

**Memory as a continuation of Movement: Effects of Auditory Temporal Structure on Memory
Performance with Differing Cognitive Loads**

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Author Note	3
Abstract	4
Memory as a Continuation of Movement	5
Scale Invariance	8
Implications of Thresholds: Movement and Memory	9
Narrowing Down to One Parameter	14
Scale Invariance Supporting Memory through Cross-Scale Interactions	18
Hierarchy: Scales and Chunks	20
Connecting Movement to Memory: A Methodological Example	21
Hypotheses	26
Method	27
Participants	27
Materials	28
Design	29
Procedure	30
Data Analysis	31
Hypothesis 1: Postural Sway	31
Hypothesis 2: Cognitive Load	33
Discussion	35
Implications about manipulations	35
Limitations to Consider in Future Work	35
<i>Scoring of Trials</i>	36
<i>Longer Time Scales</i>	36
<i>Order Effects</i>	37
Future Directions	38
References	40
Appendix A	59
Appendix B	60
Appendix C	61
Appendix D	62

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Abstract

The following thesis aimed to test the empirical support for an embodied memory by investigating the relationship between power-law structure in auditory stimulation, posture, and memory performance in tasks of differing cognitive load. The shared power-law framework offers a common operationalization between manipulated stimulation and measured movement. We began by manipulating power-law structure explicitly in stimulation, we then estimated the resulting power-law exponents in movement, and finally, tested for a difference in memory performance. Participants ($N=36$) participated in a Corsi Block tapping task with high and low load trials. While participating, they were exposed to one of three auditory stimuli with differing levels of power-law structure. Participant performance and movement were measured and analyzed using detrended fluctuation analysis. Memory performance was analyzed using a factorial ANOVA. Cognitive load had a main effect on memory performance, but all other differences were nonsignificant. Future work may need to account for the multitude of power laws throughout the body that may moderate the response to power-law structure in stimulation.

Keywords: scale invariance, Corsi block tapping task, memory, encoding, embodiment, perception-action-cognition

Memory as a Continuation of Movement

Memory is our mental organization of past events, allowing us to make sense of what might happen in the future (Glenberg, 1997). We organize each remembered event in the context of other memories in ways that reflect our personal values and goals (Barandiaran, 2016; Barandiaran et al., 2009; Farrell, 2012; Laney & Loftus, 2008; Sargent et al., 2010). This contextual organization of memory thus entails a hierarchy built from the perspective of the integrated organism using the memories it creates (Farrell, 2012; Gobet, 2013). For example, a memory of studying for one exam is nested within longer-term memories of the entire week in which you studied. The subjective nature of memory is important to note because the memories we encode describe events we are actively perceiving. Even throughout what feels like our most passive intake and encoding of events, we are shaping our experience through our capacity to take in events around us by exploring, directing our focus near or far, and organizing events into groups or relationships (Glenberg, 1997; Rhodes & Turvey, 2007). This thesis aims to emphasize the role of movement in memory and the integrated approach of a whole organism to movement-inclusive memory-based tasks.

This project aims to examine memory as a possibly continuous outgrowth of action. First, I will review the two aspects in which our memory-based contact with the past is much like our movement-based contact with the present: 1) riddled with scale-invariant structure, and 2) involving nested relationships. When paired, these aspects entail a hierarchical structure. Hierarchy will be established as a focal point for understanding both memory and sensory experience. I will follow this recognition of hierarchy in memory by reviewing an analogous hierarchy in bodily movement. These steps will motivate a manipulation of bodily

movement through auditory stimuli, leading to the eventual question of how that manipulation might influence memory performance. The current work aims to advance contemporary theorizing about memory in a way that might inform practical applications in the focus of attention, support learning, and the treatment of post-traumatic stress.

This thesis takes up an initial experimental test that makes an important step toward understanding how embodiment might root memory in action. Operationally, this thesis will investigate how individuals participate in a memory task that specifically requires motor skill along with memory. The memory task will involve a simple repetitive finger-tapping motion that requires remembering a spatial pattern. More theoretically, this thesis will seek a connection between memory and movement, through the mathematical structure of power laws—a function in which values of “y” quickly taper off and approach an asymptote as values of “x” increase.

Power laws are not novel to psychological science, appearing within diverse subfields from psychophysics (Stevens, 1957; Thomas et al., 2023) to social psychology (Mellado et al., 2023; Pincus et al., 2018) and appearing in cognitive domains (Beggs & Plenz, 2003) such as memory (Akyürek et al., 2017; Anderson & Schooler, 1991; Donkin & Nosofsky, 2012a; Donkin & Nosofsky, 2012b; Farrell, 2012; Gobet, 2013; Pine et al., 2013). Two salient examples of power laws have appeared repeatedly in the history of the field—and in the present work, memory. First, we can find power laws named explicitly in the “power law of learning” or of “practice” (Newell & Rosenbloom, 1980) according to which time or errors on the way to task completion dwindle as a power function of number of repetitions, i.e., with a negative exponent on number of repetitions. This proposed “law” appeared first in the work of Snoddy

(1926) and Crossman (1959), attracted controversy decades later (Heathcote et al., 2000; Stratton et al., 2007), and survives in nuanced form to the present day (Donner & Hardy, 2015). Second, and more relevant to memory, there is the power-law forgetting curve first pioneered by Ebbinghaus and modeled by subsequent memory researchers to the present day (Anderson & Schooler, 1991; Glenberg, 1976), with ongoing debate providing a similarly nuanced conclusion that power laws remain widely applicable (Maylor et al., 2001; Radvansky et al., 2022; Wixted, 2022a; Wixted, 2022b). In both cases, the decreasing power-law model appeals to the intuitive fact that psychological change (e.g., forgetting or learning) can begin drastically and then taper off. In both cases, the nuanced conclusion is quite similar: there is not merely one ideal power function but many. There are limitations to the applicability of these power functions, but they remain widely useful even in their variations for expressing key features of psychological processing.

Psychology develops such affinity for and controversy around power laws because they carry a rather strange and curious mix of obvious and nonobvious theoretical implications. The curiosity here hinges on two properties of power laws. First, beyond the intuitive idea that “forgetting or learning starts quickly and tapers off,” there is the compelling feature of scale invariance in power laws. Power laws maintain the same shape across all ranges of time and therefore are not bounded by thresholds. Such a trait raises the theoretical question of whether psychological process might have infinite potential for flexibility—at all scales of stimulation and response. This specific implication of scale invariance conflict with decades of theoretical reliance on thresholds and constraints, and it warrants careful inspection as the background to the present thesis. If the nuance of modern power-law modeling can make

scale-invariance any more widely palatable, the second property of power laws might have much to offer psychological theorizing. This second property has crucially to do with what sort of mechanism is likely to produce scale invariance: scale invariance may reflect hierarchical organization in which many scales of activity interact across the body of an active organism. This possibility would thus equip power laws to give formal voice to decades of hierarchical theorizing of psychological processes (e.g., Anderson et al., 2004).

Scale invariance rests at the heart of this thesis about memory. This thesis will manipulate scale invariance explicitly in stimulation, it will estimate the resulting scale invariance in movement, and finally, test for a difference in scale-invariant memory processes. Hence, before introducing the specific domain of memory and without dragging movement in as a curious add-on, this thesis will begin with scale invariance at the center of focus. It will emerge that scale invariance is an organizing theme that may gather both movement and memory at once into a coherent perspective on embodied memory.

Scale Invariance

Scale invariance is a striking feature of power-law functions. If we imagine a function as expressing the relations between stimulus and response, a power-law shape for this function would be a progressive multiplicative change in response with a comparable multiplicative change in stimulus size (e.g., for every doubling of stimulus intensity/size we might see a tripling of response size). This multiplicative relationship of response to stimulus remains the same across all ranges of stimulus size. Since power laws stem from multiplicative relationships, those relationships continue to exist regardless of the scale at which the power law is examined. For example, 10 divided by 2 is 5; 5 divided by 2 is 2.5; 2.5 divided by 2 is 1.25, and

so on. If we continue to do this infinitely, we reach infinitely smaller numbers. We will never reach zero (Hart et al., 2018; Kello et al., 2008).

Scale invariance seems to contradict the wisdom of a psychological field heavily reliant on thresholds. In the example of hearing, thresholds tell us when a person can or cannot hear a sound at a given frequency. It feels intuitive to think of thresholds as rigid, that there is a set range within which things can occur (one can hear) and outside of that range they stop being possible (one can no longer hear). But those thresholds may change with scale (Hadlington et al., 2004; McNeil et al., 2013). Physiological evidence shows flexibility of the thresholds of even individual neurons (Platkiewicz & Brette, 2010). In the same example of hearing, upon closer inspection, these rigid thresholds seem to migrate based on factors like age and task (Brännström et al., 2020; Essien, 2023). To continue with the example of hearing, after we surpass the apparent threshold of what is audible, we can observe infrasound and ultrasound.

Scale invariance provides a formalism within which we can start to understand the flexibility that seemingly rigid thresholds can show. The scale-invariant nature of relationships in physiology, movement, and cognition suggests a flexibility of thresholds in which interactions can take place across scales (Hove & Keller, 2015; Qian et al., 2013; Van Orden et al., 2003). Scale invariance in embodiment allows psychological science to loosen previously rigid thresholds and perhaps clarify not just coherence across scales but coherence within an integrated, whole organism.

Implications of Thresholds: Movement and Memory

To resolve our view of perceiving-acting organisms as embodying both thresholds and scale invariance, we should acknowledge that the modern perspective on thresholds reflects a

concern for limitations on finite resources. The mind runs on a plethora of resources under physiological and thermodynamic constraints as well as the metabolic necessities of the organism. Thresholds feel implicit in movement, such that the shortest span of time between waiting to act and an eventual action may be the lower end of a movement threshold. For example, if a student in a classroom wants to check the time, the minimum energetic costs, and the time needed to emit a motor command, e.g., to turn toward the clock on the wall, define the thresholds between no-movement and movement initiation. Similarly, orienting our movements with respect to external stimulation requires that the external stimulation be strong enough to activate a neurophysiological response to interrupt the organism's voluntary behaviors (Cruse, 1990). For example, a student in a classroom can only take appropriate notes on a lecture with sufficient auditory or visual stimulation, i.e., the professor lecturing at an audible volume, the clarity of the content, etc. As for what the student remembers, limited physiological resources for cognitive processes indicate possible thresholds for memory, i.e., attention, length, space, and time (Gold & Park, 2009; Lara, 2023; Nevisipour et al., 2023). The limited physiological resources coupled with the limited storage capacity of neural pathways ultimately results in forgetting. As each moment passes, there are new memories to encode and limited space to store them in. We have a short span of time we can hold onto memories before encoding new information. The finite capacity for these resources entails limits on the length of storage (Anderson & Schooler, 1991).

Despite these constraints, both movement and memory have the flexibility to exist beyond many of the thresholds we might foresee within these constraints. In studying movement, there seems to be no span of time in which the organism does nothing or is

perfectly still. There are progressively smaller-scale movements that exist before an organism decides to look at the clock (Marlow et al., 2015; Stephen & Anastas, 2011). Though visually undetectable to casual observation, systematic measurement of the body shows a nested structure in movement that persists across even the shortest measured scales of time, with larger movements growing continuously as a power-law function of time scale (Van Orden et al., 2003). If we return to the student in a classroom, this persistence of movement over multiple time scales would mean that in order to raise their hand to ask a question, the student is not emitting a simple motor command, rather there is a vast network of small-scale movements occurring at all times to develop larger-scale movements. There is no quiescent time period after which movement can begin, and the slowest, largest, and most deliberate movements grow continuously along the same power-law relationship from the quickest, smallest, and least voluntary movements. Thus, no matter the physiological threshold or any single motor neuron, we see the behavior of the organism is brimming with activity, with its many physiological details goading each other into action—even at the shortest time scales (Dewey, 1948). Goal-directed movements do not manifest in any clear break or phase shift from the smallest twitches. Rather, the scale-invariant growth of movement size across time scale indicates that human response extends beyond any single cutoff point.

The finite resources of memory may also extend beyond thresholds. Whereas the previous example of movement focused on exploring lower thresholds, scale invariance may explain the extension of memory past the larger threshold. If we consider the classic forgetting curve that depicts the number of remembered items (the vertical axis) across tests progressively later in time (the horizontal axis), we can see an initially rapid but then more

progressively gradual decay of studied items in memory (e.g., Ebbinghaus, 1880). The tails of these forgetting curves stretch outward towards a later time, becoming thinner as the mind loses progressively more of its remembered content. Cognitive psychologists have spent considerable time trying to find the best-fitting model, and that best-fitting model appears to be power-law (Anderson & Schooler, 1991). Power law evidence of scale invariance supports this persistence across time. Besides clarifying models of memory performance, this finding has several implications for forgetting. Forgetting occurring in a scale-invariant fashion opens the possibility of a lack of finite bound on the time that one can hold a given memory. A scale-invariant model of forgetting would show power-law decay in which the loss of remembered content would occur at first rapidly but taper off toward zero (the point at which there would be no memory). Power-law-like forms appear throughout memory performance (Healey et al., 2019), e.g., in classic forgetting curves, in the distribution of inter-retrieval time intervals in free recall, and the distribution of retrieval in prospective memory (Chater & Brown, 2008; Rhodes & Turvey, 2007). Scale-invariant power-law distributions show up all through the body, both in the neurons that process information in the brain (Beggs & Plenz, 2003; Platkiewicz & Brette, 2010) and the body that collects and integrates these neural events. However, as previously discussed, these models never reach zero, and therefore extend infinitely. A power law would model forgetting as occurring very slowly over time and would support that forgetting occurs across scales (Donkin & Nosofsky, 2012a; Donkin & Nosofsky, 2012b).

The interactivity of small-scale detail within a larger-scale context may reflect properties of scale invariance. This would reflect internal organization within the organism (Abney et al., 2021; Kello et al., 2010). It may not simply be coincident similarity across independent scales

but rather reflect interactivity across scales—within the processes of and across an integrated organism. While scale-invariant structures within individual processes (e.g., either memory or movement alone) suggest internal coherence, scale-invariant structure in multiple processes may indicate coherence and continuity across a whole, integrated organism (Grosu et al., 2023). That is, the multiplicative relationships that keep the power law from vanishing may reflect nonlinear interactivity linking multiple scales of activity into a coordinated action (Favela et al., 2021). This continuity may imply that these processes may equally support and be supported by each other (Holden et al., 2009; Holden et al., 2011; Kello et al., 2010; Van Orden et al., 2003). Consider the hypothetical example of writing the letter “a”. The memory of how one learned to write the letter “a” informs one’s future movements when writing future letters. These movements then inform how the letters are remembered. It is possible that there are scale-invariant multiplicative relationships linking the movement system on its fine-scale response and the memory system on its large-scale organization of events. The overlapping of scale invariance across the structures supporting an organism may imply that scale invariance is not a bug, but a feature of an integrated organism. Contextual features, such as sound (Kelty-Stephen et al., 2023), goals (Barandiaran, 2016), and orientation in the environment (Johnston & Turvey, 1980), act as mechanisms through which the integrated nature of the organism becomes apparent.

This theoretical connection could point us directly toward an embodiment of memory in human subjects: if our new memories grow from action, and our action stems from our memories, the similar trait of scale-invariance may not only be informative for embodied memory but a requirement of an integrated organism. The shared trait of scale invariance

between memory and movement might not be purely of coincidence, but rather a reflection of internal coherence across bodily systems. To demonstrate such an effect, we must include a task that utilizes movement in the service of memory. To make these claims about the role of scale invariance testable, we must operationalize scale invariance with a single parameter standard to both auditory stimulation and movement.

Narrowing Down to One Parameter

This theoretical approach tests for a common thread of scale invariance throughout the organism. The common power-law framework of scale invariance offers a common operationalization between manipulated stimulation and measured movement: strength of the scale invariance—encoded as a power-law exponent H (or the Hurst exponent), described below, specifically addressing a power-law form of temporal sequence. In the examples of twitching, turning, flipping, and taking notes, the size of the movement itself increases with time scale. If we were to then use densely sampled motion capture to measure the student in our example, we would likely find scale invariance within this growth of movement size with time scale.

Classically, psychological science has used linear autocorrelation and power spectrum analysis to understand memory — construed statistically — in a time series measurement. By looking at memory with a time series measurement, it is possible to find correlations between moment-to-moment variations (Box et al., 2015; Cohen et al., 2013; Wagenmakers et al., 2004). Both linear autocorrelations and power spectrum analyses show power-law structured decay (Chater & Brown, 2008; Granger & Joyeux, 1980; Wiener, 1964). Empirical research often estimates power-law structure as a specific power-law decay of amplitude with frequency (e.g.,

in Fourier spectra)-- that is, a specific relationship of “how big” with “how often.” The size of changes across time will decay with progressively higher frequency (i.e., as those changes happen faster the changes shrink). We can encode the strength of the power-law structure using a parameter, specifically the exponent H indicating how the standard deviation of fluctuations grows with time (e.g., $SD \sim t^H$). Values of H closer to 0.5 indicate randomness or a lack of temporal structure, and those closer to 1.0 indicate correlations of movement size across progressively larger timescales (Mandelbrot & Benoit, 1985).

We can use H as a common language for understanding both stimulation and movement during a memory task. For instance, it is possible to measure movements in time and estimate H by calculating the growth of movement SD over very many time scales (Peng et al., 1995). To test the claims of the current thesis, we must manipulate H . It is also possible to generate and manipulate stimulation with progressively higher or lower H values.

Memory has historically been studied alongside auditory background noise (Baker & Holding, 1993; Bell, 1984; Carlson et al., 1997; Duarte et al., 2023; Han et al., 2020; Hayashi & Igarashi, 2009; Herff et al., 2020; Kim et al., 2023; Manippa et al., 2024; Marrone et al., 2015; Skarlatos & Georgiou, 2001; Söderlund et al., 2010; Söderlund et al., 2007; Talamini et al., 2022; Weinhold et al., 2022). Often in studies such as these, the auditory stimuli are simply described as background noise or left altogether undescribed, in which case we can assume that the study implements uncorrelated sound stimulus, known as white noise. When said background noise includes a white-noise condition, whether explicitly stated or otherwise, the study can be understood to have used noise with an H exponent of 0.5 (white noise). Making H explicit allows us to experimentally evaluate the effects of scale invariance by manipulating the H of

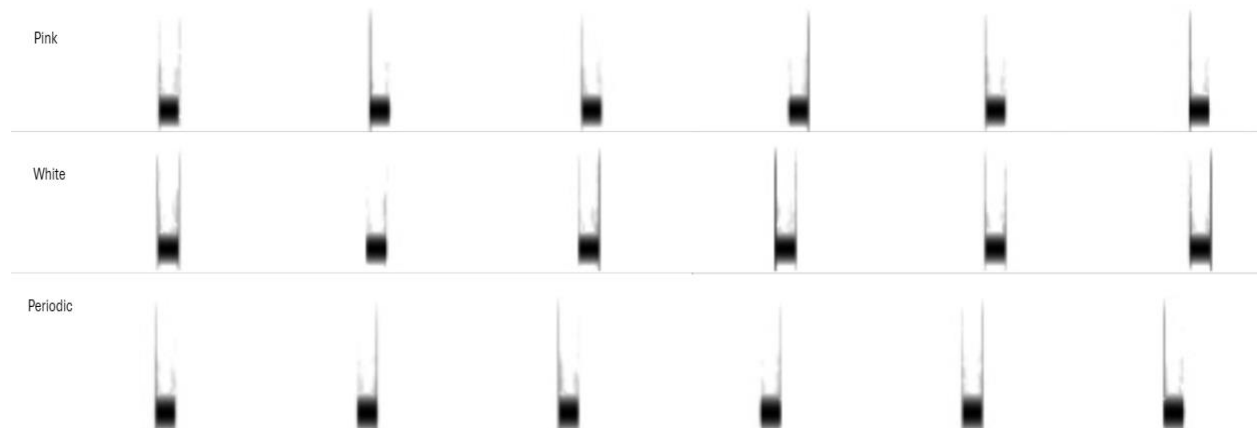
auditory stimulation (e.g., Hove & Keller, 2015; See Figure 1). Additionally, there is research examining scale invariance in auditory stimulation (Blackwell et al., 2016; Geffen et al., 2011; Hove & Keller, 2015; Mandelbrot & Van Ness, 1968). However, as noted above, the open question is whether the scale invariance in auditory stimulation might support memory specifically by resonating with the movement system and cultivating greater scale invariance in movement. We can evaluate whether this scale-invariant stimulation is impacting the scale invariance of the movement system enlisted to enact the memory task by designing background noise to include various fluctuations using explicit manipulations of H to generate the random stimulation. We can then measure the effect of the manipulation of H on performance.

This thesis will test the degree to which changes to the power law structure within background noise might affect the power law structure of the movement system. We used H to parameterize sequential correlations across intervals between metronome onsets (i.e., "beeps") on average 1 second apart with a standard deviation of 0.05 seconds in the conditions with manipulated H values (See Figure 1). Different H exponents entail auditory stimuli with different temporal sequences thus changing the power-law structure stimulating an organism (Kelty-Stephen & Dixon, 2013a; Kelty-Stephen & Dixon, 2013b; Raffalt et al., 2021a; Raffalt et al., 2021b; Raffalt et al., 2023a; Raffalt et al., 2023b). To ensure the organism absorbs or attunes to the temporal structure of the stimulation, we can measure the power-law structure in bodily movements such as the movement of the torso (Kelty-Stephen & Dixon, 2013a). This movement can then be used to calculate the H exponent of the power-law structure in movement (Holden et al., 2011). This effect of scale-invariant auditory stimulation on the

movement system could potentially impact memory performance beyond traditional factors such as cognitive load.

Figure 1

Temporal structure in amplitude waveforms of three different auditory stimulation



Note. Shows the difference in temporal structure on the sound stimuli over an interval of approximately 6 seconds. Each group of lines represents one onset. In the periodic stimuli (bottom) each interval between beeps is the same length. For white noise (middle) the length of each interval is random, that is, short onsets do not necessarily follow short onsets. In the pink noise condition (top), short intervals are often followed by short intervals, and long intervals are followed by long intervals. This is due to the difference in H -values. White noise has an Hurst exponent (or H) of close to 0.5 whereas pink noise has an H exponent of closer to 1.0.

Scale Invariance Supporting Memory through Cross-Scale Interactions

The standard operationalization for scale invariance across scales using the H parameter allows us to formalize movement as supporting memory in an integrated organism. As previously noted, a powerful explanation for the existence of power-law structure in a system is interactions across time scales. With this in mind, these “cross-scale interactions” may become a mechanism by which hierarchical processes, such as memory and movement, support one another.

To understand exactly what cross-scale interactions mean, we can return to the example of learning in the classroom. At the longest scale of our example, the student in a classroom is in pursuit of the goal of learning. At the finest scale, we have the eventual on-command recall of a newly learned concept. To cross the distance between these timescales, the student may tailor a response, such as raising a hand, to a keyword from the professor. Between the goal of learning and its achievement, there are intermediary-scaled events, with each involving some form of movement. On a yet longer timescale, a student attending a lecture with the goal of learning must stare in the right direction, move their eyes to read the professor’s presentation and maintain an upright posture. Not only does the student then use this information to encode what is being learned, but the student then uses the same information encoded for retrieval. Scale invariance is suggestive of fine-scale interactions supporting large-scale interactions. With the understanding of scale invariance as occurring in both the memory and movement systems, we can explain the way in which the systems of an organism may be connected. Such cross-scale interactions might explain how an organism uses its whole body to develop its memory to make sense of its memory.

Memory is the organization of information collected based on the goals and perspective of a perceiving-acting organism (Barandiaran, 2016; Barandiaran et al., 2009; Blau & Wagman, 2022; Izadifar et al., 2023; Laney & Loftus, 2008). Traditional models have diminished the importance of the movement system within memory. Instead, these models opt to isolate movement to procedural memory if including it in the memory system at all (e.g., Tulving, 1985). More embodied approaches aim to emphasize that movement is more integral to the memory system than previously discussed (Barsalou, 2007; Barsalou, 2009; Dutriaux & Gyselinck, 2016; Glenberg, 1997; Iani, 2019; Marre et al., 2021; Park et al., 2023; Sutton, 2006; Trakas, 2021; Vitale et al., 2021). Embodied perspectives try to root cognition in action, suggesting that memory content has a structure reflecting bodily exploration collecting the information from the environment, e.g., searching, walking, or touching (Kelty-Stephen & Dixon, 2013a). Embodied perspectives emphasize that movement and memory systems support each other. For instance, if we expect memories to seamlessly support action, then we should expect memory processes to situate information in terms of movement. Therefore, recall could be an embodied extension of movements that supported original storage and encoding. As such, further movement might rest on that same storage and encoding. With an understanding of typical cross-scale interactions within power-law structure, we can begin to look at these seemingly separate systems as interacting.

A logical next step then would be to examine how cross-scale interactions may fit into modern memory theory. We can see this in the hierarchical structure of memory as outlined in many dominant models (Anderson et al., 2004; Holden et al., 2009; Kello et al., 2008; Van Orden et al., 2005). The next section will detail the possible complementary nature of cross

scale interactions to modern memory theory. Specifically, cross-scale interactions between the movement and memory systems may explain the development of hierarchical memory structure in a goal-pursuing organism.

Hierarchy: Scales and Chunks

Even without an explicit interest in scale invariance or power laws cross-scale interactions are prevalent in much of memory theory, e.g., the contribution of short-term and long-term memories is regularly invoked in prevailing summaries of performance (Atkinson & Shiffrin, 1968). We see these cross-scale interactions through hierarchy, an important feature of most classical memory theory.

We can recognize hierarchy in memory through two crucial features: scales and nesting relationships. First, scale is a well-known facet of memory. We can remember specific, fine-scale information or overarching, large-scale information. Second, memory processes can zoom in on coarse time scales or zoom out from finer ones, i.e., chunks are nested in other chunks (Atkinson & Shiffrin, 1968; Ekuni et al., 2011; Gilbert et al., 2015a; Malamberg et al., 2019; Miller, 1956). Nesting of chunks across many time scales could support the emergence of scale invariance and cross-scale interaction in the form of power laws (Ericsson, 2013; Farrell, 2012). This nested kind of structure is not only in the mind but, as previously discussed, is also in the body. Embodied approaches insist that movement supports memory through cross-scale interactions, and the alignment of scale invariance in memory and movement is a clear support for this theoretical connection. To further solidify this point, however, there must be evidence of interactivity between these scale-invariant patterns. The two scale-invariant processes must interact in some way to truly support an integration of the memory and movement system.

The theoretical alignment of scale-invariant structure in multiple psychological processes then leads to the question of whether we could find scale-invariant stimulation influencing scale-invariant movement to support memory. To begin to answer this question, we will need to also use a memory task in which overt movement is essential for task completion. The empirical work in this thesis aims to test whether this manipulation leads, first, directly to differences in estimates of H in measured postural sway and, second, to better memory performance.

This thesis intends to articulate that scale-invariant movement can become an explicit parameter for supporting cognitive memory. As discussed, the echoes of scale invariance throughout bodily movement and memory may not be purely coincidental but may reflect the embodied roots of memory within an integrated organism. If power laws entailed in embodiment support the power-law structure of memory, introducing power-law structure into ambient stimulation might influence memory performance. So, for this thesis, I needed a well-established memory task in the cognitive psychological tradition that enlists a clear, overt movement contribution.

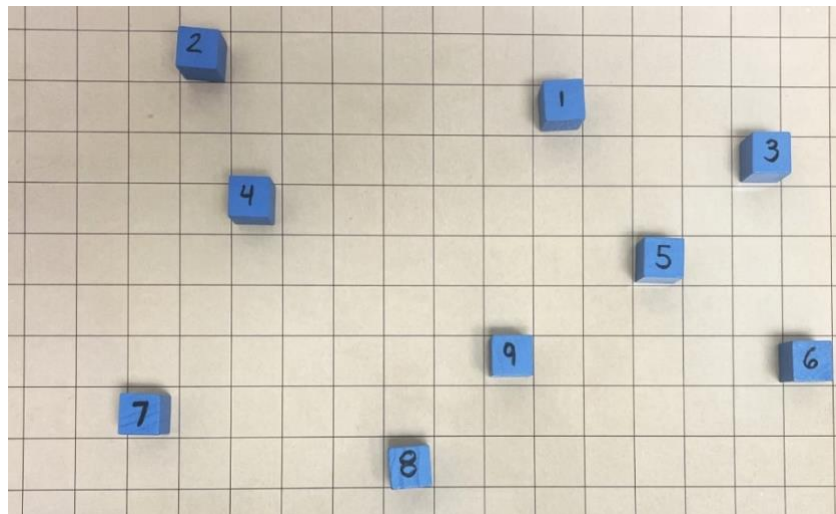
Connecting Movement to Memory: A Methodological Example

To bring movement into the same frameworks as memory, this thesis uses the Corsi block tapping task (see Figure 2). The Corsi block tapping task measures memory of spatially situated sequences and concerns how memory is challenged by the complexity of its layout. In the task, nine blocks are placed on a table. The participant watches the researcher tap a sequence of blocks. The participant is then cued to tap the blocks in the same order as shown. The researcher then scores the participant in terms of accuracy. The Corsi block tapping task

has been used across cultures and ages in both cognitive (Berch et al., 1998; Camp et al., 2023) and neuropsychology (Berch et al., 1998; Callahan et al., 2022; Zsebi et al., 2023). Originally, Corsi (1972) developed this task to study short- and long-term memory. Since then, the task has been adapted to include many different methods, sizes, and extents of movement (Arce & McMullen, 2021). The Corsi task affords memory research an easy manipulation of cognitive load, in terms of number of blocks and spatial crossings. The number of blocks tapped and the times a participant must cross the array of blocks in a series have been shown to affect the difficulty of the task itself (Orsini et al., 2001). Increasing difficulty of the spatial path may increase the demand on motor planning, with more blocks and crosses complicating the planned movements.

Figure 2

Corsi block tapping task as seen by participants.



Note. The figure shows the layout of the blocks as viewed by participants during the Block Tapping Task. The layout of blocks is based on the work of Orsini et al. (2001).

The current thesis adds auditory background noise to the task to experimentally introduce scale invariant structure. Curiously, in surprising relevance to the current work, there is interest in the impact of ambient background auditory stimulus on Corsi task performance (Stahl & Marentakis, 2017). However, in line with much of modern memory theory, studies on this topic presume (as many previously mentioned studies do) that the default setting on background noise is an H of 0.5. Studies thus far have not specifically tested the impact of scale-invariant auditory stimuli on memory nor its support by and of the movement system. The parameter H offers a continuous range across which to compare the uncorrelated and non-scale-invariant pattern of white noise with the correlated, scale-invariant pink noise. The current thesis aims to take a step towards remedying this oversight and study the impact of pink noise, an H of 1.0 on movement and subsequent memory performance.

The methodology used in the current thesis introduces auditory stimuli to perturb ongoing exploratory movement while in the middle of completing a cognitive task (Hart et al., 2018). Previous work has used scale invariant stimuli with similar results (e.g., Kelty-Stephen et al., 2023; Raffalt et al., 2021a; Raffalt et al., 2021b; Raffalt et al., 2023a; Raffalt et al., 2023b). Extending this relationship to include memory would necessitate demonstrating the relationship between scale-invariant stimulation interacting with scale-invariant movement while showing eventual support for memory. Exposing participants to scale-invariant auditory stimuli might perturb their postural sway (Kelty-Stephen et al., 2023). Of course, various embodiment-agnostic theories of hierarchical psychological processing (e.g., Anderson et al., 2004) might not see background noise as having any principled implications for cognitive

performance. However, the proposed connection follows directly from an embodied perspective on cognition that interprets scale-invariant patterning as the product of cross-scale interactions. The proposed study would then need to include a memory task that directly involves movement. The Corsi block tapping task shows participants a path through a series of blocks (See Table 1.). Participants are then told to recreate the path they were shown, tapping each block in sequence. The difficulty of the task increases as longer sequences are used and as more crosses are added to the sequence (Orsini et al., 2001; See Figures 2 and 3). Cognitive load was manipulated by developing sequences of six blocks with directional changes (i.e., the path changes from moving in one direction-- left, right, up, or down-- to another direction) and crosses (i.e., the path between blocks crosses over a previous path of the same sequence). High load trials contained as many as 4 directional changes and 5 crosses, and as few as 3 directional changes and one cross. Low load trials contained as many as 4 directional changes and 1 cross, and as few as 1 directional change with no crosses.

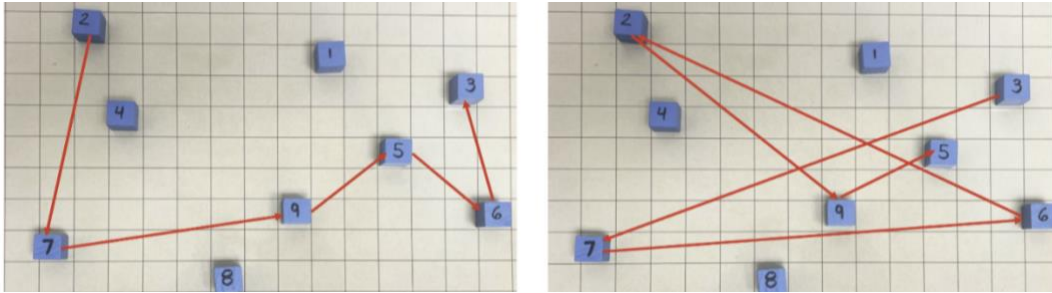
Table 1*Corsi block tapping task conditions and paths*

High Load	Low Load
376295	279563
854193	895314
167342	631247
927138	789312
643981	984136
467329	369742
286734	247863
591463	236954
782619	789612
541928	421598
625341	563124
826417	124769

Note. Both conditions are experienced by all participants. Load is defined by directional changes (i.e., the path changes from moving in one direction-- left, right, up, or down-- to another direction) and crosses (i.e., the path between blocks crosses over a previous path of the same sequence). Participants randomly received one of three possible path orders. Participants randomly experienced the high or low load condition first. Low load paths were developed as simplified versions of the high load paths (Orsini et al., 2001).

Figure 3

Corsi block tapping task with example paths.



Note. Shows an example of a path as viewed by participants during the Block Tapping Task. The layout of blocks is based on the work of Orsini et al. (2001). The image on the left shows a low-load path (279563). The image on the right shows a high-load path (376295). See Appendix B for all paths.

Hypotheses

The current thesis holds two main hypotheses. The first hypothesis addresses the impact of noise and cognitive load on posture: Increased H in stimulation will lead to an increased H in posture. I anticipate a main effect of cognitive load on posture (1a) and of auditory stimulation on posture (1b). Though the literature does not support a directional hypothesis, I anticipate an interaction between noise and cognitive load on posture (1c), such that values of H will change as cognitive load changes (MacKenzie, 2013; Slifkin & Eder, 2014; Tinker & Velazquez, 2014).

The second hypothesis addresses the impact of noise and cognitive load on memory performance: I anticipate a main effect of noise on memory performance such that participants will perform best in the memory task when presented with the pink noise condition (2a). I do

not anticipate any difference in performance between the periodic and white noise conditions. I predict a main effect of cognitive load on memory performance such that participants in the low load condition will do better than the high load condition (2b). Finally, I expect to see an interaction between temporal correlation in stimuli and cognitive load condition (2c), such that pink noise will lead to better performance, with a ceiling effect in the low load condition.

Method

Participants

Thirty-seven SUNY New Paltz Community members participated in this study. Subject pool participants received three SONA credits for participation in the study toward introductory psychology requirements or graduation requirements. Alpha Phi Omega members received 0.5 service hours toward a total requirement of 30 service hours every semester. A number of participants were volunteers who received no reciprocation. One participant, participant 05, was excluded from the final sample due to a corruption of the data file. The final sample consisted of 8 men, 23 women, and 5 gender nonconforming/non-binary students. The average participant age was 21.33 years, with the sample ranging from 18 to 31 years old. Each auditory condition consisted of 12 participants. In advertising the study, individuals with atypical gaits were asked not to participate. Advertising was exclusive to individuals with or pursuing a college degree to ensure cognitive ability.

White-noise stimulation has had effect sizes ranging from $f = .305$ and $.362$ to $.670$ (Han et al., 2020; Luy et al., 2020; Usher & Feingold, 2000) but pink noise has a larger effect $f = .674$ (Luy et al., 2020). According to G*Power 3.1.9.6 (Erdfelder et al., 1996), these effects reach 80% power at total sample sizes of 81 or 60 and as small as 21 for 3 x 2 mixed designs. Given the

primary interest of the current study is the stronger case of power-law structure in pink noise, a sample size between 21 and 60 is ideal.

Materials

The block tapping task used nine blue wooden blocks, each 0.8" in diameter, placed on a 17"x13" grid. The task took place on a table approximately 30 inches tall.

Postural sway measurement require a harness (See Figure 4) that can hold a smartphone measuring accelerometry-- while leaving the phone accessible for the researcher to use. The researcher also required access to an app that accurately measures and saves accelerometry files. The current study used SensorLogger. Though this is a third-party app, the anonymous data remained on the phone for downloading and eventual analysis.

Figure 4

Image of harness worn by participants.



Note. Image of the harness used in the current study. The smartphone was facing the researcher on the participant's back.

Design

The proposed study used a 3-level (auditory stimulus) x 2-level (cognitive load) mixed design. There were three auditory conditions. Each condition consisted of beeping at different intervals (a periodic condition, a white noise condition, and a pink noise condition), and remaining at a constant decibel level. There were 12 participants in each condition.

Participants performed Corsi tasks in both levels of a cognitive load condition. Over 24 trials (12 different block configurations for each level of cognitive load), the researcher measured performance (correct trials vs. incorrect trials) and postural sway through accelerometry using a personal smartphone (Kelty-Stephen et al., 2023). Each trial consisted of an instructed path along a sequence of six blocks followed by the participant's remembered path. Trials were intended to have 4 crosses in the high load condition and 3 or fewer in the low load condition (Orsini et al., 2001). Due to inconsistency within the block-tapping task literature, and the need for longer block sequences in the current study, this criteria was slightly adjusted such that both crosses and directional changes of the spatial path were used to develop high load trials. Said trials were simplified using the same method as Orsini et al (2001). Trials in the high load condition had a maximum of 3 crosses and 5 directional changes with a minimum of 1 cross and 2 directional changes. Those in the low load condition had a maximum of 1 cross and 1 directional change with some not including and crosses.

Procedure

Once verbal consent was obtained, a harness was placed on the participant's torso such that the smartphone was held on the participant's back. The volume of the auditory stimulus was measured to be about 50db. The participant was then handed the headphones and cued to put them on. The participant confirmed that the volume of the stimulus felt comfortable. Accelerometry was recorded for each trial and the auditory stimulus looped for the study's full duration, approximately 15 minutes.

For each trial, participants were shown one of twelve block sequences, tapping on each block with the pointer finger on their dominant hand. The participant then repeated the sequence. Each sequence consisted of six blocks. After repeating the sequence, the researcher manually recorded the trial as correct or incorrect. For a trial to be marked as correct, the full sequence was repeated correctly. Once participants completed the first load condition, the researcher began a new accelerometry recording while ensuring consent was maintained. Each participant received the same twelve low cognitive load sequences and twelve high cognitive load sequences but in random order. Half of the participants received the low-load condition prior to the high-load condition and the other half received the high-load condition before the low-load condition.

Data Analysis

Data analysis consisted of a 3-level (auditory stimulus) x 2-level (cognitive load) mixed ANOVA on number of correct trials, fractal analysis of absolute value of displacements in postural-sway accelerometry to determine whether auditory stimulus (between-subjects variable), cognitive load (within-subjects variable), and their interaction will influence the H exponent of postural-sway, and a second 3-level (auditory stimulus) x 2-level (cognitive load) mixed ANOVA on the H exponent in postural-sway.

The current thesis used detrended fluctuation analysis (DFA) of bodily movement to develop average H values for participants across trials (Peng et al., 1995; Hardstone et al., 2012; see Appendix A). Power law exponents reflect the growth of fluctuations over time (as discussed in an earlier section) and therefore require testing that allows for the statistical observation of said growth. In discussing movement, we must also consider detrending due to the impact of idiosyncrasies of the task on our estimates of H . For example, the current study included crosses in the Corsi block task, some crosses being larger than others. Participants will show large fluctuations in movement based on the requirements of the task, resulting in a less reliable measure.

Results

Hypothesis 1: Postural Sway

1a. A repeated measures ANOVA showed that cognitive load condition also did not have a main effect on the Hurst exponent of postural sway ($M_{\text{high/pink}} = 1.08$, $SD_{\text{high/pink}} = .0827$; $M_{\text{low/pink}} = 1.10$, $SD_{\text{low/pink}} = .0855$; $M_{\text{high/white}} = 1.07$, $SD_{\text{high/white}} = .0606$; $M_{\text{low/white}} = 1.06$, $SD_{\text{low/white}} = .0611$; $M_{\text{high/periodic}} = 1.08$, $SD_{\text{high/periodic}} = .0401$; $M_{\text{low/periodic}} = 1.08$, $SD_{\text{low/periodic}} = .285$; $F(1,33) =$

.793, $p = .380$; see tables 2 and 3 (see Appendix C for all descriptives).

1b. Noise condition did not have a main effect on the Hurst exponent of postural sway ($F(2,33) = .797, p = .459$)

1c. There was no interaction between Hurst exponent of posture and cognitive load condition ($F(2, 33) = 1.283, p = .291$).

Table 2

Effect of Hurst in Noise condition on Postural Sway Within Subjects Effects

	Sum of Squares	df	Mean Square	<i>F</i>	<i>p</i>	η^2_p
Hurst	0.0130	1	0.0130	0.777	0.385	0.025
Hurst × Noise	0.0420	2	0.0210	1.258	0.299	0.077
Hurst × Load Order	0.0107	1	0.0107	0.640	0.430	0.021
Hurst × Noise × Load Order	0.0286	2	0.0143	0.857	0.434	0.054
Residual	0.5005	30	0.0167			

Note. Type 3 Sums of Squares

Table 3*Effect of Hurst in Noise condition on Postural Sway Between Subjects Effects*

	Sum of Squares	df	Mean Square	<i>F</i>	<i>p</i>	η^2_p
Hurst	0.0294	2	0.0147	0.80261	0.458	0.051
Hurst × Noise	1.33e-4	1	1.33e-4	0.00729	0.933	0.000
Hurst × Load Order	0.0590	2	0.0295	1.61395	0.216	0.097
Hurst × Noise × Load Order	0.5486	30	0.0183			

Note. Type 3 Sums of Squares**Hypothesis 2: Cognitive Load**

2a. Noise did not have a significant effect on performance ($M_{\text{high/pink}} = 5.75$, $SD_{\text{high/pink}} = 3.77$; $M_{\text{low/pink}} = 7.67$, $SD_{\text{low/pink}} = 2.70$; $M_{\text{high/white}} = 3.75$, $SD_{\text{high/white}} = 2.96$; $M_{\text{low/white}} = 7.50$, $SD_{\text{low/white}} = 2.88$; $M_{\text{high/periodic}} = 5.67$, $SD_{\text{high/periodic}} = 3.03$; $M_{\text{low/periodic}} = 8.92$, $SD_{\text{low/periodic}} = 2.81$; see Appendix D for all descriptives), such that $F(2, 33) = 1.20$, $p = .313$. However, there is a slight, nonsignificant effect of pink noise compared to white noise in the high load condition (see

Tables 4 and 5).

2b. There was a significant effect of Cognitive load on performance such that $F(1,33) = 37.29, p < .001$. There also was a significant impact of load order on performance such that participants who experienced a decrease in difficulty (high-load then low load) did better in the block-tapping task than those who experienced an increase in difficulty (low load followed by high load; $F(1,30)=5.62, p=.024, \eta^2_p =.158$).

2c. No interaction was observed between Noise and Cognitive load on performance ($F(2,33) = 1.26, p = .296$).

Table 4

Effect of Noise Condition on Performance Within Subjects Effects

	Sum of Squares	df	Mean Square	<i>F</i>	<i>p</i>	η^2_p
Performance	159.01	1	159.01	36.814	< .001	0.551
Performance × Noise	10.78	2	5.39	1.248	0.302	0.077
Performance × Load Order	4.01	1	4.01	0.929	0.343	0.030
Performance × Noise × Load Order	7.11	2	3.56	0.823	0.449	0.052
Residual	129.58	30	4.32			

Note. Type 3 Sums of Squares

Table 5*Effect of Noise Condition on Performance Between Subjects Effects*

	Sum of Squares	df	Mean Square	<i>F</i>	<i>p</i>	η^2_p
Noise	34.3	2	17.2	1.38	0.267	0.084
Load Order	70.0	1	70.0	5.62	0.024	0.158
Noise × Load Order	27.4	2	13.7	1.10	0.345	0.068
Residual	373.6	30	12.5			

Note. Type 3 Sums of Squares

Discussion

Implications about manipulations

Despite null effects in the current study, developing a method for observing empirical evidence of the theoretical interaction between the memory and movement systems continue to provide interesting avenues for not only future memory and movement research but could also organize the evidence from previous studies in clearer terms. Scale-invariant stimuli can lead to significant effects on cognitive functions such as gait stabilization (Priplata et al., 2003; Priplata et al., 2005, Stephen et al., 2012; Galica et al., 2009; Aboutorabi et al., 2017; Miranda et al., 2016) and distance replication (Kelty-Stephen et al., 2023). By manipulating scale invariance via the *H* exponent, we can further study the complex integration of bodily systems within an organism.

Limitations to Consider in Future Work

The current study's null effects can be attributed to several external factors. More importantly for replications, there are several possible aspects of the study design that could

benefit from reconsideration. Specifically, the scoring of trials and length of time scales within the block-tapping task should be considered in studies of a similar nature.

Scoring of Trials

The dichotomous nature of the traditional operationalization of performance in this task left little room to capture variation between the intended path shown by the researcher and the remembered path. Cognitive load in the current study was scored based on accuracy, such that if a participant displayed any path outside of the intended path, the trial was marked as incorrect. For example, many participants tapped the correct blocks in the wrong order. This was marked as incorrect in the current study but is less incorrect than the participant tapping blocks that were not included in the intended path. Future work could account for this spectrum of correctness by recording which blocks are tapped by the participant in each trial. Other methods of scoring performance in serial memory tasks include using the edit distance, or the number of edits required to make the current sequence match the intended one (Gonthier, 2023).

Longer Time Scales

Additionally, the current study looked at the effects of ambient background noise across 24 trials of the Corsi task. Elaborations on this task could benefit from more variation within and between participant trials (i.e., longer sequences, more time between the showing and repeating portions of the task, etc.). The reasoning for such an adjustment to the task comes back to the previously discussed need for more variability between trials. Longer time scales could strengthen our estimate of what movement is most common over the course of a participant's performance. If such is the case, longer timescales of performance would lead to

more variability. Thus, allowing for a better glimpse of the common movement associated with the current Corsi task and strengthening the signature of deviation from that common movement.

Stronger Manipulations

It is possible that the manipulations used in the current study were not strong enough to elicit significant effects on performance. Future replications may consider raising the *SD* of the intervals between onsets in the pink and white noise stimulation. The *SD* of 0.05 seconds between onsets in the pink and white noise conditions may have been too slight for participants to have noticed or attended to. Additionally, it is possible that the block tapping paths used were not different enough in load level to impact postural sway despite being strong enough to elicit difference in performance. One block-tapping trial in the low load condition was made up of 4 directional changes and 1 cross. This trial could be compared to one of the high load trials that featured the same number of directional changes and crosses. This occurred because of a scaling error when enlarging the Orsi et al., procedure. Despite this error, the difference in performance between load conditions remained significant. Future iterations of this work should use larger blocks to avoid issues of scale.

Order Effects

The current study looked at cognitive load as a within subjects variable. Because of this, it is imperative to consider order effects of on performance. A repeated measures ANOVA was conducted to determine the impact of load order on performance in the block-tapping task. Participants who experienced a decrease in difficulty (high-load then low load) did better in the block-tapping task than those who experienced an increase in difficulty (low load followed by high load; See Tables 4 and 5). Because of this, there is room to be concerned about carryover

and practice effects that impacted performance. Replications should consider studying cognitive load as a between subjects variable.

Future Directions

The null effects of the current thesis further solidify the need for research clarifying the nature of interactions across scales within an organism. The null findings of the current study show us that embodied cognition either is not empirically supported or requires a different approach than that of the current study. Additionally, they provide us with an understanding that other forms of analysis may better examine the possible interactions between systems within an organism. Organisms function within the world based on both internal factors (such as goals) and external factors (the environment). We must consider that the effect of external stimulation (such as auditory stimulation) depends on the organism's own variations in movement (Kelty-Stephen et al., 2023). There may be deeper ways in which the participant's own bodily variations that they brought willfully to the task reshaped the effects of the stimulation. These intentional, bodily variations can be tied to the ecological concept of agency. Agency refers to the egocentric and active role of the organism within its environment (Carello et al., 2012a; Van Yperen, 2003). The bodily movements we explored through *H* are only a glimpse into the scale invariance within an organism. Bodies exhibit much more than one power law at a time, resulting in the need for a "multifractal geometry" (Kantelhardt et al., 2002; Kelty-Stephen & Wallot, 2017). With a multifractal approach, we could begin to examine the many scales of scale invariant structure within the organism. In doing so, we could better examine the agentic properties of movement and the possibility of other bodily systems impacted by goals and perspective, such as memory (Barandiaran, 2016; Barandiaran et al.,

2009; Kelty-Stephen & Wallot, 2017). Actions in the present, on many scales, determine what our memories consist of. With more empirical work, a theory of memory featuring agency could expand our current theoretical models toward a more intentional exploration of the environment.

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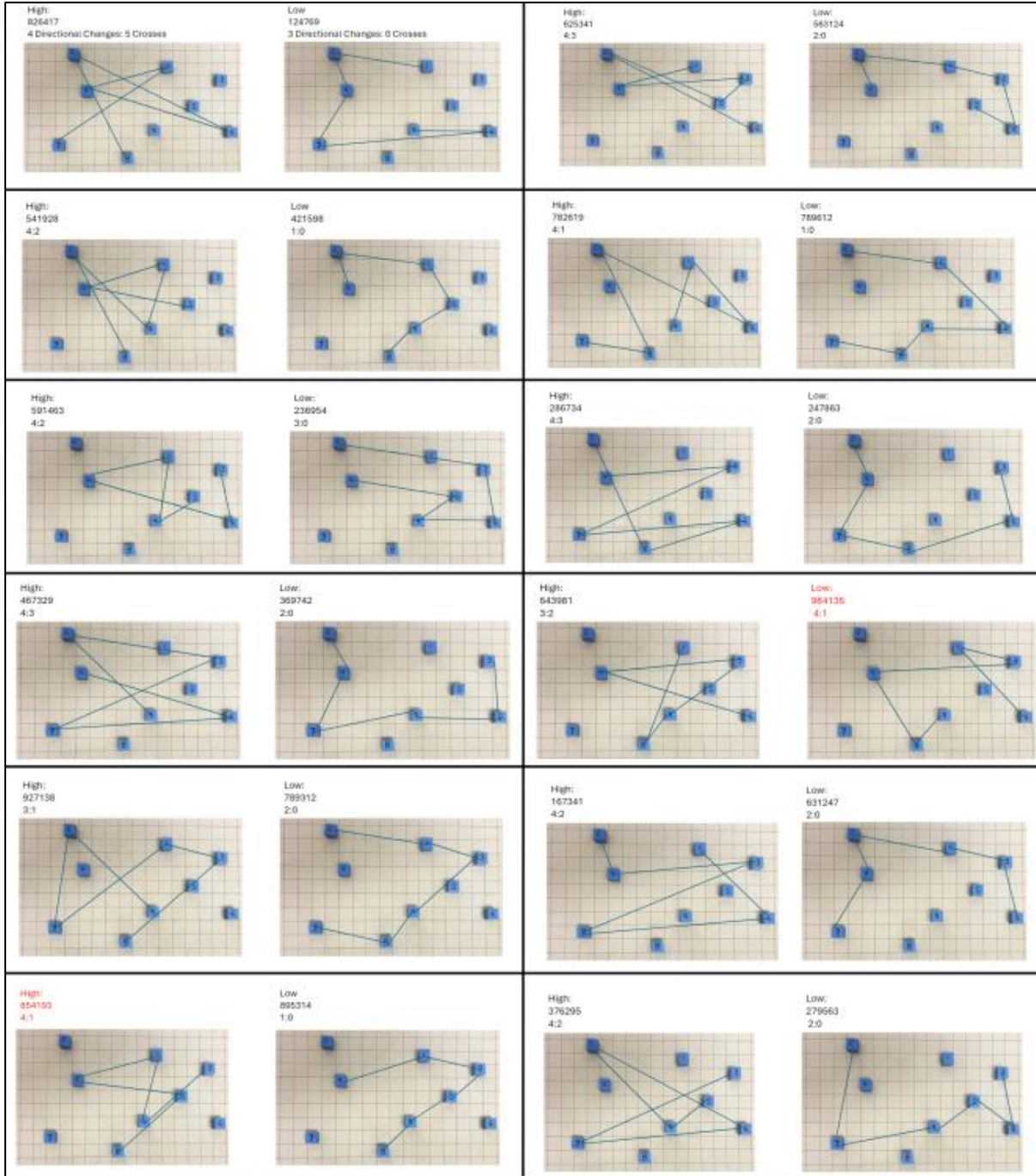
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Appendix A Corsi Paths



Appendix B

Detrended Fluctuation Analysis (DFA)

DFA integrates a time series of N -length to produce a cumulative sum time series in which each value is the sum of the current value and all previous values, subtracting the average of the time series. DFA further expands to a more general case of fluctuations from the average resting point of the time series it analyzes. To clarify, DFA integrates the following equation:

$$SD(t) \sim t^H$$

In doing so, we develop

$$y = \sum_{i=1}^N x(i) - \overline{x(t)}$$

where $\overline{x(t)}$ is the mean of $x(t)$. Linear regressions $y_n(t)$ detrend from the average resting point of the time series to account for fluctuation. This leaves us with the following equation:

$$F(n) = \sqrt{\frac{1}{n} \sum [y(t) - y_n(t)]}$$

For $n < N / 4$, $F(n)$ increases as

$$F(n) \sim n^H$$

Since power-law structured time series are often in terms of $.5 < H \leq 1.0$

$$\log F(n) = H \log n$$

The slope of $F(n)$ in double-log plots is taken to estimate H (Peng et al., 1995).

Appendix C
Descriptive Statistics of Performance

Descriptives

	Noise Condition	High Load Trials Correct	Low Load Trials Correct
N	Pink	12	12
	White	12	12
	Periodic	12	12
Missing	Pink	0	0
	White	0	0
	Periodic	0	0
Mean	Pink	5.75	7.67
	White	3.75	7.50
	Periodic	5.67	8.92
Std. error mean	Pink	1.09	0.782
	White	0.854	0.830
	Periodic	0.873	0.811
Median	Pink	6.00	8.00
	White	3.50	8.50
	Periodic	4.50	9.50
Standard deviation	Pink	3.77	2.71
	White	2.96	2.88
	Periodic	3.03	2.81
Minimum	Pink	0.00	3.00
	White	0.00	3.00
	Periodic	2.00	4.00
Maximum	Pink	10.0	11.0
	White	10.0	11.0
	Periodic	11.0	12.0

Appendix D
Descriptive Statistics for *H*

Descriptives

	Noise Condition	High Load Hurst	Low Load Hurst
N	Pink	12	12
	White	12	12
	Periodic	12	12
Missing	Pink	0	0
	White	0	0
	Periodic	0	0
Mean	Pink	1.08	1.10
	White	1.07	1.06
	Periodic	1.09	0.998
Median	Pink	1.07	1.08
	White	1.08	1.07
	Periodic	1.08	1.08
Standard deviation	Pink	0.0827	0.0855
	White	0.0606	0.0611
	Periodic	0.0401	0.285
Minimum	Pink	0.979	1.01
	White	0.947	0.896
	Periodic	1.04	0.106
Maximum	Pink	1.24	1.24
	White	1.14	1.14
	Periodic	1.18	1.15