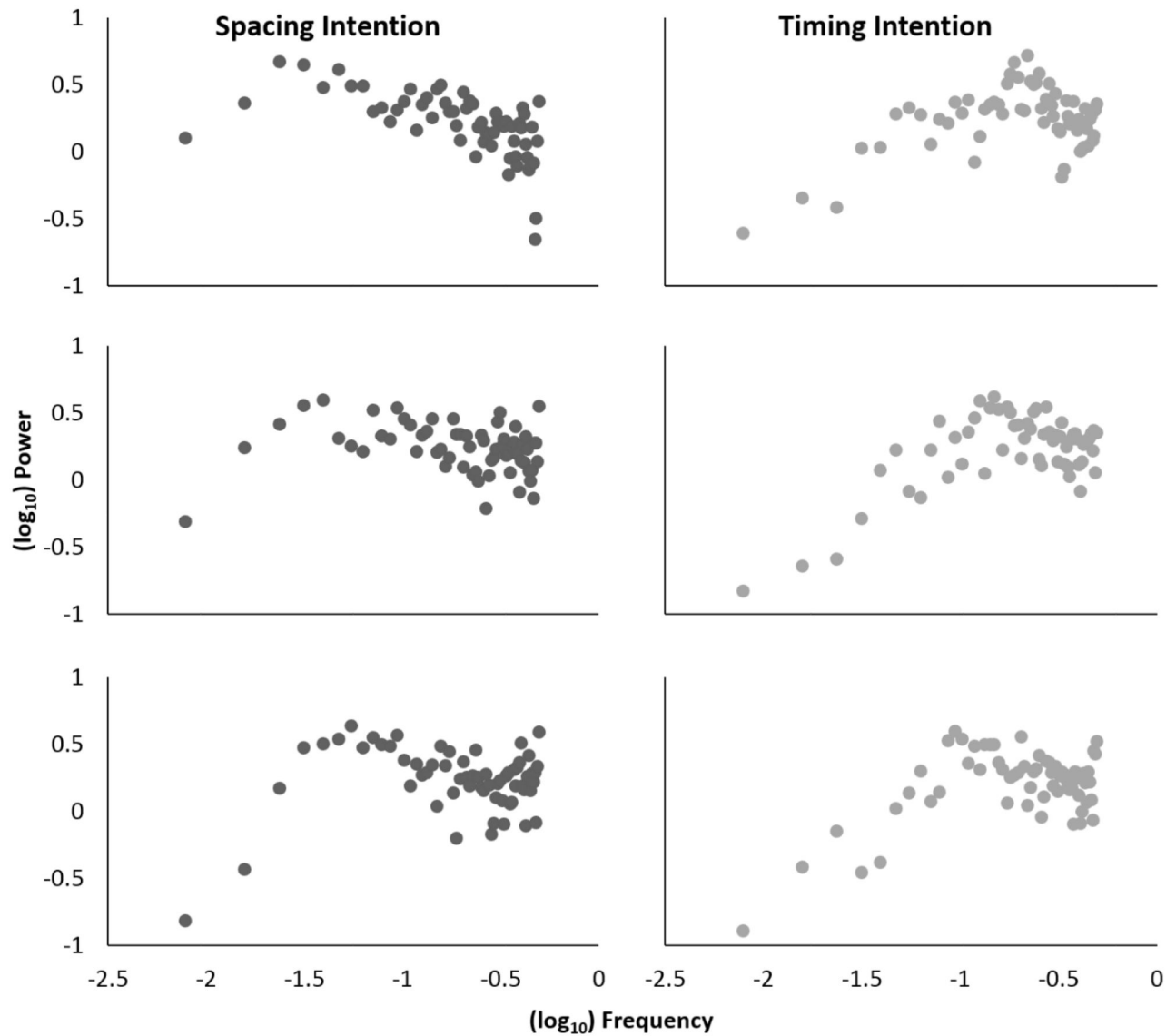


Figure 1.

Spectral plots, for the period time series during the test trial, of three participants from the spacing (left column) and timing (right column) intention groups. These example plots show the tendency for participants in the timing group to produce larger, low-frequency anti-persistent scaling regions than participants in the spacing group. All plots have the same axes, allowing for direct visual comparison.

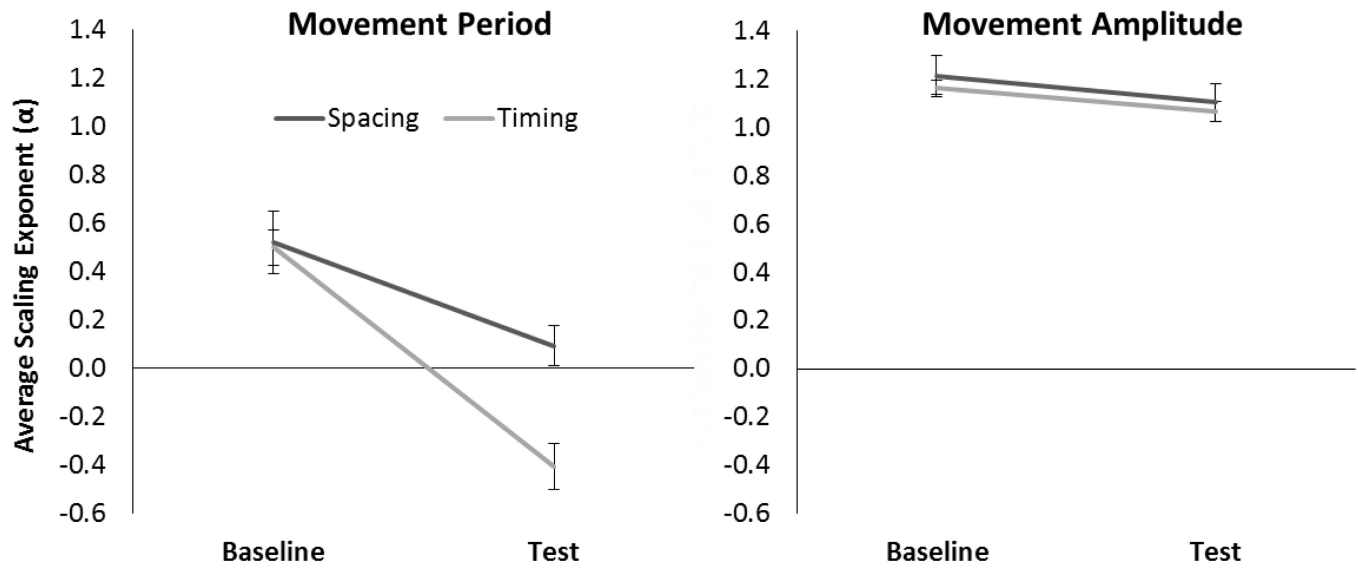


Figure 2. Mean scaling exponents for movement period (left) and amplitude (right) in each of the intention conditions (spacing, timing), and under both trial conditions, as assessed through PSD analysis. Error bars show standard error.

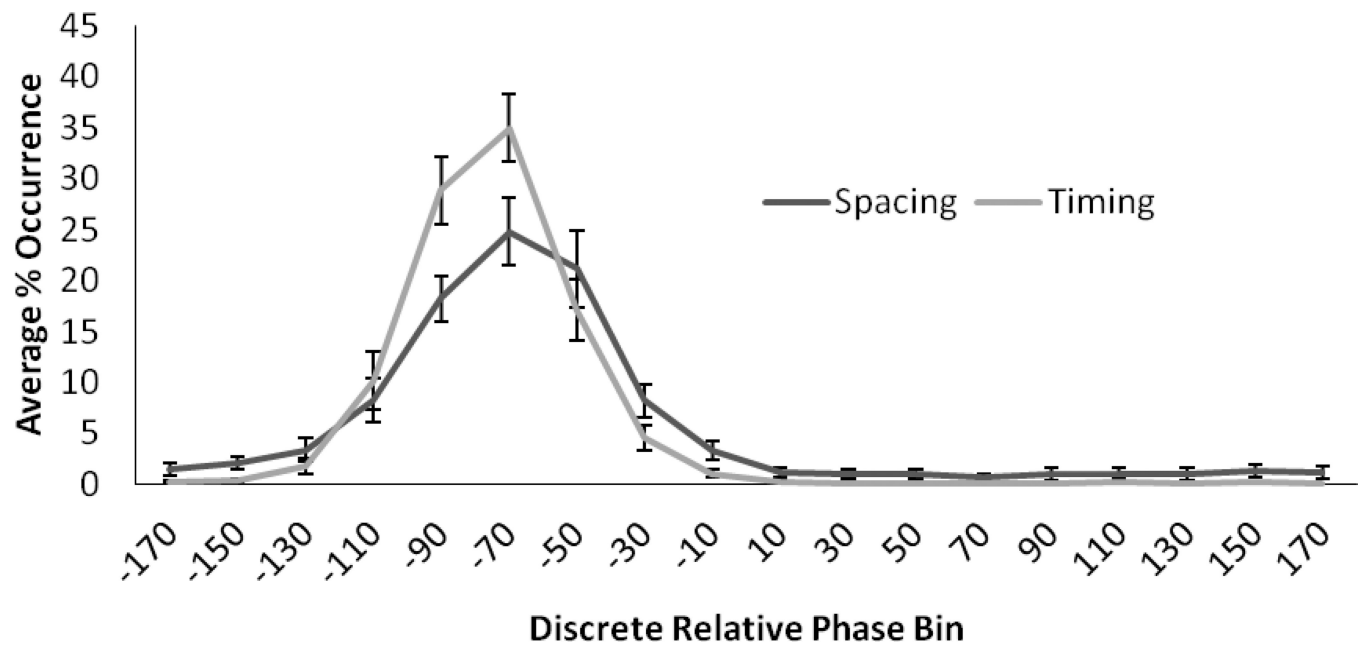


Figure 3.

Mean proportion of trial spent in each discrete relative phase (DRP) bin during test trials for each intention condition. Note: DRP bins are labeled by the midpoint of the range of relative phase values they contain. Error bars show standard error.

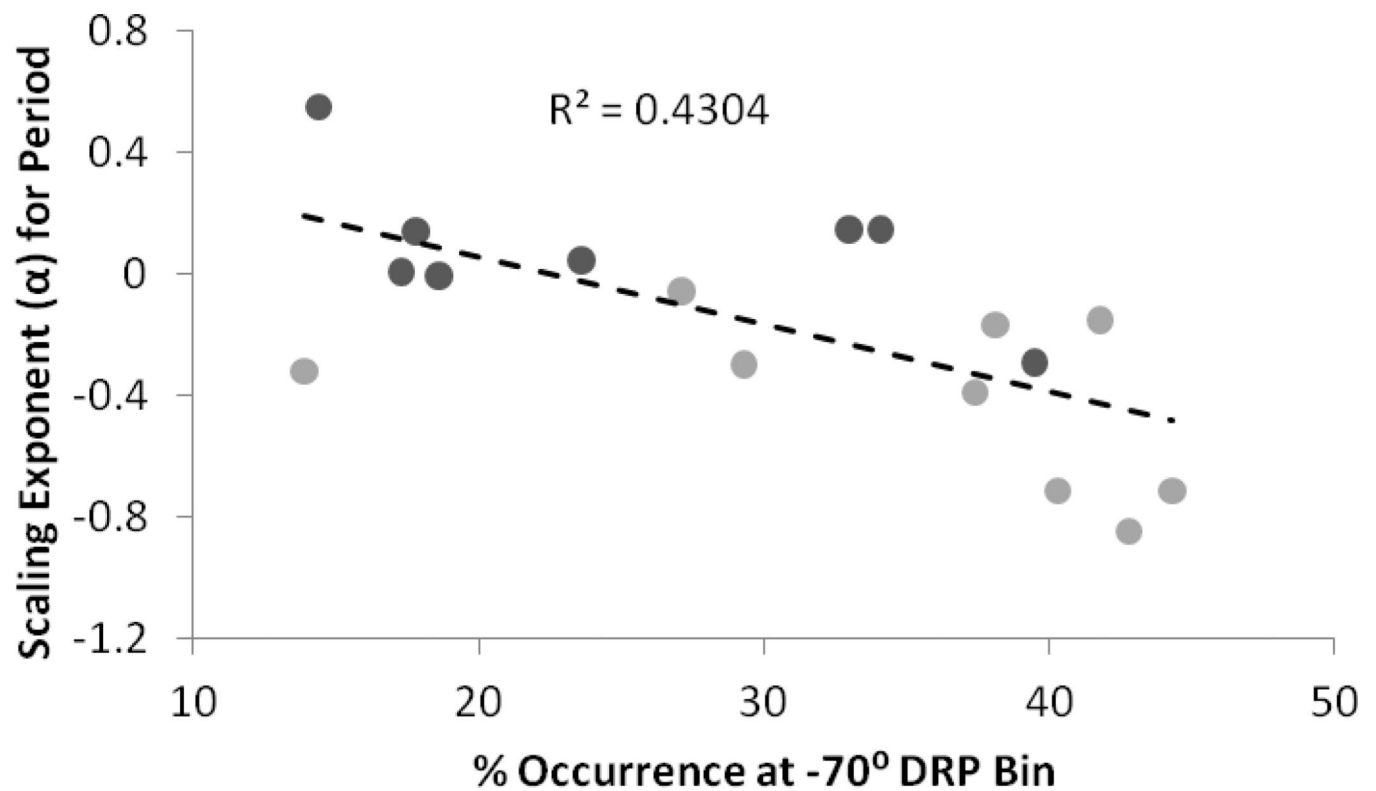


Figure 4.

Scatterplot of the percent of time spent in the most visited DRP bin (60°–80°) and the scaling exponent for movement period, during test trials. Black dots are used to represent participants in the spacing intention condition, and gray dots are used to represent those in the timing intention condition.

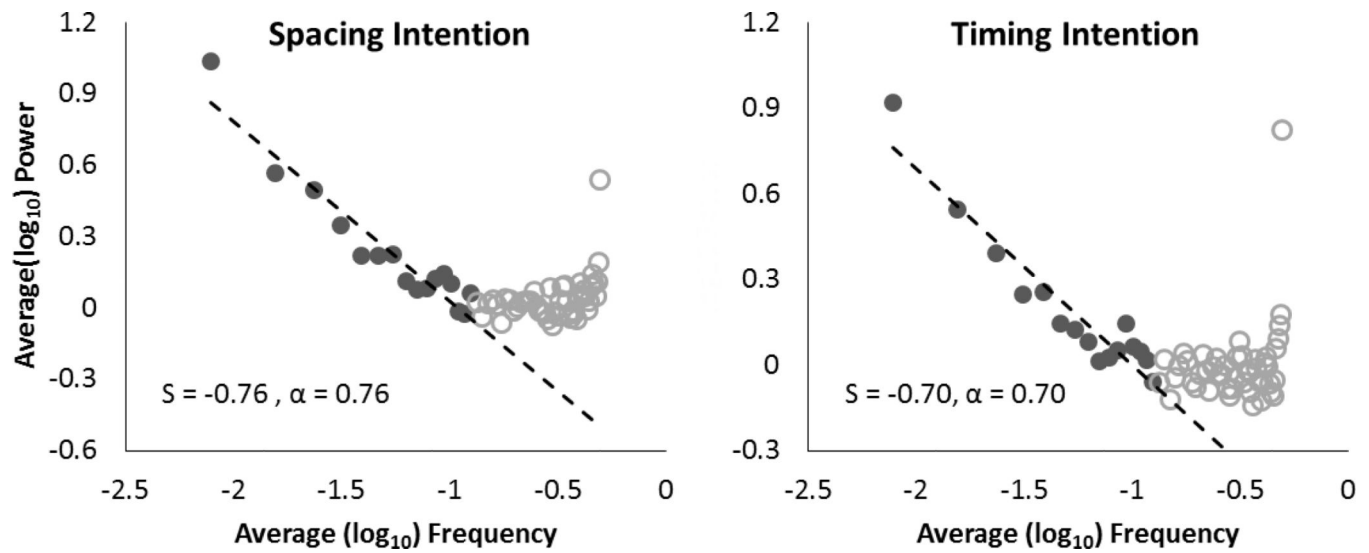


Figure 5.

Average spectral plots for the movement period series during the baseline trial for both intention groups. The filled, dark grey circles indicate the lower-frequency scaling region, from which the scaling exponent was estimated. The empty, light grey circles indicate the higher-frequency scaling region that was not included in the estimation of the scaling exponents.

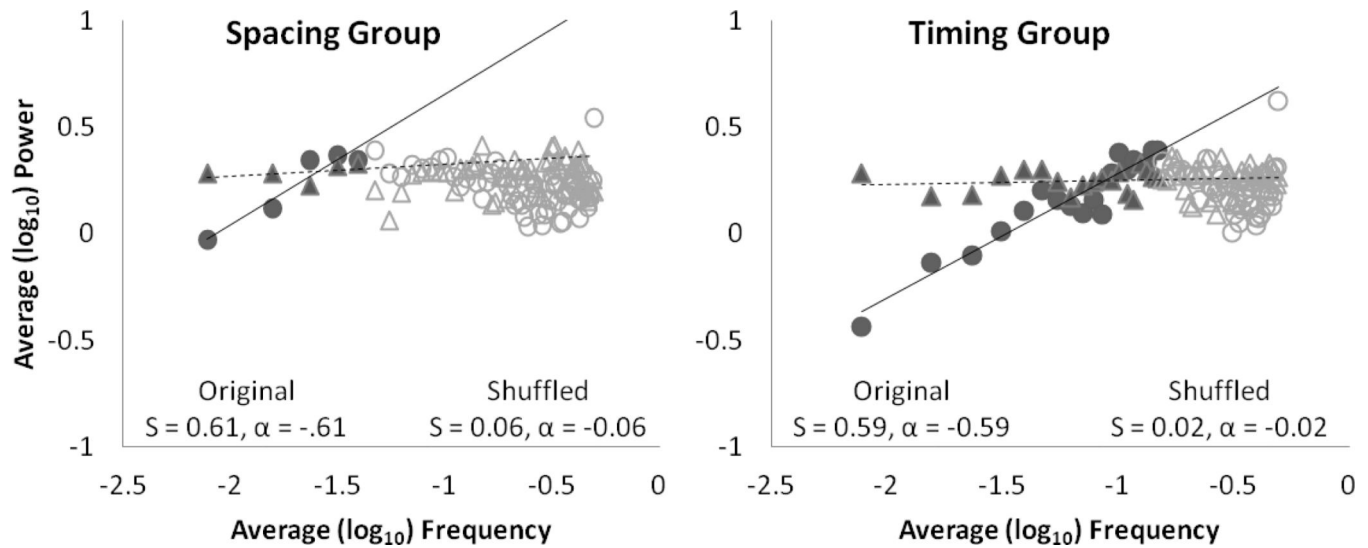


Figure 6.

Average spectral plots for the movement period series during the test trial for both intention groups. The filled, dark grey circles indicate the lower-frequency scaling region and the empty, light grey circles indicate the higher-frequency scaling region. Triangles indicate the results of an analysis on the shuffled time series, which demonstrated scaling near true random variation.

Table 1

Generalized Schema for the Relationships between Constraint, Control, and Variability in Performance

Existing Constraint	Control	Variability	Classification	Scaling Exponent (α)
Insufficient to support behavior	Exaggerated Voluntary	Overly regular	Brown Noise	≈ 2
Low	Balanced Voluntary/Involuntary	Self-similar	Pink Noise	≈ 1
Moderate	Largely Involuntary	Random	White Noise	≈ 0
Provides accuracy feedback	Corrective Processes	Anti-persistent	Blue Noise	$\approx -.5$

Note. While this general scheme appears to exist across behavioral domains, the set of approximate scaling exponents for each type of constraint may be higher or lower for specific behaviors.

Table 2

Consistency of Movement Period and Amplitude

	Spacing Intention			Timing Intention		
	Period (s)		Amplitude (cm)	Period (s)		Amplitude (cm)
	Mean	SD	Mean	SD	Mean	SD
Baseline Trial	0.57	0.04	72.51	6.92	0.50	98.81
Test Trial	0.50	0.03	52.61	5.53	0.50	77.24