



# Whole-body multifractal synergies support cognitive visual word search

Damian Kelty-Stephen, Madhur Mangalam, Mélen Guillaume, Cédric T. Bonnet

## ► To cite this version:

Damian Kelty-Stephen, Madhur Mangalam, Mélen Guillaume, Cédric T. Bonnet. Whole-body multifractal synergies support cognitive visual word search. *Ecological Psychology*, 2025, 10.1080/10407413.2025.2587061 . hal-05355700

**HAL Id: hal-05355700**

**<https://hal.science/hal-05355700v1>**

Submitted on 9 Nov 2025

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

---

# WHOLE-BODY MULTIFRACTAL SYNERGIES SUPPORT COGNITIVE VISUAL WORD SEARCH

---

**Damian G. Kelty-Stephen**

Department of Psychology  
State University of New York at New Paltz  
New Paltz, NY 12561, USA  
keltystd@newpaltz.edu

**Madhur Mangalam**

Division of Biomechanics and Research Development,  
Department of Biomechanics,  
Center for Research in Human Movement Variability  
University of Nebraska at Omaha  
Omaha, NE 68182, USA  
mmangalam@unomaha.edu

**Mélen Guillaume**

Department of Psychology  
Université de Lille  
59000 Lille, France

**Cédrick T. Bonnet**

Department of Psychology  
Université de Lille  
59000 Lille, France  
cedrick.bonnet@univ-lille.fr

February 27, 2025

## ABSTRACT

Turvey viewed perceptual facility with words as a nonlinear prestress of whole-body synergies, forming a multifractal tensegrity rather than a computational cognitive mechanism. This reanalysis of an upright-postural Stroop-like conjunction search links three aspects of multifractal synergies to the cognitive processes involved in the visual word search. Young adults participated in four foot/body positions and two tasks while standing all the time. First, searching tightly constrained task space benefits from reducing multifractal postural variability. Visual search for incongruently colored words occurred with less multifractal nonlinearity in the postural center of pressure (CoP), particularly for targets within a narrow visual angle. Second, excessive constraint requires compensatory multifractal variability elsewhere. Restraining stance led successful search to become associated with increased multifractal nonlinearity in movement fluctuations at the head and clavicle. Third, different tasks elicit different synergies. Searching for inverse-incongruent words (e.g., a red-colored “blue” instead of a blue-colored “red”) benefited from the reduction of multifractal nonlinearity in clavicle rather than in CoP displacement. Subsequently, greater multifractal nonlinearity in head movements was associated with successful searches for centrally located targets. Multi-joint synergies of multifractal nonlinear interactions support visual-word search by responding to or imposing constraints and reorganizing in response to intentional shifts.

**Keywords** cascade dynamics · fractal · multifractal · nonlinear dynamics · postural control · suprapostural dexterity

## 1 Introduction

Grasping a single word that might describe Michael T. Turvey is not just difficult—it is almost comically impossible. His impact demands many words, some seemingly unrelated, bound together only by the remarkable genius with which he found and wove connections among them. The breadth of Turvey’s intellectual reach has few true analogs in contemporary science. The rigid silos of academia make it difficult for most to embrace the kind of polymathy that came naturally to him. Yet Turvey was never interested in polymathy for its own sake; he pursued something deeper—an interdisciplinary integrity that united diverse fields, expertise, and ideas. For him, uncovering the hidden

links between seemingly disparate domains was just as vital as fostering the communities of scholars who would carry those connections forward. His work did more than challenge conventional boundaries—it reshaped them, leaving an intellectual landscape more expansive, interconnected, and profoundly enriched.

Grasping a single word was a challenge that Turvey appreciated. Reading was, in fact, one of the domains that most absorbed his interest. It also stands out as one of the more difficult domains for retrospective views to integrate with the rest of the Turvey portfolio—if not for Turvey himself, then at least for some of his more admiring followers, colleagues, and students. The present work’s authors include people in any, two, or all of those latter categories. We confess that we were all too young when we first interacted with Turvey and carried far too narrow expectations. He had a direct hand in maturing our perspectives and broadening our views. One of us recalls a late-night discussion with Turvey at the pub, asking—provokingly and, in retrospect, immaturely—what the point of studying reading was if we were also to avoid investing our theories in mental representations or, indeed, symbolic representations of any kind, like words. Turvey did not miss a beat, replying with characteristic precision that reading ability was one of the better predictors of a happy future outside the criminal justice system (e.g., Chow et al., 2022; Shippen et al., 2010). The stakes, he made clear, were high. He also acknowledged that a natural law eschewing representations could not enact any perception-action or cognition without meeting its complement in the constraints that formed the stock-in-trade of computational psycholinguistics (Pattee, 1974; Turvey, 1992). The then-humbled and newly enlightened coauthor returned to his drink and has not, we can report over a decade later, stopped thinking about that conversation.

“How?” has been the single most burning word that rises to us in our notes on what Turvey said and how we use it. We, as perceiving-acting systems fluent in both affordances and object classification (e.g., Gibson, 1979; Withagen and Chemero, 2012), somehow hop from dynamical law in affairs like step-on-ability (Warren, 1984) to classifying the objects. Turvey’s priorities were clear, and he left judicious room for the possibility of a future connection between the dynamical laws underwriting action and the symbolic constraints of words. He did not want us to worry immediately or too much about “How?”—likely because he knew much work remained to be done in this vein. Thus, unearthing a once-silly, once-student’s question is not a disrespectful *gotcha*. The present manuscript attempts to return to the question, even if it is no longer possible to return to the bartender, with some later-developed ideas. We are seeing—always too late—new possibilities for integrating some of the variegated pieces that Turvey brought to our attention.

## 1.1 The long fractal roots of how words might get into muscles

The possible connections we propose here for understanding the grasp of a single word may have only begun to dawn on Turvey himself relatively late. Yet the roots ran deep and early: Turvey had a distinguished career as a psycholinguist (Lukatela et al., 1980; Lukatela and Turvey, 1998; Ognjenovi et al., 1983; Turvey et al., 2017). He also began drawing other psycholinguists from the connectionist tradition into questions about dynamical law and emergence beyond mere computational or symbolic constraints (Van Orden et al., 2003). This latter pull need not have been too strong—connectionism itself had quite constraints-averse beginnings, favoring cascades and flows that verged on the anarchic amid the reign of information-processing models (McClelland, 1979). Turvey called some connectionists back to their grounding values, steering them away from their compromises with traditional information-processing frameworks to maintain legitimacy within cognitive psychology. These anarchic themes carried forward into Turvey’s absolutely visionary collaborations with Guy Van Orden and Jay Holden, helping to launch bold new proposals on how the fractal and power-law evidence that had simmered in the psychological empirical record for decades might signal the self-organization supporting cognition itself (Holden, 2002; Van Orden and Holden, 2002; Van Orden et al., 2003, 2005). Turvey and colleagues first identified this fractal patterning in spoken-response times. Kello later recruited Van Orden and Holden to explore similar patterns in spoken-syllable and spoken-word sequences (Kello et al., 2008). Revolution felt almost palpable in the air.

Suddenly and briefly, Turvey appeared to grasp the connection between our mental handling of individual words and the fractal patterning of our bodily movements. His work with Rhodes provided preliminary evidence linking power-law-like scaling in memory recall to power-law-like foraging dynamics, suggesting a deeper, shared organizational principle across cognitive and ecological domains (Rhodes and Turvey, 2007). Holden then led Van Orden and Turvey in a remarkable encore, examining power-law and power-law-like distributions in word-reading times (Holden et al., 2009). This work sparked several follow-up demonstrations of similar patterns across various language-use domains and populations (Holden and Rajaraman, 2012; Holden et al., 2014). Turvey offered us a glimpse into the entanglement of memory and visual word recognition with our bodily movement system, cultivating a scale-invariant froth of interactions across events large and small. The task of so-called “processing” language—one individual word at a time—was no longer merely an affair written at the scale of discrete symbols, that is, symbols large enough for us to recognize or write as individual letters (Turvey, 1977b), yet arbitrary enough to frustrate any devotee of natural law (Turvey et al., 1981). No, for a fleeting moment, Turvey planted the seed for a naturalization of language use—one that promised to embed the symbolic word within a fluid cascade of dynamics, whose richly nested structure pervaded the body that

wielded and responded to those very symbols. This insight was at once perfectly consonant with Turvey’s enduring commitments to motor theories of language use (Galantucci et al., 2006) and, at the same time, more foundational than any appeal to articulatory gestures alone (e.g., Fowler, 2006). Turvey laid the groundwork for the idea that the fractal patterning of language use was inseparable from the fractal patterning of perception-action systems.

Turvey’s own progress on the connection between the grasp of single words and the movement system gradually slowed. His stamp on the fractal-themed proceedings above remains indelible and unmistakable, yet his engagement with fractal dynamics became increasingly brief—more glancing, intermittent, and perhaps less confident. Between 2007 and 2014, Turvey’s involvement in fractal-themed work grew sporadic, and he occasionally retreated behind his characteristic agnosticism, referring to such work as “not uninteresting.” Shortly thereafter, critical papers cast serious doubt on the reliability of the recent surge in power-law evidence for foraging behavior (Clauset et al., 2009; Edwards et al., 2007). Rhodes, however, continued to confirm his original results, applying the heightened statistical rigor these skeptical voices had called for (Kerster et al., 2016; Rhodes et al., 2014). Turvey, meanwhile, followed the example of one of his cherished model systems—the jumping spider—biding his time and waiting for stronger evidence before leaping to broader conclusions. One of the present coauthors sought to carry forward the fractal tradition as a student just a few doors down from Turvey at the University of Connecticut, enlisting him as a dissertation committee member. Their work occasionally intersected in coauthored papers (Palatinus et al., 2014) or citations (Turvey and Carello, 2011), particularly when fractality and its so-called “multifractal” variation provided insight into how static holding or support could still generate exploratory value. Privately, Turvey expressed concern that fractal dynamics had yet to bear all the fruit he had once hoped for.

## 1.2 The tensegrity connection called back to the fractal response to words

The tensegrity and bodywide pre-stress rekindled Turvey’s interest in fractal dynamics, bringing us to the unifying theme of the present work. Turvey and Fonseca (2009) recognized the fractal-like structure of connective tissues as the architectural glue knitting the musculoskeletal system together. In 2014, they began to promote mathematical arguments suggesting that the tensegrity structure of connective tissues must be *multifractal*, as the balance of tension and compression elements appeared nested across multiple scales (Turvey and Fonseca, 2014). Whereas *fractal* dynamics follow a single, scale-invariant power-law relationship between fluctuations (e.g., standard deviation) and scale of time or of space, *multifractal* dynamics refer to all those systems and processes whose fractal scaling can vary, thereby supporting multiple different power-law relationships. The fractal case only requires one power-law exponent for a complete description. In contrast, the multifractal case requires a continuum or *spectrum* of power-law exponents increasing on the real-numbered and so *fractional* domain. Meanwhile, fractal analysis only pursues a single fractional—so, “fractal,” the multifractal formalism estimates the width of a multifractal spectrum of these power-law exponents.

Why multifractal and not just fractal? It is worth asking because, to the unfamiliar reader, fractal scaling can seem exotic enough without asking for the more cumbersome-sounding abundance of *multifractality*. The multifractal tensegrity hypothesis reflected a line of reasoning that involved at least two steps. The reasoning that tensegrity might be at least fractal was that the connective tissues supporting the musculoskeletal system functioned through a dynamic balance of tension and compression elements—an intriguing nuance being that what was tensile at one scale could manifest as compressive at another and vice versa. The heterogeneity of the bodily form and its boundedness at the skin had previously prompted suggestions that a single fractal parameter could not do justice to the wider range of this scale-invariant property. Furthermore, the interactivity across scales held the potential of something more fluidly cascading. Echoing Pattee’s (2001) intuition, what seemed like a rigid compressive constraint at one scale might be supported by more fluid tension at another. This more fluid interdependence made nonlinear interactivity across scales a firmer requirement, and the best formalism for carrying this requirement to date is the multiplicative cascade. The best statistics for estimating the underlying parameters of a cascade are multifractal statistics—a point established by Mandelbrot (1974; 1982; 2013) and brought home to a psychological audience by Ihlen and Vereijken (2010). The multifunctionality that had confounded simplistic attempts to characterize motor degrees of freedom (Turvey et al., 2014) requires a more nuanced characterization than a single scale-invariant parameter to rule the whole system.

A specific connection to test between word recognition and the multifractal tensegrity hypothesis was clearly in the spirit, if not the letter, of Turvey’s written opus. His interest in tensegrity as a pre-stressed hierarchy of tensions and compressions aligned neatly with his long-standing emphasis on speech as intricate coordination (Turvey, 2007), enlisting a vast number of degrees of freedom to work in concert even for uttering the simplest syllable (Abbs and Connor, 1989), and his enduring interest in the immediate adaptation of speech to articulatory perturbations (Kelso et al., 1984; Fowler and Turvey, 1980). These features of speech production would later appear as the *concinnity* implicated in tensegrity’s hierarchical grasp of parallel processes and the *ultrafast* capacity of this tensegrity for global resolution of local perturbations (Turvey and Fonseca, 2014). Turvey’s work supporting Moreno and Stepp revisited

the classic paradigm of visual single-word recognition. Supporting and before the classic fingertap response (e.g., in a button press) to register recognition of a word, pseudoword, or nonword, Moreno et al. (2011) revealed a whole cascade of anticipatory postural adaptations, with postural muscles in the shoulder, torso, and thigh anticipating the perturbing influence of a fingertap. They replicated the classic patterns of fingertap response time to the letter strings on the screen, but more crucially, they showed that the classic patterns of response time appeared much sooner in the electromyography of those shoulder, torso, and thigh muscles, pre-stressed to keep the fingertap from upsetting the reading organism's upright posture. Tensegrity goes unmentioned in this latter work, and it is truly a tidy piece of scholarship—short and to the point, just as Turvey preferred. However, reading this work alongside the studies published in quick succession before and after it (e.g., Turvey and Fonseca, 2009; Turvey and Carello, 2011; Turvey and Fonseca, 2014), we are extremely doubtful that Turvey's affection for the ultrafast, multifractal tensegrity was far from his mind. But then again, who can know? The paper trail fuzzes from view, and pure coincidence is always possible.

### 1.3 Aiming the multifractal tensegrity hypothesis at single-word recognition

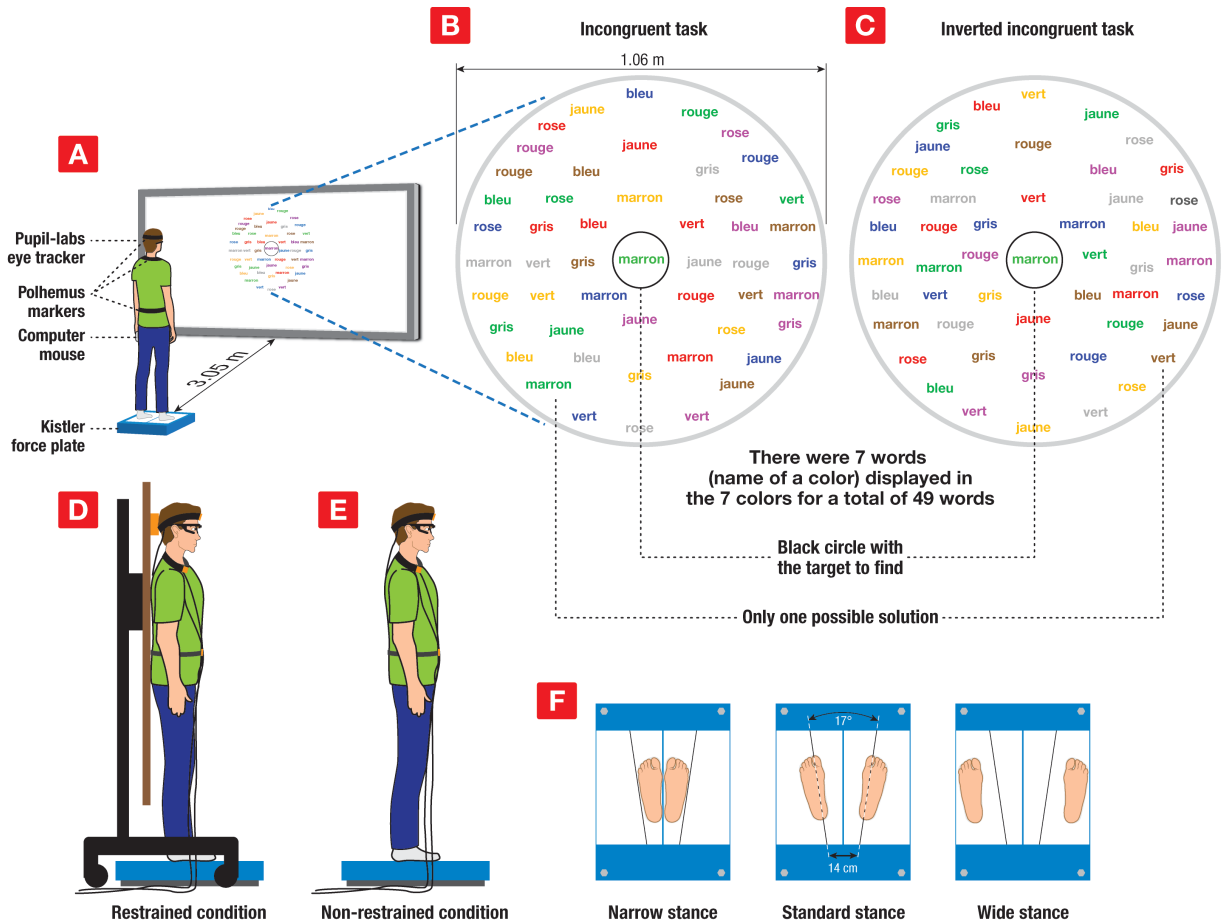
So, the present work aims at a research question inspired by Turvey's lifelong steadfast work trying to unite such disparate domains as visual word recognition and the multifractal tensegrity coordination of the movement system. We do not come to this task completely out of the blue or simply in a fit of mourning. There is prior work documenting that speech is indeed as multifractal as it should be if a tensegrity structure were producing it (Kelty-Stephen et al., 2023b), and then, the multifractality of speech appears to be a distinguishing feature of speech supporting the attention and perception of human listeners (Hasselmann, 2015; Ward and Kelty-Stephen, 2018). Multifractal structure of speech supports spoken word recognition, particularly as human listeners listen to a coherent narrative, even as word recognition hinges less on individual word features and more on the narrative structure (Bloomfield et al., 2021). What is more, if the listening task is self-paced and so explicitly requiring fingertap movements to elicit more spoken words, listeners who bring more multifractality in their fingertap sequences in this speech event appear to have better recognition memory for the words they have heard in the narrative (Bloomfield et al., 2021). Hence, we have preliminary evidence consistent with tensegrity-based answers to Turvey's questions about language use on the speech side. We now offer the latest step, this time towards tensegrity-based answers to questions about the reading side.

Grasping a single word may rest in our grasp for the ground, and the multifractal tensegrity hypothesis may help unlock a scientific view into that relationship. The present work aims to forge the strongest linkage between visual word recognition and upright postural control. Turvey had long been a champion of the ecological-psychology insight (e.g., Gibson, 1966, 1979; Riccio and Stoffregen, 1991) that upright posture and vision were intimately connected (Balasubramaniam et al., 2000; Riley et al., 1997, 1998; Turvey, 1977a). Once the multifractal aspects of posture had begun to show consonance with a tensegrity model of perception (e.g., Ihlen et al., 2013; Morales and Kolaczky, 2002), Turvey began to show an interest in the multifractality of posture for haptic perception (Palatinus et al., 2014). Multifractality became a new way for Turvey to understand how the organism might shift its attention, making quick and agile shifts in using the same tissues to accomplish different perceptual feats.

#### 1.3.1 Postural stance in support of searching for Stroop-incongruent words

To ensure that this research question is worthy of the scholar who inspired it, we aim to clearly articulate how it honors the complementarity between law and constraint—an idea fundamental to Turvey's ecological-psychological approach (Pattee, 1974; Turvey, 1992). On the lawful side, multifractal dynamics reflect nonlinear flows unfolding across all scales without being tied to a native scale of measurement (e.g., Kugler and Turvey, 2015; Warren, 1984). On the constraint side, enabling constraints shape bodily capacity for movement as well as the task settings that support it (Baggs et al., 2020; Raja and Anderson, 2021). Our participants stood upright while performing a word-recognition task designed as a word search. This choice avoids the representational challenges inherent in distinguishing words, non-words, and pseudowords. At the same time, it still probes single visual word recognition by requiring participants to use word status and meaning to identify the correct target. A search task also facilitates the exploration of connections between posture and word recognition because postural constraints, such as stance width, influence search performance (Mitra and Fraizer, 2004). In particular, we examined postural constraints under four settings: a self-selected comfortable stance width, a restrained stance in which the participant stands with their back against a vertical surface, a narrow stance, and a wide stance. This restraint against a surface does not address stance width, but it does appear important in limiting the exploratory possibilities of postural sway for perceiving structure in the ambient layout of surfaces (Mark et al., 1990).

Beyond the strictly bodily constraints, we must also consider the task constraints. The task we have chosen to probe visual word recognition might have appealed to Turvey's love of tradition. He sought with Rhodes to probe for fractal dynamics in the traditional Bousfield and Sedgewick's (1944) paradigm of categorical free recall (Rhodes and Turvey, 2007). Now, we take our multifractal-tensegrity inquiry yet deeper into the psychological canon to Stroop's (1935)



**Figure 1: Experimental setup and task conditions.** (A) Participants stood on a force plate while performing a visual search task. Eye movements were tracked using an eye tracker, and active markers recorded body motion. A computer mouse was used for target selection. (B) In the incongruent task, participants searched for a color word (e.g., “marron”) displayed in the corresponding color among distractors with conflicting color-word associations. (C) In the inverted incongruent task, the spatial arrangement of words was mirrored, adding a layer of complexity. In both tasks, the priming word was centrally located and enclosed in a black circle, with only one correct answer per trial. Participants performed the task in two postural conditions: restrained (D), where movement was restricted using a vertical support frame, and non-restrained (E), where they stood freely. (F) Three stance conditions were tested: narrow stance, standard stance (14 cm apart), and wide stance, to examine the effects of postural constraints on cognitive performance.

classic paradigm. The present task was not a Stroop task per se, but it leaned on the capacity of color words to engage an incongruence with the color in which their letters appear. The task embedded Stroop-type incongruence in the time-honored cognitive-psychology paradigm of visual search (Treisman and Gelade, 1980). All trials used a priming color word presented in an incongruent color to guide the search for a target word amongst a circular display of color words printed in often incongruent colors.

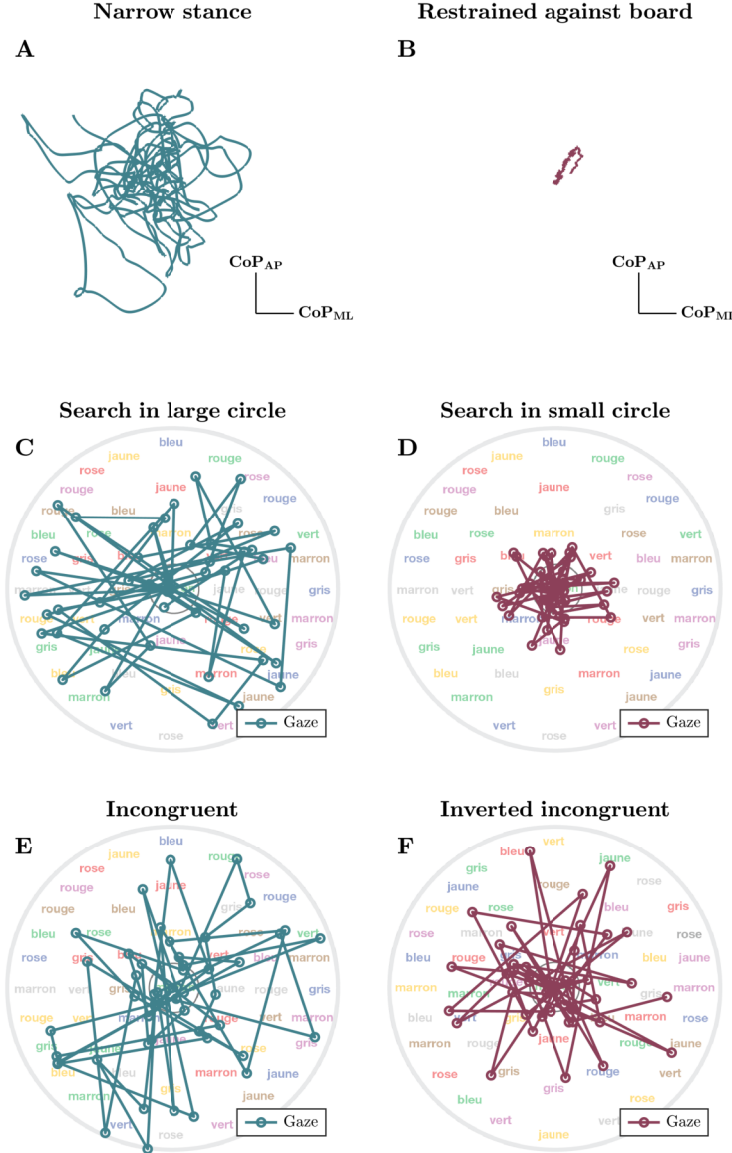
We manipulated two major constraints in this Stroop-inspired search task (Figure 1). The first was the radial distance between the target and the priming word, with the priming word always appearing at the center of the circular display while the target word appeared within a small, medium, or large circle around it. The second constraint was the relationship between the Stroop-type incongruence of the priming and target words. In one setting, participants searched for a target word identical to the priming word, the same color word in the same incongruent color. In the second setting, they searched for a target word that inverted the priming word’s incongruence—finding the word describing the priming word’s color, printed in the color described by the priming word.

Turvey's interest in seeing similarity beyond superficial differences led us to envision that each task constraint offered visual analogs to the postural constraint described above. Postural sway is key for visual exploration (Riccio and Stoffregen, 1991; Stoffregen and Riccio, 1988). Maintaining a narrower stance prompts instability and requires the postural system to constrict movement degrees of freedom to stabilize exploration on the visual display (**Figure 2A–B**). A narrower stance does, it is true, prompt instability in postural degrees of freedom. However, it is precisely because of this instability that a narrow stance requires subsequent constraints of postural degrees of freedom. Standing with the soles of the feet closer than is comfortable will destabilize posture, and the upper segments of the postural system will consequently work to constrain postural degrees of freedom. Much as yoking attention to the centrally located priming word prompts subsequent expansion of search behaviors across the visual field on each trial, restraining posture against a vertical surface prompts a compensatory release of postural degrees of freedom to allow visual exploration to unfold. This release might only be available to the upper body, for example, the chest, the head, or the eyes. After all, the tensegrity perspective might free our view of postural control from the classic inverted-pendulum model and instead allow the possibility of postural fluidity shifting up and down the multiple body segments. The circle-width constraint served as a visual analog to the postural constraint of stance width. Targets in the smallest circle would require constricting search behaviors toward the center of the visual field (**Figure 2C–D**).

We also aimed to envision the inversion of incongruence less as a strictly cognitive-psychological variable and more as a potential constraint on the fluidity of a multisegmental tensegrity system. The standard cognitive-psychological perspective on inversion might appeal to the so-called “cognitive load” of the task by adding another feature to be maintained in so-called “working memory” (Treisman and Gelade, 1980). However, Turvey was clear about the pitfalls of “working memory” concepts (Turvey, 1977a). The inversion of incongruence might more straightforwardly enlist search more likely to invite participants to look back from the circular surroundings to the center of the visual display when evaluating candidate words as potential correct targets (**Figure 2E–F**). The added difficulty of inverting the task is thus likely to invite participants to cling visually toward the center, much as locating targets in the smallest circle would. The back-and-forth shift between the circular surround and the central priming word constrains visual search. This constraint may also amplify multifractal flow contributions higher in the postural system, such as near the chest and head.

Within these constraints, we expected the fluidity of multifractal scale invariance to encode lawful possibilities for how perception-action dynamics exploit the task context in word finding. Specifically, lawful multifractal flows within the postural system should reflect the loosening of movement degrees of freedom to support search (Kelty-Stephen et al., 2021). We intend this point to be analogous to the standard ecological understanding that postural sway supports exploration (Riccio and Stoffregen, 1991; Stoffregen and Riccio, 1988): search is just a form of exploration, which is true no matter the search task. To maintain an upright stance and stabilize posture within the base of support, the postural system reduces its multifractal variability, indicated by a narrower multifractal spectrum and smaller deviations from linear surrogates when instability threatens a quiet stance versus in stable posture (Bell et al., 2019; Kelty-Stephen et al., 2021; Kelty-Stephen, 2018). Hence, the following hypotheses followed from a general proposal that multifractal nonlinearity waxes and wanes according to the release or constraint of degrees of freedom, and they aimed to address the multifractal nonlinearity as a means to operationalize degrees of freedom across the postural system in exploration for the purpose of word search and recognition.

- Our first hypothesis predicted that successful search performance would be associated with lower multifractal nonlinearity  $t_{MF}$ , measured as the  $t$ -statistic comparing the original multifractal spectrum width to that of its linear surrogates, in center-of-pressure (CoP) displacements (Hypothesis 1).
- This relationship should be strongest when constraints further restrict movement degrees of freedom, such as a narrower stance (Hypothesis 2a), a target appearing in a smaller circle (Hypothesis 2b), or their interaction (Hypothesis 2c). It is true that a narrower stance will prompt instability, but that is precisely the sense in which a narrower stance prompts the postural system to constrain its degrees of freedom. The reduction of multifractal nonlinearity is a protective response constraining degrees of freedom when posture is less stable.
- Conversely, when a vertical surface constrains posture, the system must free some degrees of freedom elsewhere to allow exploration. We, therefore, anticipated a reversal of the earlier relationship: a compensatory rise in multifractal nonlinearity, indicating that the postural system has expanded its capacity for exploratory movement. In this scenario, better search performance should coincide with higher multifractal nonlinearity  $t_{MF}$  at parts of the body that retain more freedom to move than the CoP. Specifically, pressing the back against a vertical surface shifts the search-promoting multifractal fluctuations toward the clavicle, head, or eyes. However, because overall movement is more restricted, this benefit might only appear for the smallest circle of the visual display (Hypothesis 3).
- Finally, we expected that searching for an inversion of the priming word's incongruence would promote more constrained search patterns, likely benefiting from reduced multifractal nonlinearity. However, as suggested above, the inverted task would also favor better search performance when reductions in multifractal nonlinearity occur at upper-body anatomical locations within the postural system (Hypothesis 4a). This hypothesis also warranted



**Figure 2: Hypothesis comparisons of postural sway and gaze behavior across postural and task conditions.** (A–B) Postural sway in narrow vs. constrained stance: The center of pressure (CoP) trajectory is expected to be more constrained in the restrained condition (B) compared to the narrow stance (A), supporting the hypothesis that restraining the body imposes constraints that reduce the span of postural sway along both the ML and AP axes. (C–D) Gaze search in large vs. small circles: The gaze trajectory is anticipated to be more localized when searching for words in the smaller circle (D) compared to the larger circle (C), supporting the hypothesis that search area size modulates gaze dispersion, with a smaller area producing more constrained gaze shifts. (E–F) Gaze patterns in incongruent vs. inverted incongruent task conditions: The incongruent task condition (E) shows a more distributed gaze trajectory, while the inverted incongruent condition (F) exhibits more radial gaze movements. In the inverted incongruent task condition, the gaze is expected to visit the center more often, supporting the hypothesis that inversion constrains gaze control, biasing fixation patterns toward central locations.

a manipulation check to confirm that the inversion of the incongruence did, in fact, change gaze behavior in the proposed direction, that is, in prompting more recursion back to the center. We predicted that gaze positions in the inverted-incongruent task would show reduced root-mean-square *rms* dispersion of positions around the average resting position in the center of the display (Hypothesis 4b). We expected that restraining posture with a vertical



surface would counteract this negative effect of upper-body multifractal nonlinearity in the inverse-incongruent task setting, particularly for narrower circles of the visual display (Hypothesis 4c). Hypothesis 4a and 4c were similarly directional but exploratory as Hypothesis 3 for the same reasons.

For the third and fourth hypotheses, we expected these multifractal effects to arise at relatively higher locations in the postural system. We measured head, clavicle, trunk, and eye-gaze positions and examined potential interactions between multifractal nonlinearity at each location and the relevant postural or task constraints. Given the novelty of this approach and the limited prior research on network-like relationships across the upright-postural system (Mangalam et al., 2020), we treated this hypothesis as exploratory, allowing for multiple upper-body locations to be tested. Constraining the back against a vertical surface naturally makes it harder to free up degrees of freedom at the trunk but more likely at the clavicle, head, or gaze. This redistribution of movement flexibility could reveal compensatory strategies, where the dynamic interplay between different levels of the postural system maintains overall stability despite localized constraints.

This project primarily concerns search behavior, with multifractal nonlinearity from a multifractal tensegrity playing only a supporting role. It is important to emphasize that the primary outcome measure in these hypotheses is accurate search performance, except for the manipulation check (Hypothesis 4b). The foregoing acknowledges associations between changes in multifractal nonlinearity and changes in accurate search performance. However, we did not manipulate multifractal nonlinearity; rather, we estimated its endogenous variations across different postural and task settings. While we recognize that postural and task settings might influence the relationship between multifractal nonlinearity and search performance, we did not design this study to test direct causal effects. The absence of manipulation leaves unclear the causal relationship between search behaviors and multifractal nonlinearity.

Nonetheless, we wish to clarify that we do not explicitly predict differences in multifractal nonlinearity as an outcome measure. We do not focus on whether multifractal nonlinearity should change but on how constraints interact with multifractal nonlinearity to shape and support adaptive behavior. To our understanding, multifractal nonlinearity emerges from tensegrity-type nonlinear correlations and global pre-stress that form the foundation of coordinated and flexible behavior. We do not assume that task settings should inherently diminish the body’s adaptive capacity or impose rigid constraints undermining flexibility. Therefore, we introduce Non-Hypothesis 1 to articulate our lack of expectations regarding systematic differences in multifractal nonlinearity—while acknowledging that this question remains interesting to readers. This non-hypothesis is not meant to suggest that we are advocating for a null hypothesis but rather to emphasize the contrast between, on the one hand, predicted differences in behavior resulting from the interaction between multifractality and constraints and, on the other, any incidental changes in multifractal nonlinearity itself.

## 2 Methods

### 2.1 Participants

Twenty-one healthy students (7 women;  $M \pm SD$  age:  $22.4 \pm 2.2$  years; body mass:  $66.1 \pm 14.0$  kg; height:  $170.9 \pm 8.9$  cm) from the University of Lille participated in this study. All participants provided their informed written consent to participation approved by a local ethical committee (Study No. 2021-546-S100). All participants diligently wore masks and willingly signed a comprehensive document addressing their responsibility in light of the ongoing COVID-19 pandemic.

### 2.2 Experimental setup and visual search task

During the experimental sessions, the participants positioned themselves 3.05 m in front of a large flat display (custom-made mobile image wall by Antycip, 4 stereo 120 Hz with 4 Canon video-projectors; height: 2 m; width: 4 m; **Figure 1**). This display presented a circular image (radius: 0.53 m; visual angle:  $20^\circ$  at eye level, directly in front of the participants). Within this circular image, a central priming word appeared within a small black circle, surrounded by 49 words arranged in three virtual circles (**Figure 1A**). This priming word was a color word printed in an incongruent color in the spirit of Stroop (1935), for example, the word “blue” written in red. The objective was to use the priming central word to find a unique target word among the 49 surrounding words consisting of seven color words (that is, blue, green, red, brown, pink, gray, and yellow), each displayed in one of the seven colors. There were two task settings: as elaborated below, one task setting involved finding a target word that was the same as the priming word, printed in the same incongruent color, and the other task setting involved finding an incongruently colored target word with the inverse incongruence, for example, priming with the word “blue” written in red prompted the participant to find the word “red” written in blue. The small, medium, and large virtual circles contained 8, 16, and 25 words, respectively. Subsequent modeling encoded these different virtual circles as the variable *CircleSize* with values

“Small” and “Medium”, allowing us to model relatively more focal than peripheral visual search behavior, using a reference value of “Large.” The positioning of the 49 words and the selection of the centrally located prime within the black circle was randomized for each image. The centrally located prime could only be a color name presented in a different color, offering 42 of the 49 possible randomized choices. We prepared 24 images with 49 words randomly arranged for the planned 24 trials to ensure variability. Participants relied on a handheld computer mouse as their primary interface—with every click on either of the two buttons, the central prime underwent a random alteration. Notably, after each click, the central prime was carefully programmed never to replicate its previous appearance until the 43rd click had occurred.

At the beginning of each 2-minute 3-second trial, participants focused on a central black cross within the small black circle for three seconds. Subsequently, the cross disappeared, and the first priming word appeared. Participants were then tasked with locating the corresponding target word, and this search continued for the next two minutes within each trial. Clear instructions were provided to participants, emphasizing the importance of maximizing target identification during each trial while minimizing errors.

The displacement of the postural center of pressure (CoP) along the participants’ anatomical AP and ML axes was recorded using a dual top force platform (120 Hz; AMTI Inc., Watertown, MA). The head, neck, and belt positions were recorded with a Polhemus Liberty 240/8-8 System (240 Hz; Polhemus Inc., Colchester, VT). The head marker was attached to the front of the participant’s headband, while the other two were placed on the front of the neck and belt. Eye movement was tracked using a Pupil-labs eye-tracker (Pupil Labs Inc., Berlin, Germany; eye cameras: 120 Hz; scene camera: 50 Hz) worn by the participants (**Figures 1, A & B**). All devices were synchronized using a custom MATLAB script (MathWorks Inc., Natick, MA).

### 2.3 Visual task manipulation

We manipulated the visual search task at two levels, which appeared in subsequent modeling as a class variable *InvertedTask* with values “Non-inverted” meaning the search for a target with the same Stroop-type incongruence as the priming word different from “Inverted” meaning the search for a target with inverted Stroop-type incongruence relative to the priming word, and participants’ goal was to find as many targets as possible. In the incongruent task without inversion, participants searched and located, among the 49 words, the same word as the priming word displayed within the small black circle in the center of the display. For example, if the central priming word was “red” written in “blue,” participants had to find “red” written in “blue” (**Figure 1B**). Once they identified the target word, participants fixated on it for one second and clicked the mouse. Subsequently, the central priming word changed, and participants searched for and located the new target within the visual display. In the inverted incongruent task, participants found the priming word within the small central circle and had to find the target amongst the 49 remaining words on the display that had the inverse Stroop-type incongruence. For example, if the central target was “red” written in blue, the participants had to find “blue” written in red (**Figure 1C**). The contrast between incongruent and inverted-incongruent tasks is analogous to the classical experimental-psychological distinction between single-feature and conjunction search (Treisman and Gelade, 1980). It is not that the non-inverted case is a “single-feature” search, but the inversion adds another feature that the searching participant must bring to their evaluation of a correct finding. Previous studies have focused on contrasting congruent tasks (e.g., finding “blue” written in blue) and incongruent tasks (e.g., finding “blue” written in red) (Caron et al., 2023; Rosenbaum et al., 2017; Smith et al., 2019). While the congruent case may be solved by recognizing the stimulus without processing word meaning, the non-inverted incongruent task requires Stroop-type conflict resolution to maintain awareness of the target word.

### 2.4 Postural manipulation

The manipulation of difficulty of postural control had four levels and is incorporated in subsequent modeling as a class variable *PosturalCondition* with values “Restrained”, “Narrow”, and “Wide” relative to a reference value of “Standard.” In the restrained condition, participants leaned against the vertical plank of wood measuring  $83 \times 156$  cm (**Figure 1D**), eliminating the need for balance. The participants had to stand and push their backs against this surface under this condition. In this restrained condition, the participants had to sustain the cushion behind their heads and were invited to place their two feet slightly forward. To hold their back firmly against the piece of wood, the participants had to put their feet about 20 cm forward—without pressure on the toes to push them back against the board, their bodies would have fallen forward. Participants adopted varying stance widths in the other three non-restrained conditions without restricting their upright posture. In the restrained-stance and standard-stance conditions (**Figure 1D & E, left**), participants positioned their feet with a standardized stance width of 14 cm and a stance angle of  $17^\circ$  (McIlroy and Maki, 1997). To mark this foot position, two papers were affixed above the platform. In the narrow stance condition (**Figure 1E & F, middle**), participants stood with their feet close together, each foot placed on a separate force platform.

In the wide stance condition (**Figure 1E & F, right**), participants were allowed to choose their stance angle but were required to align one part of the foot with the outer edge of the corresponding platform.

## 2.5 Experimental procedure

The participants participated in eight experimental conditions, with two trials conducted for each condition, which is 16 trials per participant. To maintain consistency, the order of the eight conditions and the sequence of the 16 images were randomized for each participant. However, the two trials per condition were presented consecutively in a blocked fashion to prevent frequent changes in the experimental design. The total number of correct searches was recorded in each trial, serving as a performance measure for each combination of manipulation of visual and postural tasks.

Upon arrival in the experimental room, participants were promptly engaged in reading, filling out, and signing various documents. Following comprehensive instructions for the different tasks, the experimenters attached the Polhemus marker to the participants' heads and calibrated them. Before beginning the recordings, participants completed four brief preliminary tests lasting 1 minute each, allowing them to familiarize themselves with the tasks at hand—two trials for each visual task. Participants were comfortably seated on stools during these pre-trials to prevent fatigue while the investigator ensured their adherence to the instructions. During these pre-trials, the investigator verified that the participants complied with instructions. Subsequently, participants performed the 24 barefoot trials. Gripping the mouse in their preferred hand, they maintained contact with the lateral part of their thigh to facilitate clicking. For added relaxation, participants were encouraged to sit down whenever they felt the need for a break. Participants were thanked for their valuable contribution after the study. Following COVID-19 health guidelines, all equipment was meticulously cleaned with a hydraulic solution, and the experimental room was refreshed for at least two hours.

Participants were instructed to stand comfortably with arms extended along their bodies in all conditions. They were prohibited from making voluntary movements unrelated to the task, such as moving their hands. Specifically, in the restrained condition (refer to **Figure 1A**), participants were required to minimize head rotation and sway. To achieve this, they exerted pressure against a tape roll to stabilize their head against the vertical plank of wood. Failure to apply sufficient pressure would cause the head to fall forward. Additionally, participants were instructed to position their feet slightly ahead of vertical alignment ( $\approx 15$  cm) to prevent activation of leg muscles that could cause them to lean forward. Participants could turn their heads as necessary in the other three non-restrained conditions.

### 2.5.1 Dependent measures

The primary dependent measure we sought to statistically model and explain was the total number of correct targets found  $N_{\text{found}}$ . We confirmed this by visual inspection of videos of the gaze position during each trial. We standardized this measure to control for inevitable variations across the concentric circles. The smallest, medium, and largest circle contained 8, 16, 25 possible targets, so we calculated  $N_{\text{sFound}}$  as  $N_{\text{found}}$ ,  $N_{\text{found}}/2$ , and  $N_{\text{found}}/3.125$  for the smallest, medium, and largest circles. We modeled this performance measure regarding the visual and postural task manipulations and the multifractal nonlinearity of endogenous movement variability. We collected six concurrent measurements to model how bodily fluctuations and exploration moderated the effect of *InvertedTask* and *PosturalCondition*. First, we measured the time intervals between consecutive search responses. We summarized these inter-response intervals with their arithmetic mean  $IRI_{\text{mean}}$ , expecting that this average response latency would indicate mental effort or “processing” load for the decision process in interpreting visual stimuli as in previous literature (Parr et al., 2023). Second, third, and fourth, we measured the 3D position displacement time series of Head, Clavicle (using the neck marker), and Trunk (using the belt marker) at 240 Hz as  $x_{\text{head}}(t)$ ,  $x_{\text{clavicle}}(t)$ , and  $x_{\text{trunk}}(t)$ , respectively. Fifth and sixth, we measured the CoP displacement time series  $x_{\text{CoP}}(t)$  and the 2D gaze displacement time series  $x_{\text{gaze}}(t)$  from the coordinates on the force platform and the viewed projector screen, respectively, at 120 Hz. These measures appeared in subsequent modeling as moderators of the task covariates' higher-order interaction  $PosturalCondition \times Task \times CircleSize$ . Given our stated interests in testing hypotheses about cascade dynamics in bodily exploration through operationalization by multifractal nonlinearity  $t_{\text{MF}}$ , we used Euclidean displacements of consecutive points in the second through sixth series for estimating the multifractal spectrum and the amount of multifractality attributable to nonlinear correlations. The inter-response interval series was too short for multifractal analysis, but as noted below, later modeling drew on  $IRI_{\text{mean}}$  in formally similar ways as it drew on the multifractal nonlinearity estimates for the more continuous bodily measurements that are,  $t_{\text{MF,head}}$ ,  $t_{\text{MF,clavicle}}$ ,  $t_{\text{MF,trunk}}$ ,  $t_{\text{MF,CoP}}$ , and  $t_{\text{MF,gaze}}$ .

### 2.5.2 Signal processing

Dexterous postural control relies on a hierarchy of distinct mechanisms operating across multiple temporal and neural scales. These mechanisms include short-latency reflexes (SLRs), long-latency reflexes (LLRs), and compensatory postural adjustments (CPAs), each playing a unique role in maintaining balance and stability. SLRs, exemplified by the

stretch reflex, provide the fastest response (20–50 ms to sudden perturbations, offering immediate postural stabilization (Chen and Zhou, 2011; Shimba et al., 2010). LLRs emerge between (50–100 ms post-perturbation, bridging the gap between SLRs and CPAs (Colebatch et al., 2016; Nashner, 1976; Schieppati et al., 1990; Woollacott and Nashner, 1982). These intermediate responses involve higher-level processing to fine-tune muscle activity for sustained balance, varying magnitude based on protocol and individual neural characteristics (Nardone et al., 1996; Shemmell et al., 2010). CPAs, occurring after 100 ms, represent the most complex response, involving coordinated muscle activations and joint movements (Kanekar and Aruin, 2014; Santos et al., 2010a,b). While these mechanisms share temporal overlap, they remain distinct in their neural pathways and functions. SLRs and LLRs primarily utilize muscle afferents, specifically relying on the group I input (Duysens et al., 2008). LLRs process this group I afferent activity through both spinal and supraspinal circuits (Bacsi and Colebatch, 2005; Bloem et al., 1995; Kurtzer, 2015; Soteropoulos and Baker, 2020; Taube et al., 2006). In contrast, CPAs integrate a broader range of somatosensory inputs (Mergner and Rosemeier, 1998; Mergner, 2010) and involve higher neural centers including the premotor cortex and basal ganglia (Adkin et al., 2008; Bolton, 2015; Chvatal and Ting, 2013; Jacobs and Horak, 2007; Slobounov et al., 2005; Soto et al., 2006). These mechanisms work synergistically in a cascade-like fashion (Haas et al., 1986), where initial perturbations propagate through the postural system via SLRs and LLRs, while longer-term corrections through CPAs modulate and reshape shorter perturbations (Furmanek et al., 2021; Kelty-Stephen et al., 2021; Mangalam and Kelty-Stephen, 2021a; Mangalam et al., 2021). For data analysis, sampling rate considerations are crucial. High-frequency data collection (1,000 Hz) benefits from low-pass filtering (e.g., 60 Hz) to remove noise while preserving key responses. However, at lower sampling rates (120 Hz), such filtering may distort CoP displacements. Therefore, multifractal analysis of unfiltered data is preferred to preserve these structural components and ensure accurate results.

## 2.6 Estimating cascade-dynamical descriptors

### 2.6.1 Assessing multifractal spectrum width using the direct-estimation of singularity spectrum

Chhabra and Jensen’s (1989) direct method estimates multifractal spectrum width  $\Delta\alpha$  by sampling a time series  $x(t)$  at progressively larger scales using the proportion of signal  $P_i(n)$  falling within the  $v$ th bin of scale  $n$  as

$$P_v(n) = \frac{\sum_{k=(v-1)n+1}^{v \cdot N_n} x(k)}{\sum x(t)}, \quad n \in \{4, 8, 16, \dots\}, \quad n < \frac{T}{8}. \quad (1)$$

As  $n$  increases,  $P_v(n)$  represents a progressively larger proportion of  $x(t)$ ,

$$P_v(n) \propto n^{\alpha_v}, \quad (2)$$

suggesting a growth of the proportion according to one “singularity” strength  $\alpha$  (Mandelbrot and Mandelbrot, 1982).  $P(n)$  exhibits multifractal dynamics when it grows heterogeneously across time scales  $n$  according to multiple singularity strengths, such that

$$P_v(n) \propto n^{\alpha_v}, \quad (3)$$

whereby each  $v$ th bin may show a distinct relationship of  $P(n)$  with  $n$ . This binning in Chhabra and Jensen’s (1989) method is a 1D multifractal elaboration of classical box-counting analyses (Mandelbrot and Mandelbrot, 1982). The width of this singularity spectrum,  $\Delta\alpha = (\alpha_{\max} - \alpha_{\min})$ , indicates the heterogeneity of these relationships (Halsey et al., 1986; Mandelbrot, 2013).

Chhabra and Jensen (1989) method estimates  $P(n)$  for  $N_n$  non-overlapping bins of  $n$ -sizes and transforms them into a “mass”  $\mu(q)$  using a  $q$  parameter emphasizing higher or lower  $P(n)$  for  $q > 1$  and  $q < 1$ , respectively, in the form

$$\mu_v(q, n) = \frac{[P_v(n)]^q}{\sum_{j=1}^{N_n} [P_j(n)]^q}. \quad (4)$$

The multifractal analysis is motivated by the cascade dynamics formalism, which involves a variety of fluctuations across different scales that interact with each other. This suggests that there are interactions between events of different sizes, both large and small. One key aspect of the multifractal analysis is using a  $q$  parameter, which can be adjusted to accentuate events of different sizes to a greater or lesser extent. By gradually adjusting this parameter, multifractal analysis can create a range of size-accentuated series from a single measurement series. This allows for identifying contributions from fluctuations of different sizes and estimating continuous variation in temporal structure across all sizes. For instance, with  $q = 1$ , all-sized fluctuations are treated similarly, whereas with  $q > 1$ , larger fluctuations are characterized, and with  $q < 1$ , smaller fluctuations are characterized.

Then,  $\alpha(q)$  is the singularity for mass  $\mu$ -weighted  $P(n)$  estimated as

$$\begin{aligned}\alpha(q) &= - \lim_{N_n \rightarrow \infty} \frac{1}{\ln N_n} \sum_{v=1}^{N_n} \mu_v(q, n) \ln P_v(n) \\ &= \lim_{n \rightarrow 0} \frac{1}{\ln n} \sum_{v=1}^{N_n} \mu_v(q, n) \ln P_v(n).\end{aligned}\quad (5)$$

Each estimated value of  $\alpha(q)$  belongs to the multifractal spectrum only when the Shannon entropy of  $\mu(q, n)$  scales with  $n$  according to the Hausdorff dimension  $f(q)$  (Chhabra and Jensen, 1989), where

$$\begin{aligned}f(q) &= - \lim_{N_n \rightarrow \infty} \frac{1}{\ln N_n} \sum_{v=1}^{N_n} \mu_v(q, n) \ln \mu_v(q, n) \\ &= \lim_{n \rightarrow 0} \frac{1}{\ln n} \sum_{v=1}^{N_n} \mu_v(q, n) \ln \mu_v(q, n).\end{aligned}\quad (6)$$

For values of  $q$  yielding a strong relationship between Eqs. (5 & 6)—in this study, correlation coefficient  $r > 0.95$ , the parametric curve  $\{\alpha, f(\alpha)\}$  constitutes the multifractal spectrum, and  $\Delta\alpha = \alpha_{\max} - \alpha_{\min}$  constitutes the multifractal spectrum width. This use of  $r$  ensures only estimates of  $\alpha$  and  $f$  compose the multifractal spectrum when representing equally strong scaling relationships. We computed the multifractal-spectrum width  $\Delta\alpha$  for the Euclidean displacement time series of the Head, Clavicle, Trunk, CoP, and Gaze:  $x_{\text{head}}(t)$ ,  $x_{\text{clavicle}}(t)$ ,  $x_{\text{trunk}}(t)$ ,  $x_{\text{CoP}}(t)$ , and  $x_{\text{gaze}}(t)$ .

## 2.6.2 Assessing multifractality due to nonlinearity using surrogate testing

To identify whether a nonzero  $\Delta\alpha$  reflects multifractality due to cascade-like interactivity,  $\Delta\alpha$  for the original time series is compared to  $\Delta\alpha$  for 32 Iterated Amplitude Adjusted Fourier Transform (IAAFT) surrogates (Ihlen, 2012; Schreiber and Schmitz, 1996). IAAFT randomizes original values time-symmetrically around the autoregressive structure, generating surrogate time series that randomize phase ordering of the original series' spectral amplitudes while preserving linear temporal correlations. The one-sample  $t$ -statistic (henceforth,  $t_{\text{MF}}$ ) takes the subtractive difference between  $\Delta\alpha$  for the original series and the 32 surrogates, dividing by the standard error of the spectrum width for the 32 surrogates; the greater the value of  $t_{\text{MF}}$ , the greater the multifractality in the original series due to nonlinear as opposed to linear sources. As noted above, we used multifractal-spectrum width  $\Delta\alpha$  for  $x_{\text{CoP}}(t)$ ,  $x_{\text{head}}(t)$ ,  $x_{\text{clavicle}}(t)$ ,  $x_{\text{trunk}}(t)$ , and  $x_{\text{gaze}}(t)$  from the prior step and computed  $\Delta\alpha$  as well for phase-randomized linear surrogates of these time series. The comparison of  $\Delta\alpha$  for each original series to 32 of its corresponding surrogate time series allowed calculating  $t_{\text{MF,CoP}}$ ,  $t_{\text{MF,head}}$ ,  $t_{\text{MF,clavicle}}$ ,  $t_{\text{MF,trunk}}$ , and  $t_{\text{MF,gaze}}$ .

## 2.7 Statistical analysis

### 2.7.1 Modeling search performance

We used a linear mixed-effect model in R (R Core Team, 2024) using the function `lmer()` from package “lme4” (Bates et al., 2009) observing an alpha level of 0.05 for significant testing using package “lmerTest” (Kuznetsova et al., 2017). We used this procedure to model the dependent measure of the circle-standardized correct number of targets found  $N_{\text{sFound}}$  as a weighted sum of predictors (**Supplementary Dataset S1 & Model S1**). Linear regression modeling estimated a coefficient  $b$  for each predictor, indicating the average change in  $N_{\text{sFound}}$  with a unit increase in the predictor value, and each coefficient had a corresponding *s.e.* term indicating the variability of the change due to the predictor. Modeling proceeded through three major steps. First, it began with six families of interaction, respecting the five estimates of multifractal nonlinearity  $t_{\text{MF}}$  at each of the five measurement locations on the body  $t_{\text{MF,CoP}}$ ,  $t_{\text{MF,head}}$ ,  $t_{\text{MF,clavicle}}$ ,  $t_{\text{MF,trunk}}$ , and  $t_{\text{MF,gaze}}$  as well as one estimate of speed through the average inter-response-interval  $IRI_{\text{mean}}$  defined as the average of the time intervals between each successive mouse click. We fit interactions of each of these predictors with the higher order interaction  $\text{PosturalCondition} \times \text{Task} \times \text{CircleSize}$ . In the second step, we trimmed all higher-order interactions that failed to meet the  $p < 0.05$  benchmark for significance. Third, to acknowledge the fact that multifractal fluctuations at different measurement locations might interact, we included any interactions among  $t_{\text{MF,CoP}}$ ,  $t_{\text{MF,head}}$ ,  $t_{\text{MF,clavicle}}$ ,  $t_{\text{MF,trunk}}$ , and  $t_{\text{MF,gaze}}$  that significantly improved model fit while ensuring that the final model satisfied the convention of requiring a minimum of 10 observations per predictor (Babyak, 2004; Troutt, 2004).

This model selection strategy aimed to capture the predictive impact of multifractal spectrum width on cognitive performance in a visual search task, specifically due to nonlinear temporal correlations, after accounting for all the

traditional, non-multifractal features of the tasks. We were particularly interested in how multifractal nonlinearity, at different points in the multi-jointed postural system, might influence the effect of task constraints on cognitive performance in a visual search task.

This model selection strategy prioritizes multifractal nonlinearity over incorporating more straightforward and familiar measures of variability within the same model. By exploring its interactions across a comprehensive marker set, the approach provides a nuanced perspective on how multifractal effects propagate across different body parts and depend on postural width, task complexity, and specific spatial subsets of the search area while also remaining constrained by the 10-observation-per-predictor limit, leaving little room for additional interactions with conventional variability measures. Previous research with fewer task parameters has included fluctuation series' mean and standard deviation (*s.d.*) alongside fractal and multifractal metrics within the same models (Kelty-Stephen and Dixon, 2014; Stephen et al., 2010; Stephen and Hajnal, 2011). For example, a single model could include  $mean * Trial$  and  $t_{MF} * Trial$ , allowing the regression model to assess the relative strength of these terms. However, our emphasis on capturing the rich interactions of multifractal nonlinearity across the extensive task parameters precluded the simultaneous inclusion of more familiar measures of variability in this modeling approach. However, we ran alternate models demonstrating that regression modeling performed more effectively using multifractal variability metrics than traditional variability measures such as *s.d.*. Specifically, we modified our final model to create three alternative versions, each replacing  $t_{MF}$  with a different metric. One model substituted Mean for  $t_{MF}$  in both its main effect and all comparable interactions, another replaced  $t_{MF,CoP}$  with *s.d.* in the same manner, and the third replaced  $t_{MF,CoP}$  with  $\Delta\alpha$ . The AIC and BIC values for the *mean* and *s.d.* models were both higher than those for the multifractal-nonlinearity model, indicating weaker model fits: the Mean model had AIC and BIC values 17.147 and 17.147 points higher, respectively, while the *s.d.* model had values 13.450 and 13.450 points higher, supporting the superior fit of the multifractal-nonlinearity model (Burnham and Anderson, 2004).

The raw multifractal model using  $\Delta\alpha$  was comparably stronger than the models dedicated to more traditional measures of variability, and it had only negligible differences from the multifractal-nonlinearity model. It did have lower AIC and BIC than the multifractal-nonlinearity model using  $t_{MF}$  and not  $\Delta\alpha$ , that is, a marginal difference of 5.152 and 5.152, respectively. This difference suggests minuscule improvements in the fit of the raw-multifractal model, but we do not report this model for theoretical and empirical reasons. First, the present work aims to speak specifically to the nonlinear interactivity across scales of activity in the perceptual system. So, we prefer to address our modeling and remarks specifically on the nonlinear components of the multifractal results. Besides that primary goal, the interpretability of raw multifractal spectrum width is classically rife with confusion and ambiguity because, although multifractal geometry was designed to explain nonlinear dynamical processes, empirical estimates of multifractal spectrum width are sensitive to linear features of measurements contributing to those estimates (Veneziano et al., 1995). In a sense, although it does not include any  $\Delta\alpha$  terms, our multifractal-nonlinearity model does already control for the linear features because the multifractal-nonlinearity metric we use  $t_{MF}$  expresses significant difference from spectrum widths for a set of linear surrogates. Our second reason for neglecting to pursue the raw-multifractal model is that, besides its theoretical opacity about nonlinearity, a difference in AIC or BIC less than 6 is insufficient to reject one model for another (Richards, 2005, 2008). So, though the differences greater than 10 between models with multifractal metrics and non-multifractal metrics is a compelling reason to prefer the multifractal treatments, the empirical differences in AIC and BIC are not sufficient to outweigh the theoretical reasons for focusing our attention on the multifractal-nonlinearity model.

## 2.7.2 Manipulation check on root-mean-square of gaze fixations

We used a linear mixed-effect model in R (R Core Team, 2024) using the function `lmer()` from package “lme4” (Bates et al., 2009) observing an alpha level of 0.05 for significant testing using package “lmerTest” (Kuznetsova et al., 2017). We calculated the root-mean-square (*rms*) of gaze fixations to quantify the spatial variability in eye movements during the task (**Supplementary Dataset S2 & Model S2**). Specifically, we first computed the mean gaze position across all fixations and then subtracted this average from each individual fixation. Next, we squared these mean-centered deviations for the horizontal (*x*) and vertical (*y*) display coordinates and took the square root of their averaged sum. To analyze how experimental conditions influenced gaze variability, we modeled the *rms* of gaze fixations using a full-factorial linear mixed-effects model. The model included the higher-order interaction  $InvertedTask \times PosturalCondition \times Trial$  along with all lower-order interactions and main effects.

## 2.7.3 For testing for any differences in multifractal nonlinearity for Non-Hypothesis 1

We used a linear mixed-effect model in R (R Core Team, 2024) using the function `lmer()` from package “lme4” (Bates et al., 2009) observing an alpha level of 0.05 for significant testing using package “lmerTest” (Kuznetsova et al., 2017). Rather than apply this model to separate locations, we created a categorical *Location* variable whose baseline value was *CoP* and other values included *Head*, *Clavicle*, and *Trunk* (**Supplementary Dataset S3 &**

**Table 1: Significant effects from the linear mixed-effects model<sup>1</sup> examining the influence of multifractal nonlinearity, postural and task constraints, and their interactions on the circle-standardized correct number of targets found in the visual word search,  $N_{\text{sFound}}$ .**

Factor	$b \pm s.e.$	$t$	$p^2$
<i>Intercept</i>	$1.505 \times 10^1 \pm 1.313 \times 10^0$	11.465	$< 2.000 \times 10^{-16}$
<i>InvertedTask</i> <sub>TC2</sub>	$-8.538 \times 10^0 \pm 1.228 \times 10^0$	-6.953	<b><math>6.360 \times 10^{-12}</math></b>
<i>IRI</i> <sub>mean</sub>	$-2.564 \times 10^0 \pm 2.612 \times 10^{-1}$	-9.813	$< 2.000 \times 10^{-16}$
<i>CircleSize</i> <sub>small</sub> : <i>IRI</i> <sub>mean</sub>	$-8.381 \times 10^{-1} \pm 3.687 \times 10^{-1}$	-2.273	<b>0.023</b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>IRI</i> <sub>mean</sub>	$1.910 \times 10^0 \pm 2.637 \times 10^{-1}$	7.242	<b><math>8.960 \times 10^{-13}</math></b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>CircleSize</i> <sub>small</sub>	$-4.784 \times 10^0 \pm 1.416 \times 10^0$	-3.378	<b>0.001</b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>CircleSize</i> <sub>small</sub> : <i>IRI</i> <sub>mean</sub>	$1.012 \times 10^0 \pm 3.719 \times 10^{-1}$	2.722	<b>0.007</b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>PosturalCondition</i> <sub>PCond2</sub>	$3.738 \times 10^0 \pm 1.481 \times 10^0$	2.524	<b>0.012</b>
<i>CircleSize</i> <sub>small</sub> : <i>t</i> <sub>MF,CoP</sub>	$-3.036 \times 10^{-2} \pm 1.544 \times 10^{-2}$	-1.967	<b>0.049</b>
<i>PosturalCondition</i> <sub>PCond3</sub> : <i>CircleSize</i> <sub>small</sub> : <i>t</i> <sub>MF,CoP</sub>	$-7.530 \times 10^{-2} \pm 3.003 \times 10^{-2}$	-2.507	<b>0.012</b>
<i>PosturalCondition</i> <sub>PCond2</sub> : <i>CircleSize</i> <sub>small</sub> : <i>t</i> <sub>MF,head</sub> : <i>t</i> <sub>MF,clavicle</sub>	$9.235 \times 10^{-3} \pm 3.849 \times 10^{-3}$	2.423	<b>0.016</b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>t</i> <sub>MF,CoP</sub>	$3.145 \times 10^{-2} \pm 1.019 \times 10^{-2}$	3.086	<b>0.002</b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>t</i> <sub>MF,clavicle</sub>	$-6.696 \times 10^{-2} \pm 3.313 \times 10^{-2}$	-2.021	<b>0.044</b>
<i>InvertedTask</i> <sub>TC2</sub> : <i>PosturalCondition</i> <sub>PCond2</sub>	$1.935 \times 10^{-1} \pm 6.769 \times 10^{-2}$	2.858	<b>0.004</b>
<i>CircleSize</i> <sub>small</sub> : <i>t</i> <sub>MF,head</sub>			

<sup>1</sup>  $N_{\text{sFound}} \sim t_{\text{MF,head}} * \text{PosturalCondition} * \text{InvertedTask} * \text{CircleSize} + (t_{\text{MF,head}} * t_{\text{MF,clavicle}}) * (\text{InvertedTask} + \text{CircleSize} + \text{PosturalCondition} * \text{CircleSize}) + t_{\text{MF,CoP}} * (\text{PosturalCondition} * \text{CircleSize} + \text{InvertedTask} + \text{PosturalCondition} + \text{CircleSize}) + (\text{PosturalCondition} * \text{InvertedTask} + \text{CircleSize}) + t_{\text{MF,clavicle}} * (\text{PosturalCondition}) + \text{InvertedTask} * \text{CircleSize} * \text{IRI}_{\text{mean}} + \text{PosturalCondition} * \text{InvertedTask} * \text{CircleSize} + (1|\text{ParticipantCircleSize})$ .

<sup>2</sup> Boldfaced values indicate statistical significance at  $p < 0.05$ .

**Model S3).** We modeled the resulting outcome measure using a full-factorial model of the higher-order interaction  $\text{Location} \times \text{InvertedTask} \times \text{PosturalCondition}$  and all component lower-order and main effect terms. Including *Trial* as part of this interaction did not improve model performance and, in fact, altered the apparent significance of a previously significant term in the three-way interaction, leading us to exclude this term. Consequently, we report results based on the simplified full-factorial model, which better captures the primary effects of interest while avoiding unnecessary complexity.

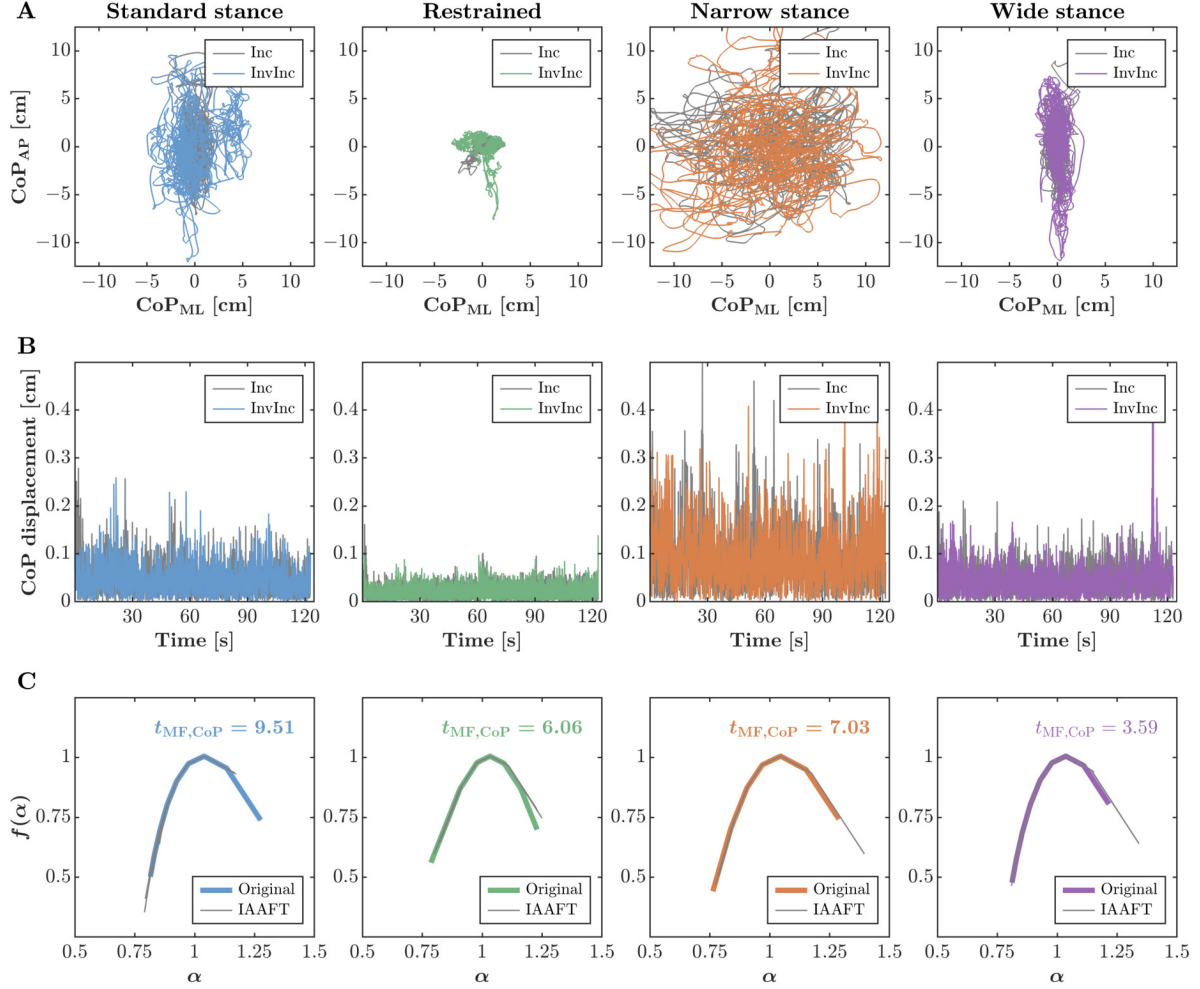
### 3 Results

**Figure 3** illustrates an example of participant's CoP trajectories, CoP Euclidean displacement time series, and multifractal properties in different posture stances and for inverted vs. non-inverted settings of the task.

**Table 1** reports the significant effects of our regression model of search performance. The nonsignificant effects appear in **Supplementary Material**. Below, we first examine the effects of the experimental constraints independent of multifractal nonlinearity. We then focus on the significant effects of multifractal nonlinearity and explore their interactions with the experimental constraints.

#### 3.1 Greater difficulty and longer search times for inverted-incongruent targets

First, the standardized number of targets found ( $N_{\text{sFound}}$ ) was significantly lower in the more difficult inverted-incongruent task variant ( $b = -8.538 \times 10^0 \pm 1.228 \times 10^0, t = -6.953, p < 2.000 \times 10^{-16}$ ).  $N_{\text{sFound}}$  was also significantly lower for participants who, on average, exhibited longer intervals between mouse clicks ( $b = -2.564 \times 10^0 \pm 2.612 \times 10^{-1}, t = -9.813, p < 2.000 \times 10^{-16}$ ). This result reflects the expected relationship between faster search



**Figure 3: Center of posture (CoP) dynamics under different stance conditions (Standard, Restrained, Narrow, and Wide) for the two search task conditions (Incongruent and Inverted incongruent) for a single participant. (A)** CoP trajectories for each stance condition along the anteroposterior (AP) vs. mediolateral (ML) axes. The movement patterns vary across conditions, with the constrained stance showing the least variability, the narrow stance exhibiting the most dispersed trajectories, and the wide stance having a trajectory extended along the AP axis. **(B)** Time series of CoP displacement, highlighting differences in postural fluctuations between the two task conditions. The constrained stance exhibits minimal displacement, whereas the narrow stance shows pronounced fluctuations, and the wide stance shows intermediate fluctuations. **(C)** Multifractal spectral analysis of CoP displacement time series for each stance condition. The multifractal width ( $t_{MF}$ ) quantifies nonlinear variability in postural control, with distinct differences observed across conditions. Positive  $t_{MF}$  values indicate stronger multifractal signatures, while negative values suggest weaker multifractality. The IAAFT surrogates serve as a control to assess whether multifractal properties arise from temporal structure rather than random variability. These plots highlight how stance width and postural constraints influence postural dynamics, revealing differences in postural control strategies across conditions.

speed and better performance, providing convergent validity. However, this effect of speed was significantly weaker in the more challenging inverted-incongruent task variant ( $b = 1.910 \times 10^0 \pm 2.637 \times 10^{-1}$ ,  $t = 7.242$ ,  $p = 8.960 \times 10^{-13}$ ), where slower, more deliberate searching increased the likelihood of success due to the task's greater difficulty.

### 3.2 Heightened difficulty in searching for inverted-incongruent targets in the smallest circle, mitigated by narrow stance, and nullified associations with click speed

Participants' ability to find targets was influenced by the centrality of their location, specifically when targets were positioned in the smallest, innermost of the three concentric circles. The difficulty of finding inverted-incongruent targets



was particularly pronounced in this smallest central circle ( $b = -4.784 \times 10^0 \pm 1.416 \times 10^0, t = -3.378, p = 0.001$ ), but this difficulty was reduced in the narrow postural condition ( $b = 3.738 \times 10^0 \pm 1.481 \times 10^0, t = 2.524, p = 0.012$ ). The negative correlation between latency between clicks and successful searches was strongest in the smallest circle ( $b = -8.381 \times 10^{-1} \pm 3.687 \times 10^{-1}, t = -2.273, p = 0.023$ ), but this effect was canceled out when searching for inverted-incongruent targets ( $b = 1.012 \times 10^0 \pm 3.719 \times 10^{-1}, t = 2.722, p = 0.007$ ).

### 3.3 Multifractal nonlinearities in the postural system drive search performance variations across task settings

#### 3.3.1 Hypothesis 1: Search in comfortable stance improved with reductions of CoP multifractal nonlinearity

On average, more effective focus and task completion appeared to co-occur with reductions in multifractal nonlinearity. However, the cognitive task and postural constraints changed which part of the postural system showed the strongest relationship between reduced multifractal nonlinearity and better search performance. A reduction in multifractal nonlinearity in the projection of postural sway on the ground surface,  $t_{MF,CoP}$ , co-occurred with an increase in the number of incongruent targets found ( $b = -3.036 \times 10^{-2} \pm 1.544 \times 10^{-2}, t = -1.967, p = 0.049$ ).

#### 3.3.2 Hypothesis 2: Search in narrow stance improved with reductions of CoP multifractal nonlinearity, particularly for search in the smallest circle

The narrower stance altered the relationship between multifractal nonlinearity and search performance. These interaction effects between stance width and multifractal nonlinearity were significant for the smallest circle. For example, the search for incongruent targets in the small circle was significantly improved with reduced CoP multifractal nonlinearity for the narrow stance ( $b = -7.530 \times 10^{-2} \pm 3.003 \times 10^{-2}, t = -2.507, p = 0.012$ ).

#### 3.3.3 Hypothesis 3: Search with stance restrained against a vertical surface improved with compensatory increase in upper-body multifractal nonlinearity

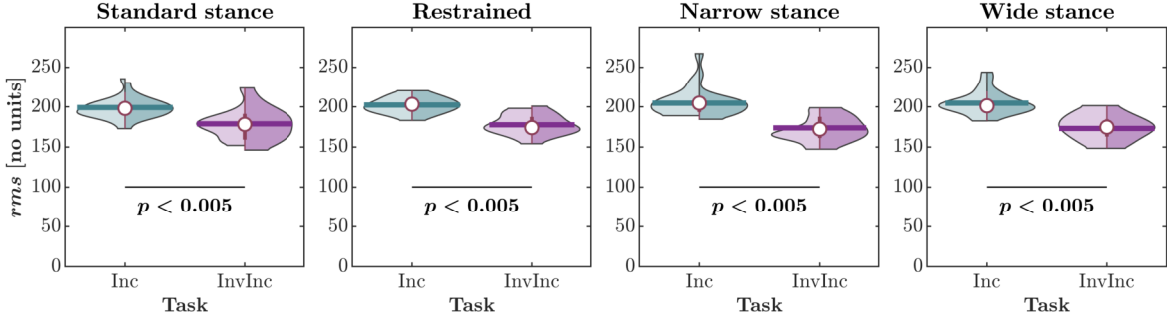
As noted before, a restraining posture against a vertical surface raises positions with significant effects of multifractal nonlinearity in the upper body. It reversed the relationship between nonlinearity and search performance from negative to positive: restraining stance against the vertical surface led to stronger search performance in the small circle with increases in multifractal nonlinearity at the head,  $t_{MF,head}$ , and clavicle together predicted more targets found ( $b = 9.235 \times 10^{-3} \pm 3.849 \times 10^{-3}, t = 2.423, p = 0.016$ ).

#### 3.3.4 Hypothesis 4: Inverted-incongruent search improved with reductions of upper-body multifractal nonlinearity

This negative relationship between CoP multifractal nonlinearity and search performance disappeared in the inverted-incongruent task setting ( $b = 3.145 \times 10^{-2} \pm 1.019 \times 10^{-2}, t = 3.086, p = 0.002$ ). Instead, as predicted in Hypothesis 4a, better inverted-incongruent search performance co-occurred with reduced multifractal nonlinearity at the clavicle,  $t_{MF,clavicle}$  ( $b = -6.696 \times 10^{-2} \pm 3.313 \times 10^{-2}, t = 2.021, p = .044$ ). As predicted by Hypothesis 4b, after we removed four trials in which participants looked off the display and generated *rms* values more than 3 standard deviations from the mean *rms*, our linear mixed-effect model of *rms* returned only a significant effect of *InvertedTask*. This effect was negative, confirming that the inverted-incongruent task did elicit gaze that returned more often to the center to consult the priming word ( $b = -20.228 \times 10^0 \pm 8.933 \times 10^0, t = 2.264, p = 0.024$ ); **Figure 4**). We found no significant effects of *PosturalCondition* or *Trial* or any interaction among these factors. Compounding the inverted task setting with postural restraint against a vertical surface accentuated these effects: the inverted-incongruent task with a restrained posture further strengthened the positive relationships between upper-body multifractal nonlinearity and search performance. Specifically, as predicted by Hypothesis 4c, restraining stance against the vertical surface led to stronger inverted-incongruent search performance in the small circle with increases in multifractal nonlinearity at the head,  $t_{MF,head}$  alone ( $b = 1.935 \times 10^0 \pm 6.769 \times 10^{-1}, t = 2.858, p = 0.004$ ).

#### 3.3.5 Non-hypothesis 1: Multifractal nonlinearity was often negative, higher for CoP, increased with the wide stance, and increased only in the upper body in the restrained condition

**Figure 5** presents what initially seems an alarming profile of the  $t_{MF}$  values: often negative. The linear mixed-effect model on  $t_{MF}$  values indicated a significant positive effect of the wide stance, suggesting that widening the stance allows for the release of degrees of freedom while completing search tasks ( $b = 2.971 \times 10^0 \pm 1.412 \times 10^0, t = 2.104, p = 0.036$ ). We also observed significant negative effects on all postural positions except for CoP, indicating that CoP exhibits significantly greater multifractal nonlinearity compared to the head ( $b = -24.804 \times 10^0 \pm 1.412 \times 10^0, t = -17.571, p < 2 \times 10^{-16}$ ), clavicle ( $b = -23.335 \times 10^0 \pm 1.412 \times 10^0, t = -16.530, p < 2 \times 10^{-16}$ ), and trunk



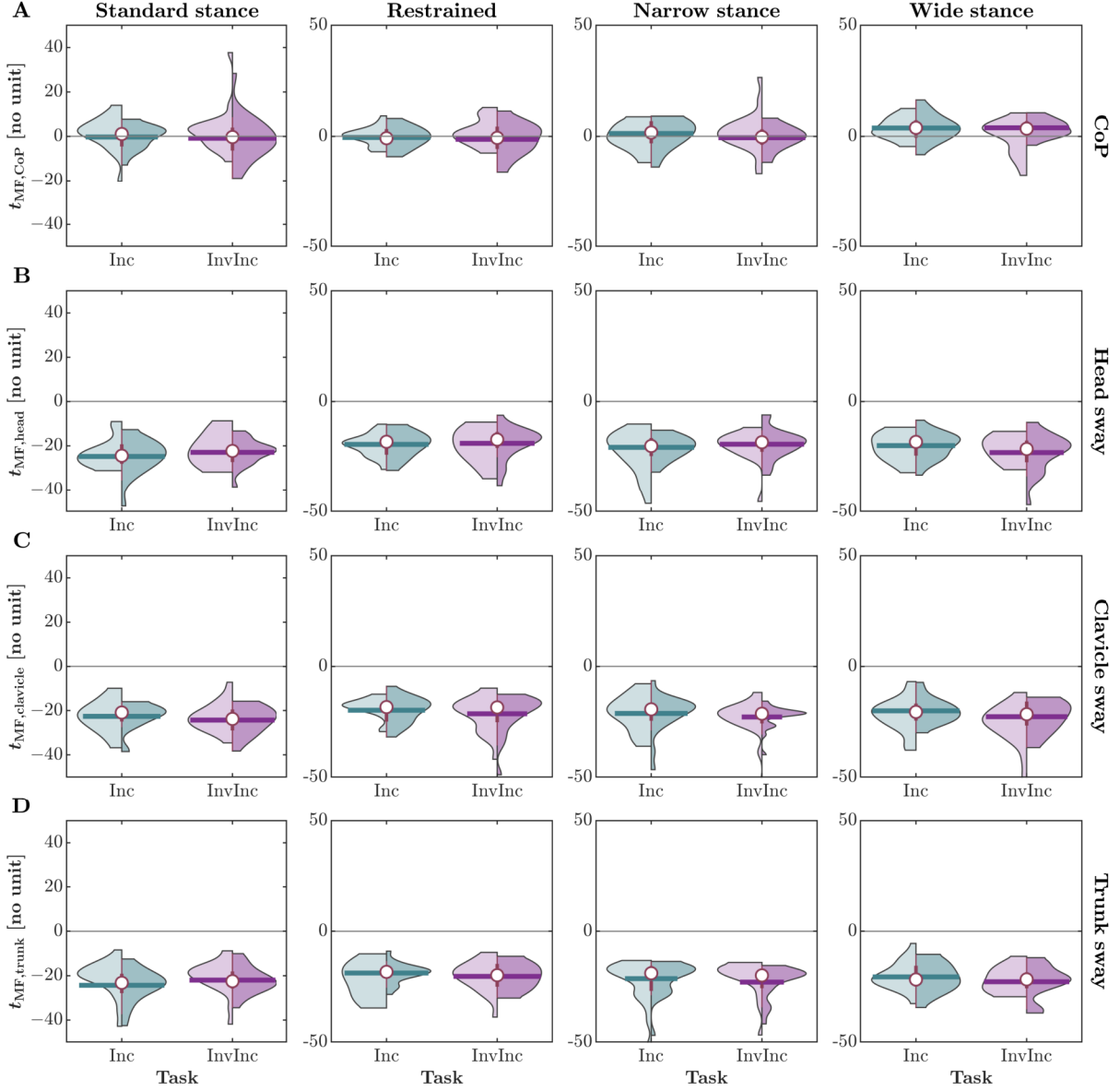
**Figure 4: Violin plots showing the root-mean-square (*rms*) values under different stance conditions (Standard, Restrained, Narrow, and Wide) for the two search task conditions (Incongruent and Inverted incongruent). Each plot displays the distribution of *rms* values, with white markers indicating the median and interquartile range. Each violin’s left and right half depict data distributions for the first and second trials. Horizontal bars indicate *mean*, and white circles indicate *median* ( $n = 22$  participants).**

( $b = -23.300 \times 10^0 \pm 1.412 \times 10^0, t = -16.505, p < 2 \times 10^{-16}$ ) during the search task. Lastly, restraining posture against a vertical surface appears to elicit a compensatory increase in multifractal nonlinearity at the head ( $b = 5.496 \times 10^0 \pm 1.996 \times 10^0, t = 2.753, p = 0.006$ ) and at the clavicle ( $b = 4.509 \times 10^0 \pm 1.996 \times 10^0, t = 2.258, p = 0.024$ ).

## 4 Discussion

We tested four hypotheses in a task that human participants completed by visually searching for Stroop-like color words printed in an incongruent color among concentric circles while standing upright (see **Figure 1**). **Figure 3** depicts the diversity of postural outcomes during different stances: standard stance, restrained, narrow stance, and wide stance. The multifractal signatures of CoP showed general support for the idea that The hypotheses addressed the possibility that successful visual word search might be sensitive to how the manipulated postural and task constraints interacted with the endogenous signatures of tensegrity-like multifractal nonlinearity in the upright posture. The first hypothesis was that search performance with a comfortable stance would improve with reductions in CoP multifractal nonlinearity, signifying a constraint of degrees of freedom to focus attention. The second hypothesis was that search performance might improve with a further reduction in CoP multifractal nonlinearity, particularly with a narrow stance (Hypothesis 2a), for targets in the smallest circle (Hypothesis 2b), and for the interaction of the narrow stance with the smallest-circle targets (Hypothesis 2c). The third and fourth hypotheses addressed how experimental postural and task constraints could highlight the association of multifractal nonlinearity with single-word recognition at relatively upper-body points in the postural system. The third hypothesis was that search performance would improve in narrower circles when upper-body multifractal nonlinearity increased to compensate for the surface-restrained stance. The fourth hypothesis was that search performance for the inversion of the priming Stroop-type incongruence would improve with reduced multifractal nonlinearity (e.g., as in Hypothesis 1) farther up in the postural system than at the CoP (Hypothesis 4a). A manipulation check confirmed that, yes, the inverted-incongruent search involved constraint of the point of eye gaze towards the center, promoting less *rms* (Hypothesis 4b). However, we predicted that a surface-restrained stance would show the same improvement in inverted-incongruent search with compensatory increases in upper-body multifractal nonlinearity as in non-inverted search (Hypothesis 4c). Results supported all of the hypotheses except for Hypotheses 2a and 2b (see **Table 1**).

As for Non-Hypothesis 1, the results indicate that multifractal nonlinearity was predominantly negative and varied by segment within the postural system, demonstrating sensitivity to postural conditions but not to search conditions. As noted in the results, this pattern may initially seem alarming due to the negative differences between the original spectrum width and that of phase-randomized surrogates. However, we welcome the opportunity to present these details transparently for further scrutiny and discussion. This outcome aligns with cascade dynamics, where linear properties may actually inflate the multifractal spectrum width—an observation supported by numerous empirical and theoretical studies (Bell et al., 2019; Carver and Kelty-Stephen, 2017; Ihlen and Vereijken, 2010; Kelty-Stephen, 2018; Kelty-Stephen et al., 2021; Kelty-Stephen and Mangalam, 2024; Lee and Kelty-Stephen, 2017; Jacobson et al., 2021; Mangalam and Kelty-Stephen, 2024). We recognize the common intuition that nonlinearity should always manifest as greater multifractality than that of surrogates. However, the more fundamental principle in surrogate testing for



**Figure 5: Violin plots showing the multifractal nonlinearity ( $t_{MF}$ ) values for CoP and head, clavicle, and trunk sway under different stance conditions (Standard, Restrained, Narrow, and Wide) for the two search task conditions (Incongruent and Inverted incongruent). Each plot displays the distribution of  $rms$  values, with white markers indicating the median and interquartile range. Each violin’s left and right half depict data distributions for the first and second trials. Horizontal bars indicate *mean*, and white circles indicate *median* ( $n = 22$  participants).**

nonlinearity is that linearity entails sequential symmetry across time or space. The purpose of testing for nonlinearity is to identify asymmetric processes that extend beyond a frozen sum of temporally and spatially invariant components (Theiler et al., 1992). Asymmetry can signal either the growth or decay of measured variability and thus, a departure from symmetry does not inherently imply a single-directional outcome. The interpretation of negative  $t_{MF}$  is precisely as suggested above: the nonlinearity of the tensegrity system supporting upright stance draws its degrees of freedom inward, constraining them in a way that optimally meets the task demands. The observed negative excess relative to surrogates suggests that an equivalent time-symmetric fluctuation within the postural system would be less stable and more variable, indicating a looser grip on the available degrees of freedom. Nonlinear correlations can both amplify and constrain variability, and this duality is critical for understanding how multifractal tensegrity relates to classical

movement coordination principles. If nonlinearity only amplified variability, there would be no meaningful analog between multifractal tensegrity and Bernstein's (1996) foundational framework on movement coordination as a problem of degrees of freedom. And let us be clear: Turvey sought to preserve this analogy (Profeta and Turvey, 2018; Turvey, 2007; Turvey and Fonseca, 2009, 2014).

Looking beyond the potentially jarring negative values in these estimates of multifractal nonlinearity, we can observe systematic changes that reflect postural nuance. More specifically, multifractal nonlinearity became more negative at the upper body segments than the CoP, suggesting that the postural system allows the greatest release of degrees of freedom at its contact with the ground while restricting this release at segments higher up in the body. The restraint of posture against a vertical surface appears to induce a compensatory release of degrees of freedom in the upper body, particularly at the head and clavicle, where multifractal nonlinearity increases. Notably, these effects emerge only during a search task, reinforcing that postural adaptation is task-dependent. Even though no differences were found across specific types of search tasks, limiting generalizations to the broader context of visual word search in an upright stance remains crucial.

Another important concern is whether fractal and multifractal measures should be treated as dependent variables expected to show group-mean differences. The significant effects observed in the LMEs for Non-Hypothesis 1 (reported in the Results section) are not necessarily evident in the means, except for the difference between CoP and other segments (**Figure 5**). This highlights a fundamental issue in interpreting fractal and multifractal results as outcome measures. First, relying on average differences can be misleading—not just in this context, but in all forms of measurement (Molenaar, 2008; Van Orden et al., 2003). This concern is even more pressing when we introduce novel descriptors and attempt to understand them strictly through their group means, as doing so risks oversimplifying the inherently complex, dynamic nature of these measures. While we aim to gain insight into the endogenous variation in the body's fractal and multifractal structure, we also want to caution against the common tendency to design seemingly straightforward experimental manipulations and assume that the resulting fractal or multifractal dynamics will neatly average and disperse in predictable ways. Our findings illustrate this complexity: although we detected a difference in multifractal nonlinearity between comfortable and wide stances, we found no interaction effects between wide stance and multifractal nonlinearity in predicting accurate search performance. Conversely, while there was no difference in multifractal nonlinearity between comfortable and narrow stances, narrow stances did exhibit multiple interactions with multifractal nonlinearity. These results suggest that the relationship between postural constraints and multifractal organization is not simply a matter of mean differences but rather an intricate interplay between system-wide coordination patterns and contextual demands.

#### 4.1 Steps toward a tensegrity-based view of single-word reading

We can summarize our findings as follows. Visual-word recognition may rely on the same postural-sway dynamics that support visual perception more broadly (Riccio and Stoffregen, 1991; Balasubramaniam et al., 2000). Postural control involves both the release and the constraint of postural degrees of freedom. Focusing visual attention on a display full of words requires drawing inward degrees of freedom that stabilize the stance and maintain visual contact with a display of potential targets. We propose that the bodywide multifractal tensegrity hypothesis (Turvey et al., 2014)—suggesting that multifractality arises from nonlinear interactions—may provide a useful lens for examining the release of degrees of freedom. The constraint of degrees of freedom necessary to maintain a stable stance or focus appears to co-occur with a reduction in multifractal nonlinearity. This relationship was previously observed in postural control during upright standing (Kelty-Stephen, 2018; Kelty-Stephen et al., 2021), and now it appears to hold for stance during visual word search. The constraints on posture and the distance of the target word from the centrally located prime can accentuate this relationship. Neither constraint alone necessarily ensures the successful search for a single word, as effective recognition relies on a broader system of interactions. The organism-wide focus on single-word recognition depends on multifractal tensegrity to coordinate nonlinear interactions, with experimental manipulations that constrain both mechanical and visual aspects further highlighting the link between accurate search performance and reduced multifractal nonlinearity.

The relationship between visual word recognition and posture appears to hinge on a locus of multifractal nonlinearity that can migrate and change its directionality. Exogenously applied restraints on the exploratory sway that posture affords required a compensatory release of degrees of freedom to support the search for the single-word target. When applied to the torso, the postural system generates this release through its upper segments, which are more free to move. Under these conditions, an increase of multifractal nonlinearity at the head and the clavicle signifies a release of degrees of freedom that made the search more successful—if only in a narrow span of the visual display, befitting the narrow range of these upper postural segments. Thus, the negative relationship between multifractality and search performance during free-standing without exogenous restraint yields a positive relationship. On the other hand, this multifractal locus's upward migration can also follow from search tasks, prompting more switches in focus between

prime and potential targets. The inversion task thus showed that task complexity can preserve the negative relationship between multifractal nonlinearity while moving the locus of reduced multifractal nonlinearity upwards, away from CoP, towards the clavicle. What is more, these two ways of drawing the multifractal locus of a posture-search relationship can coexist: restraining torso movement can prompt a more successful search in a narrow span of the visual display with the growth of multifractal nonlinearity at the head. Both task demands and physical limitations jointly determine the adaptive reorganization of degrees of freedom in word recognition.

## 4.2 Limitations and future directions: Seeking an explanation of perception-action first and multifractality as a distant second

Important limitations on the present work can highlight the future directions that this work might inform. First, single-word recognition is a scant tip of the iceberg, and searching for an individual word is a narrow subdomain of how we use words—all the more narrow for only addressing color words. Future work should press the application of the multifractal tensegrity hypothesis in reading behaviors more broadly, for example, to narrative text as well as to word-recognition situations in the built world that we all navigate through. Additionally, expanding the scope of inquiry to include linguistic contexts that involve ambiguity, metaphor, and syntactic complexity could provide deeper insights into the interaction between cognitive dynamics and reading behavior. It would be worth revisiting the classical lexical-decision paradigms from the other side of the ecological/cognitive divide. Deploying even non-ecological tasks is not a typical penchant of ecological psychologists, but it would only strengthen the ecological, psychological program if we could deflate the representationalist account of its most cherished psycholinguistic paradigms. Beyond any fears of a pitched battle across this divide, traditional information-processing perspectives on single-word reading are hungry for formalisms that might explain and predict some of the slipperiness in language use (e.g., Magnuson, 2007). Non-ecological psychologists are realizing the nonlinearities and impredicativities in their psycholinguistic work, addressing the multifunctionalities of individual components and processes in often the same terms (e.g., “pleiotropy” and “nondeterminism”) that Turvey and colleagues invoked when showcasing the difficulty of simple mappings between components and functions (Johnston and Turvey, 1980; Kugler and Turvey, 2015; Turvey et al., 1982). Second, an upright stance is a limiting case, even with the experimental application of constraints to catch the postural system in circumstances that might not occur very often in everyday life. We should hope to develop multifractal-tensegrity models of reading in more diverse postures (e.g., seated and walking) to encompass the greater range of enabling constraints from movement. Third, this research warrants a natural and necessary extension to dyadic and group communication, using either speech or written symbols to collaboratively solve problems together in some of the exciting and innovative paradigms developed by some of Turvey’s most linguistically inclined students (Galantucci, 2005; Shockley et al., 2003).

As a brief postscript on the interest in multifractal nonlinearity as a dependent variable, we acknowledge the value of designing tasks and manipulating bodily states to elicit distinct endogenous multifractal profiles. The long-term goal is to fulfill early empirical promises that multifractal stimulation might prove beneficial under certain circumstances and for specific tasks. However, the precise direction of its effects, the necessary amount of multifractality, and any assumed equivalence between exogenously applied and endogenously generated multifractal fluctuations remain beyond the understanding required for definitive recommendations. Researchers must carefully examine the complex interactions between task demands and postural conditions to understand what constitutes functional endogenous multifractality and how exogenous multifractality might contribute (Kelty-Stephen et al., 2023a). Ultimately, greater caution is needed when considering how task and posture may—or may not—affect multifractal fluctuations across body segments. The question of whether onboard multifractal fluctuations might moderate the effects of task and posture on cognitive, perceptual, or motor outcomes is important and different from testing whether multifractality will differ. We think multifractality is also much more interesting as a means to operationalize what it means for a tensegrity architecture to exploit nonlinear interactions across scales.

Turvey was always a discerning consumer of science, quick to signal his curiosity and recognize new findings as “not uninteresting,” and his ability to appreciate complexity without rushing to oversimplified conclusions is a model for how we approach the role of multifractality in perception and action. In the present case, and in much of the prior empirical work from the multifractally oriented coauthors of this paper, our primary interests lie in psychological experience and perception-action coordination, not multifractality. We are interested in explaining the same facts and abilities that occupy the curiosities of non-ecological psychologists. We are ecological psychologists not in the choices of what to study but rather in the aim for a more lawful, generic, and less unique explanation than information-processing neuroscientific approaches. We are psychologists first and only ever aspiring to command mathematics and physics as distant seconds or thirds. For us, multifractality remains a quintessentially non-psychological factor whose potential role in shaping psychological experience and perception-action coordination is, in the spirit of Turvey, undeniably “not uninteresting.” However, we largely view multifractality as an entailment and operationalization of our theoretical framework rather than the object of explanation itself. It is not that we are always uninterested in

understanding multifractality as an outcome: our work has advanced a broader understanding of cascade formalisms in the abstract, clarifying how fundamental parameters might align with multifractal outcomes (Kelty-Stephen and Mangalam, 2022, 2023, 2024; Mangalam and Kelty-Stephen, 2021b, 2022; Mangalam et al., 2023b,a,c, 2024; Mangalam and Kelty-Stephen, 2024). However, that work is only a preamble to adapting these insights from binomial cascades to a network-based model of observables that can approximate the complexity of the human movement system (Stephen et al., 2012; Carver et al., 2017; Mangalam et al., 2020).

For now, to be clear, our focus in this study has been on explaining visual word recognition, not on explaining multifractality itself. As much time as it took Turvey to articulate his interest in multifractal variation, we are equally cautious of conflating our purpose with an attempt to explain multifractality as such. Those writing and reading this paper may care about multifractality only insofar as it represents a fluid-dynamical mechanism that could, as Turvey suspected, play a role in the lawful explanation of perception-action capabilities in the pursuit of task goals.

### 4.3 Connecting the clues from Turvey and potentially lighting a path forward for ecological psychology

At a certain point, we feel that we are telling the story without the main character being able to play his role. Director Blake Edwards once found himself saddled with the task from his production studio of having to make another *Pink Panther* movie. The star had passed away, and the task was to make a whole motion picture without the leading role appearing. “B roll” and cutting-room scraps had to float a flat retrospective story. We ourselves feel the peril of saying more lest we repurpose scrap in our notebooks to fill out a hollow script or speak past the original intent. Turvey’s famous collaborator Peter Kugler used to say, “Creativity is looking for what does not exist and finding it.” We aspire to honor this ethos while acknowledging that our efforts are not intended as a critique of Turvey. Perhaps he never sought for this particular line of inquiry to emerge. Yet, we find ourselves compelled to pursue it not out of defiance but as a natural consequence of the foundation he laid. His work, whether intentionally or not, created the conditions that made such an exploration inevitable. It is not a matter of undoing his legacy but extending it in directions he may not anticipate.

Pursuing a connection between some of Turvey’s disparate interests—reading and posture—has opened a new view of the multifractal tensegrity hypothesis that crowned his life’s work. Elaborating whole-body lexical decisions towards whole-body lexical recognition shows us that the multifractal tensegrity spanning the body has a multifarious capacity to shape and deploy nonlinear interactions across scales across movement degrees of freedom. Tensegrity and its nonlinear cascading behavior have an integrity that eschews simple decomposition into independent components. However, integrity and bodywide coordination have context- and task-sensitive nuance that affords diverse solutions and exquisite detail in how it wields, reshapes, and reforms the synergies at its disposal. Multifractal nonlinearity allows us to map these relationships as they spread across the body. The physiological heterogeneity of the body is not antithetical to bodywide coordination but only part of the substrate of enabling constraints that make those coordinations fluid and adaptive to task and context. For example, there is no simple value of multifractality for single-word recognition written across the whole body. Instead, multifractality at different body parts spreads and shifts according to how the body changes contact with the multifarious aspects of the informational layout (Stoffregen et al., 2017). Multifractal nonlinearity may provide a generic framework for articulating this diversity as it supports interactivity, gives voice to differentiation of form and local perturbation, and supports bodywide engagement with the world. Indeed, we might envision how the task of single-word reading could afford an apt model system for beginning to examine network relationships across the body. Thus, Turvey’s perspective suggests that single-word reading is a network affair that might span the whole body: multifractality and its multisegmental response to task and context can provide the key to unlocking mysteries about many cognitive or perceptual tasks previously only considered in neural information-processing terms.

We understand that words may not interest some readers of ecological psychology. We understand that Gibson once distinguished perceiving affordances from identifying objects (Gibson, 1979), and the visual displays we used were displays covered in words to be read or not, to be compared with a prime or not—so, object identification sooner than affordance perception. We are aware of ongoing controversies about whether recognizing objects like words could qualify as affordance perception (e.g., Withagen and Chemero, 2012; Worgan and Moore, 2010). We sidestep this question because any relationship between postural tensegrity dynamics and word recognition would be an intriguing implication of Turvey’s opus. Turvey once acknowledged that “it is instructive to be delinquent (occasionally) in one’s faith” (Turvey, 1977a, p. 83). So, much though Turvey defended the faith in affordance perception, pursuing a connection between a multifractal tensegrity and single-word recognition strikes us as faithful to Turvey’s vision, even if not to strict Gibsonian notions of specification. Even if object identification ends up irreconcilable with affordance perception, we do not presume to argue here that the words in our display are merely arbitrary symbols devoid of perceptual significance. Rather, they function as structured stimuli that engage perceptual systems in ways that may resonate with the dynamical, multifractal structure of the bodywide postural tensegrity. Whether this resonance

aligns with or challenges strict Gibsonian notions, it remains an open and empirically testable question that warrants exploration in the spirit of Turvey’s vision of the science of perception-action. It is clear that Turvey’s vision of any sort of “mental lexicon” would require not representational mediation but rather impredicative interactions across scale in a nonlinear physical medium (Turvey and Moreno, 2006). We hope to have shown how his multifractal-tensegrity vision cut across his diverse interests, even to that most representation-hungry reading domain. How much more powerful could ecological psychology be if these most representational-hungry issues of word reading might fall along tensegrity-driven lines? For our part, we are not interested in making any proposed difference between affordances and objects a reason to limit the scope of ecological psychology. Turvey promoted a tensegrity-based path through which ecological psychology need not withhold its lawful explanations of perception-action from word reading or, indeed, any object classification.

## Supplementary material

**Dataset S1.** Dataset used to examine the influence of multifractal nonlinearity, postural and task constraints, and their interactions on the circle-standardized correct number of targets found in the visual word search.

**Model S1.** Linear mixed-effects model used to examine the influence of multifractal nonlinearity, postural and task constraints, and their interactions on the circle-standardized correct number of targets found in the visual word search.

**Dataset S2.** Dataset used to examine the influence of postural and task constraints on root-mean-square of gaze fixations.

**Model S2.** Linear mixed-effects model used to examine the influence of postural and task constraints on root-mean-square of gaze fixations.

**Dataset S3.** Dataset used to examine the influence of postural and task constraints on multifractal nonlinearity in postural sway.

**Model S3.** Linear mixed-effects model used to examine the influence of postural and task constraints on multifractal nonlinearity in postural sway.

## Acknowledgments

This research was made possible through the generous support of several funding bodies to Cédric T. Bonnet. We gratefully acknowledge the Regional Council Hauts-de-France for their research grant under the STIMULE-STIR program (Soutien aux Travaux Interdisciplinaires, Multi-établissements et Exploratoires – volet recherche exploratoire). Additionally, we thank CAPES-COFECUB for their financial support (Grant IDs: CAPES-COFECUB Ma 1005/23 and Campus France 49556YD).

Cédric T. Bonnet also extends his gratitude to the Visual Sciences and Cultures Research Federation (FR CNRS 2052 SCV) and the French National Research Agency, whose funding from the Future Investment Program (reference: ANR-21-ESRE-0030 – Equipex+ Continuum) significantly contributed to this work.

Madhur Mangalam was supported by the Center of Research in Human Movement Variability and the Center for Cardiovascular Research in Biomechanics (CRiB) at the University of Nebraska at Omaha, funded by the National Institute of General Medical Sciences (NIGMS: Grant Nos. P20GM109090 and P20GM152301).

## Author contributions statement

**Cédric T. Bonnet:** Conceptualization, Methodology, Resources, Writing – Review & Editing, Funding acquisition, Project administration; **Mélen Guillaume:** Conceptualization, Methodology, Validation, Investigation, Data Curation, Writing – Review & Editing; **Madhur Mangalam:** Conceptualization, Software, Formal analysis, Visualization, Writing – Original draft, Writing – Review & Editing; **Damian G. Kelty-Stephen:** Conceptualization, Formal analysis, Writing – Original draft, Writing – Review & Editing.

## Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that support the results reported herein are available as supplementary material.

## References

- Abbs, J. H. and Connor, N. P. (1989). Motor coordination for functional human behaviors: Perspectives from a speech motor data base. In *Advances in Psychology*, volume 61, pages 157–183. Elsevier. [https://doi.org/10.1016/S0166-4115\(08\)60021-7](https://doi.org/10.1016/S0166-4115(08)60021-7).
- Adkin, A. L., Campbell, A. D., Chua, R., and Carpenter, M. G. (2008). The influence of postural threat on the cortical response to unpredictable and predictable postural perturbations. *Neuroscience Letters*, 435(2):120–125. <https://doi.org/10.1016/j.neulet.2008.02.018>.
- Babyak, M. A. (2004). What you see may not be what you get: A brief, nontechnical introduction to overfitting in regression-type models. *Psychosomatic Medicine*, 66(3):411–421. <https://doi.org/10.1097/01.psy.0000127692.23278.a9>.
- Bacsi, A. M. and Colebatch, J. G. (2005). Evidence for reflex and perceptual vestibular contributions to postural control. *Experimental Brain Research*, 160(1):22–28. <https://doi.org/10.1007/s00221-004-1982-2>.
- Baggs, E., Raja, V., and Anderson, M. L. (2020). Extended skill learning. *Frontiers in Psychology*, 11:1956. <https://doi.org/10.3389/fpsyg.2020.01956>.
- Balasubramaniam, R., Riley, M. A., and Turvey, M. (2000). Specificity of postural sway to the demands of a precision task. *Gait & Posture*, 11(1):12–24. [https://doi.org/10.1016/S0966-6362\(99\)00051-X](https://doi.org/10.1016/S0966-6362(99)00051-X).
- Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., Dai, B., Scheipl, F., Grothendieck, G., Green, P., et al. (2009). Package ‘lme4’. *R Package Version 1.1-34*. <http://lme4.r-forge.r-project.org>.
- Bell, C. A., Carver, N. S., Zbaracki, J. A., and Kelty-Stephen, D. G. (2019). Non-linear amplification of variability through interaction across scales supports greater accuracy in manual aiming: Evidence from a multifractal analysis with comparisons to linear surrogates in the Fitts task. *Frontiers in Physiology*, 10:998. <https://doi.org/10.3389/fphys.2019.00998>.
- Bernstein, N. (1996). *The Co-ordination and Regulation of Movements*. Pergamon Press, Oxford, UK.
- Bloem, B. R., Beckley, D. J., van Vugt, J. P., van Dijk, J. G., Remler, M. P., Langston, J. W., and Roos, R. A. (1995). Long latency postural reflexes are under supraspinal dopaminergic control. *Movement Disorders*, 10(5):580–588. <https://doi.org/10.1002/mds.870100509>.
- Bloomfield, L., Lane, E., Mangalam, M., and Kelty-Stephen, D. G. (2021). Perceiving and remembering speech depend on multifractal nonlinearity in movements producing and exploring speech. *Journal of the Royal Society Interface*, 18(181):20210272. <https://doi.org/10.1098/rsif.2021.0272>.
- Bolton, D. A. (2015). The role of the cerebral cortex in postural responses to externally induced perturbations. *Neuroscience & Biobehavioral Reviews*, 57:142–155. <https://doi.org/10.1016/j.neubiorev.2015.08.014>.
- Bousfield, W. A. and Sedgewick, C. H. W. (1944). An analysis of sequences of restricted associative responses. *Journal of General Psychology*, 30(2):149–165. <https://doi.org/10.1080/00221309.1944.10544467>.
- Burnham, K. P. and Anderson, D. R. (2004). Multimodel inference: Understanding AIC and BIC in model selection. *Sociological Methods & Research*, 33(2):261–304. <https://doi.org/10.1177/0049124104268644>.
- Caron, E. E., Marusich, L. R., Bakdash, J. Z., Ballotti, R. J., Tague, A. M., Carriere, J. S., Smilek, D., Harter, D., Lu, S., and Reynolds, M. G. (2023). The influence of posture on attention. *Experimental Psychology*, 69(6):295–307. <https://doi.org/10.1027/1618-3169/a000567>.
- Carver, N. S., Bojovic, D., and Kelty-Stephen, D. G. (2017). Multifractal foundations of visually-guided aiming and adaptation to prismatic perturbation. *Human Movement Science*, 55:61–72. <https://doi.org/10.1016/j.humov.2017.07.005>.



- Carver, N. S. and Kelty-Stephen, D. G. (2017). Multifractality in individual honeybee behavior hints at colony-specific social cascades: Reanalysis of radio-frequency identification data from five different colonies. *Physical Review E*, 95(2):022402. <https://doi.org/10.1103/PhysRevE.95.022402>.
- Chen, Y.-S. and Zhou, S. (2011). Soleus H-reflex and its relation to static postural control. *Gait & Posture*, 33(2):169–178. <https://doi.org/10.1016/j.gaitpost.2010.12.008>.
- Chhabra, A. and Jensen, R. V. (1989). Direct determination of the  $f(\alpha)$  singularity spectrum. *Physical Review Letters*, 62(12):1327. <https://doi.org/10.1103/physrevlett.62.1327>.
- Chow, J. C., Wallace, E. S., Senter, R., Kumm, S., and Mason, C. Q. (2022). A systematic review and meta-analysis of the language skills of youth offenders. *Journal of Speech, Language, and Hearing Research*, 65(3):1166–1182. [https://doi.org/10.1044/2021\\_JSLHR-20-00308](https://doi.org/10.1044/2021_JSLHR-20-00308).
- Chvatal, S. A. and Ting, L. H. (2013). Common muscle synergies for balance and walking. *Frontiers in Computational Neuroscience*, 7:48. <https://doi.org/10.1371/journal.pone.0096440>.
- Clauset, A., Shalizi, C. R., and Newman, M. E. (2009). Power-law distributions in empirical data. *SIAM Review*, 51(4):661–703. <https://doi.org/10.1137/070710111>.
- Colebatch, J. G., Govender, S., and Dennis, D. L. (2016). Postural responses to anterior and posterior perturbations applied to the upper trunk of standing human subjects. *Experimental Brain Research*, 234:367–376. <https://doi.org/10.1007/s00221-015-4442-2>.
- Duysens, J., Beerepoot, V., Veltink, P. H., Weerdesteyn, V., and Smits-Engelsman, B. (2008). Proprioceptive perturbations of stability during gait. *Clinical Neurophysiology*, 38(6):399–410. <https://doi.org/10.1016/j.neucli.2008.09.010>.
- Edwards, A. M., Phillips, R. A., Watkins, N. W., Freeman, M. P., Murphy, E. J., Afanasyev, V., Buldyrev, S. V., da Luz, M. G., Raposo, E. P., Stanley, H. E., et al. (2007). Revisiting Lévy flight search patterns of wandering albatrosses, bumblebees and deer. *Nature*, 449(7165):1044–1048. <https://doi.org/10.1038/nature06199>.
- Fowler, C. A. (2006). Compensation for coarticulation reflects gesture perception, not spectral contrast. *Perception & Psychophysics*, 68:161–177. <https://doi.org/10.3758/BF03193666>.
- Fowler, C. A. and Turvey, M. T. (1980). Immediate compensation in bite-block speech. *Phonetica*, 37(5–6):306–326. <https://doi.org/10.1159/000260000>.
- Furmanek, M. P., Mangalam, M., Kelty-Stephen, D. G., and Juras, G. (2021). Postural constraints recruit shorter-timescale processes into the non-Gaussian cascade processes. *Neuroscience Letters*, 741:135508. <https://doi.org/10.1016/j.neulet.2020.135508>.
- Galantucci, B. (2005). An experimental study of the emergence of human communication systems. *Cognitive Science*, 29(5):737–767. [https://doi.org/10.1207/s15516709cog0000\\_34](https://doi.org/10.1207/s15516709cog0000_34).
- Galantucci, B., Fowler, C. A., and Turvey, M. T. (2006). The motor theory of speech perception reviewed. *Psychonomic Bulletin & Review*, 13(3):361–377. <https://doi.org/10.3758/BF03193857>.
- Gibson, J. J. (1966). *The Senses Considered as Perceptual Systems*. Houghton Mifflin, Boston, MA.
- Gibson, J. J. (1979). *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston, MA.
- Haas, G., Diener, H., Bacher, M., and Dichgans, J. (1986). Development of postural control in children: Short-, medium-, and long latency EMG responses of leg muscles after perturbation of stance. *Experimental Brain Research*, 64:127–132. <https://doi.org/10.1007/BF00238208>.
- Halsey, T. C., Jensen, M. H., Kadanoff, L. P., Procaccia, I., and Shraiman, B. I. (1986). Fractal measures and their singularities: The characterization of strange sets. *Physical Review A*, 33(2):1141. <https://doi.org/10.1103/PhysRevA.33.1141>.
- Hasselmann, F. (2015). Classifying acoustic signals into phoneme categories: Average and dyslexic readers make use of complex dynamical patterns and multifractal scaling properties of the speech signal. *PeerJ*, 3:e837. <https://doi.org/10.7717/peerj.837>.
- Holden, J. G. (2002). Fractal characteristics of response time variability. *Ecological Psychology*, 14(1–2):53–86. <https://doi.org/10.1080/10407413.2003.9652752>.
- Holden, J. G., Greijn, L. T., van Rooij, M. M., Wijnants, M. L., and Bosman, A. M. (2014). Dyslexic and skilled reading dynamics are self-similar. *Annals of Dyslexia*, 64:202–221. <https://doi.org/10.1007/s11881-014-0094-3>.
- Holden, J. G. and Rajaraman, S. (2012). The self-organization of a spoken word. *Frontiers in Psychology*, 3:209. <https://doi.org/10.3389/fpsyg.2012.00209>.

- 953 Holden, J. G., Van Orden, G. C., and Turvey, M. T. (2009). Dispersion of response times reveals cognitive dynamics.  
954 *Psychological Review*, 116(2):318–342. <https://doi.org/10.1037/a0014849>.
- 955 Ihlen, E. A., Skjæret, N., and Vereijken, B. (2013). The influence of center-of-mass movements on the variation in  
956 the structure of human postural sway. *Journal of Biomechanics*, 46(3):484–490. <https://doi.org/10.1016/j.jbiomech.2012.10.016>.
- 958 Ihlen, E. A. and Vereijken, B. (2010). Interaction-dominant dynamics in human cognition: Beyond  $1/f^\alpha$  fluctuation.  
959 *Journal of Experimental Psychology: General*, 139(3):436–463. <https://doi.org/10.1037/a0019098>.
- 960 Ihlen, E. A. F. E. (2012). Introduction to multifractal detrended fluctuation analysis in Matlab. *Frontiers in Physiology*,  
961 3:141. <https://doi.org/10.3389/fphys.2012.00141>.
- 962 Jacobs, J. V. and Horak, F. (2007). Cortical control of postural responses. *Journal of Neural Transmission*, 114:1339–  
963 1348. <https://doi.org/10.1007/s00702-007-0657-0>.
- 964 Jacobson, N., Berleman-Paul, Q., Mangalam, M., Kelty-Stephen, D. G., and Ralston, C. (2021). Multifractality in  
965 postural sway supports quiet eye training in aiming tasks: A study of golf putting. *Human Movement Science*,  
966 76:102752. <https://doi.org/10.1016/j.humov.2020.102752>.
- 967 Johnston, T. D. and Turvey, M. (1980). A sketch of an ecological metatheory for theories of learning. In *Psychology of*  
968 *Learning and Motivation*, volume 14, pages 147–205. Elsevier. [https://doi.org/10.1016/S0079-7421\(08\)](https://doi.org/10.1016/S0079-7421(08)60161-9)  
969 60161–9.
- 970 Kanekar, N. and Aruin, A. S. (2014). Aging and balance control in response to external perturbations: Role  
971 of anticipatory and compensatory postural mechanisms. *Age*, 36:1067–1077. <https://doi.org/10.1007/s11357-014-9621-8>.
- 973 Kello, C. T., Anderson, G. G., Holden, J. G., and Van Orden, G. C. (2008). The pervasiveness of  $1/f$  scaling in speech  
974 reflects the metastable basis of cognition. *Cognitive Science*, 32(7):1217–1231. <https://doi.org/10.1080/03640210801944898>.
- 976 Kelso, J. S., Tuller, B., Vatikiotis-Bateson, E., and Fowler, C. A. (1984). Functionally specific articulatory cooperation  
977 following jaw perturbations during speech: Evidence for coordinative structures. *Journal of Experimental Psychology:*  
978 *Human Perception and Performance*, 10(6):812–832. <https://doi.org/10.1037/0096-1523.10.6.812>.
- 979 Kelty-Stephen, D., Similton, O. D., Rabinowitz, E., and Allen, M. (2023a). Multifractal auditory stimulation promotes  
980 the effect of multifractal torso sway on spatial perception: Evidence from distance perception by blindwalking.  
981 *Ecological Psychology*, 35(4):136–182. <https://doi.org/10.1080/10407413.2023.2287752>.
- 982 Kelty-Stephen, D. G. (2018). Multifractal evidence of nonlinear interactions stabilizing posture for phasmids in windy  
983 conditions: A reanalysis of insect postural-sway data. *PloS One*, 13(8):e0202367. [https://doi.org/10.1371/](https://doi.org/10.1371/journal.pone.0202367)  
984 [journal.pone.0202367](https://doi.org/10.1371/journal.pone.0202367).
- 985 Kelty-Stephen, D. G. and Dixon, J. A. (2014). Interwoven fluctuations during intermodal perception: Fractality in head  
986 sway supports the use of visual feedback in haptic perceptual judgments by manual wielding. *Journal of Experimental*  
987 *Psychology: Human Perception and Performance*, 40(6):2289–2309. <https://doi.org/10.1037/a0038159>.
- 988 Kelty-Stephen, D. G., Lane, E., Bloomfield, L., and Mangalam, M. (2023b). Multifractal test for nonlinearity of  
989 interactions across scales in time series. *Behavior Research Methods*, 55(5):2249–2282. [https://doi.org/10.](https://doi.org/10.3758/s13428-022-01866-9)  
990 3758/s13428-022-01866-9.
- 991 Kelty-Stephen, D. G., Lee, I. C., Carver, N. S., Newell, K. M., and Mangalam, M. (2021). Multifractal roots of  
992 suprapostural dexterity. *Human Movement Science*, 76:102771. [https://doi.org/10.1016/j.humov.2021.](https://doi.org/10.1016/j.humov.2021.102771)  
993 102771.
- 994 Kelty-Stephen, D. G. and Mangalam, M. (2022). Fractal and multifractal descriptors restore ergodicity broken by  
995 non-Gaussianity in time series. *Chaos, Solitons & Fractals*, 163:112568. [https://doi.org/10.1016/j.chaos.](https://doi.org/10.1016/j.chaos.2022.112568)  
996 2022.112568.
- 997 Kelty-Stephen, D. G. and Mangalam, M. (2023). Multifractal descriptors ergodically characterize non-ergodic  
998 multiplicative cascade processes. *Physica A: Statistical Mechanics and its Applications*, 617:128651. <https://doi.org/10.1016/j.physa.2023.128651>.
- 1000 Kelty-Stephen, D. G. and Mangalam, M. (2024). Additivity suppresses multifractal nonlinearity due to multiplicative  
1001 cascade dynamics. *Physica A: Statistical Mechanics and its Applications*, 637:129573. [https://doi.org/10.](https://doi.org/10.1016/j.physa.2024.129573)  
1002 1016/j.physa.2024.129573.
- 1003 Kerster, B. E., Rhodes, T., and Kello, C. T. (2016). Spatial memory in foraging games. *Cognition*, 148:85–96.  
1004 <https://doi.org/10.1016/j.cognition.2015.12.015>.

- Kugler, P. N. and Turvey, M. T. (2015). *Information, Natural Law, and the Self-Assembly of Rhythmic Movement*. Routledge, New York, NY.
- Kurtzer, I. L. (2015). Long-latency reflexes account for limb biomechanics through several supraspinal pathways. *Frontiers in Integrative Neuroscience*, 8:99. <https://doi.org/10.3389/fnint.2014.00099>.
- Kuznetsova, A., Brockhoff, P. B., and Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, 82(13):1–26. <https://doi.org/10.18637/jss.v082.i13>.
- Lee, J. T. and Kelty-Stephen, D. G. (2017). Cascade-driven series with narrower multifractal spectra than their surrogates: Standard deviation of multipliers changes interactions across scales. *Complexity*, 2017(1):7015243. <https://doi.org/10.1155/2017/7015243>.
- Lukatela, G., Popadić, D., and Turvey, M. (1980). Lexical decision in a phonologically shallow orthography. *Memory & Cognition*, 8(2):124–132. <https://doi.org/10.3758/BF03213415>.
- Lukatela, G. and Turvey, M. T. (1998). Reading in two alphabets. *American Psychologist*, 53(9):1057–1072. <https://doi.org/10.1037/0003-066X.53.9.1057>.
- Magnuson, J. S. (2007). Nondeterminism, pleiotropy, and single-word reading: Theoretical and practical concerns. In Grigorenko, E. L. and Naples, A. J., editors, *Single-Word Reading*, pages 385–412. Psychology Press, London, UK.
- Mandelbrot, B. B. (1974). Intermittent turbulence in self-similar cascades: Divergence of high moments and dimension of the carrier. *Journal of Fluid Mechanics*, 62(2):331–358. <https://doi.org/10.1017/S0022112074000711>.
- Mandelbrot, B. B. (2013). *Fractals and Scaling in Finance: Discontinuity, Concentration, Risk*. Springer, New York, NY.
- Mandelbrot, B. B. and Mandelbrot, B. B. (1982). *The Fractal Geometry of Nature*. W. H. Freeman, New York, NY.
- Mangalam, M., Carver, N. S., and Kelty-Stephen, D. G. (2020). Multifractal signatures of perceptual processing on anatomical sleeves of the human body. *Journal of The Royal Society Interface*, 17(168):20200328. <https://doi.org/10.1098/rsif.2020.0328>.
- Mangalam, M. and Kelty-Stephen, D. G. (2021a). Hypothetical control of postural sway. *Journal of the Royal Society Interface*, 18(176):20200951. <https://doi.org/10.1098/rsif.2020.0951>.
- Mangalam, M. and Kelty-Stephen, D. G. (2021b). Point estimates, Simpson’s paradox, and nonergodicity in biological sciences. *Neuroscience & Biobehavioral Reviews*, 125:98–107. <https://doi.org/10.1016/j.neubiorev.2021.02.017>.
- Mangalam, M. and Kelty-Stephen, D. G. (2022). Ergodic descriptors of non-ergodic stochastic processes. *Journal of the Royal Society Interface*, 19(189):20220095. <https://doi.org/10.1098/rsif.2022.0095>.
- Mangalam, M. and Kelty-Stephen, D. G. (2024). Multifractal perturbations to multiplicative cascades promote multifractal nonlinearity with asymmetric spectra. *Physical Review E*, 109(6):064212. <https://doi.org/10.1103/PhysRevE.109.064212>.
- Mangalam, M., Lee, I.-C., Newell, K. M., and Kelty-Stephen, D. G. (2021). Visual effort moderates postural cascade dynamics. *Neuroscience Letters*, 742:135511. <https://doi.org/10.1016/j.neulet.2020.135511>.
- Mangalam, M., Likens, A. D., and Kelty-Stephen, D. G. (2023a). Multifractal nonlinearity as a robust estimator of multiplicative cascade dynamics. *arXiv preprint arXiv:2312.05653*. <https://doi.org/10.48550/arXiv.2312.05653>.
- Mangalam, M., Metzler, R., and Kelty-Stephen, D. G. (2023b). Ergodic characterization of nonergodic anomalous diffusion processes. *Physical Review Research*, 5(2):023144. <https://doi.org/10.1103/PhysRevResearch.5.023144>.
- Mangalam, M., Sadri, A., Hayano, J., Watanabe, E., Kiyono, K., and Kelty-Stephen, D. G. (2023c). Multifractal foundations of biomarker discovery for heart disease and stroke. *Scientific Reports*, 13:18316. <https://doi.org/10.1038/s41598-023-45184-2>.
- Mangalam, M., Seckler, H., and Kelty-Stephen, D. G. (2024). Machine-learning classification with additivity and diverse multifractal pathways in multiplicativity. *Physical Review Research*, 6(3):033276. <https://doi.org/10.1103/PhysRevResearch.6.033276>.
- Mark, L. S., Balliett, J. A., Craver, K. D., Douglas, S. D., and Fox, T. (1990). What an actor must do in order to perceive the affordance for sitting. *Ecological Psychology*, 2(4):325–366. [https://doi.org/10.1207/s15326969eco0204\\_2](https://doi.org/10.1207/s15326969eco0204_2).
- McClelland, J. L. (1979). On the time relations of mental processes: An examination of systems of processes in cascade. *Psychological Review*, 86(4):287–330. <https://doi.org/10.1037/0033-295X.86.4.287>.

- McIlroy, W. and Maki, B. (1997). Preferred placement of the feet during quiet stance: Development of a standardized foot placement for balance testing. *Clinical Biomechanics*, 12(1):66–70. [https://doi.org/10.1016/S0268-0033\(96\)00040-X](https://doi.org/10.1016/S0268-0033(96)00040-X).
- Mergner, T. (2010). A neurological view on reactive human stance control. *Annual Reviews in Control*, 34(2):177–198. <https://doi.org/10.1016/j.arcontrol.2010.08.001>.
- Mergner, T. and Rosemeier, T. (1998). Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions—a conceptual model. *Brain Research Reviews*, 28(1–2):118–135. [https://doi.org/10.1016/S0165-0173\(98\)00032-0](https://doi.org/10.1016/S0165-0173(98)00032-0).
- Mitra, S. and Fraizer, E. (2004). Effects of explicit sway-minimization on postural–suprapostural dual-task performance. *Human Movement Science*, 23(1):1–20. <https://doi.org/10.1016/j.humov.2004.03.003>.
- Molenaar, P. C. (2008). On the implications of the classical ergodic theorems: Analysis of developmental processes has to focus on intra-individual variation. *Developmental Psychobiology*, 50(1):60–69. <https://doi.org/10.1002/dev.20262>.
- Morales, C. J. and Kolaczyk, E. D. (2002). Wavelet-based multifractal analysis of human balance. *Annals of Biomedical Engineering*, 30:588–597. <https://doi.org/10.1114/1.1478082>.
- Moreno, M. A., Stepp, N., and Turvey, M. (2011). Whole body lexical decision. *Neuroscience Letters*, 490(2):126–129. <https://doi.org/10.1016/j.neulet.2010.12.041>.
- Nardone, A., Grasso, M., Giordano, A., and Schieppati, M. (1996). Different effect of height on latency of leg and foot short-and medium-latency EMG responses to perturbation of stance in humans. *Neuroscience Letters*, 206(2–3):89–92. [https://doi.org/10.1016/S0304-3940\(96\)12430-7](https://doi.org/10.1016/S0304-3940(96)12430-7).
- Nashner, L. (1976). Adapting reflexes controlling the human posture. *Experimental Brain Research*, 26(1):59–72. <https://doi.org/10.1007/BF00235249>.
- Ognjenovi, V., Lukatela, G., Feldman, L. B., and Turvey, M. (1983). Misreadings by beginning readers of Serbo-Croatian. *Quarterly Journal of Experimental Psychology*, 35(1):97–109. <https://doi.org/10.1080/14640748308402119>.
- Palatinus, Z., Kelty-Stephen, D. G., Kinsella-Shaw, J., Carello, C., and Turvey, M. T. (2014). Haptic perceptual intent in quiet standing affects multifractal scaling of postural fluctuations. *Journal of Experimental Psychology: Human Perception and Performance*, 40(5):1808–1818. <https://doi.org/10.1037/a0037247>.
- Parr, T., Holmes, E., Friston, K. J., and Pezzulo, G. (2023). Cognitive effort and active inference. *Neuropsychologia*, 184:108562. <https://doi.org/10.1016/j.neuropsychologia.2023.108562>.
- Pattee, H. H. (1974). The need for complementarity in models of cognitive behavior: A response to Fowler and Turvey. In *Cognition and the Symbolic Processes*, pages 21–30. Routledge, New York, NY. Weimer, Walter B and Palermo, David S.
- Pattee, H. H. (2001). The physics of symbols: Bridging the epistemic cut. *Biosystems*, 60(1–3):5–21. [https://doi.org/10.1016/S0303-2647\(01\)00104-6](https://doi.org/10.1016/S0303-2647(01)00104-6).
- Profeta, V. L. and Turvey, M. T. (2018). Bernstein’s levels of movement construction: A contemporary perspective. *Human Movement Science*, 57:111–133. <https://doi.org/10.1016/j.humov.2017.11.013>.
- R Core Team (2024). R: A language and environment for statistical computing. *R Version 4.0.4*. <https://www.R-project.org/>.
- Raja, V. and Anderson, M. L. (2021). Behavior considered as an enabling constraint. In Calzavarini, F. and Viola, M., editors, *Neural Mechanisms: New Challenges in the Philosophy of Neuroscience*, pages 209–232. Springer, Cham, Switzerland. [https://doi.org/10.1007/978-3-030-54092-0\\_10](https://doi.org/10.1007/978-3-030-54092-0_10).
- Rhodes, T., Kello, C. T., and Kerster, B. (2014). Intrinsic and extrinsic contributions to heavy tails in visual foraging. *Visual Cognition*, 22(6):809–842. <https://doi.org/10.1080/13506285.2014.918070>.
- Rhodes, T. and Turvey, M. T. (2007). Human memory retrieval as Lévy foraging. *Physica A: Statistical Mechanics and its Applications*, 385(1):255–260. <https://doi.org/10.1016/j.physa.2007.07.001>.
- Riccio, G. E. and Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. *Ecological Psychology*, 3(3):195–240. [https://doi.org/10.1207/s15326969eco0303\\_2](https://doi.org/10.1207/s15326969eco0303_2).
- Richards, S. A. (2005). Testing ecological theory using the information-theoretic approach: Examples and cautionary results. *Ecology*, 86(10):2805–2814. <https://doi.org/10.1890/05-0074>.
- Richards, S. A. (2008). Dealing with overdispersed count data in applied ecology. *Journal of Applied Ecology*, 45(1):218–227. <https://doi.org/10.1111/j.1365-2664.2007.01377.x>.

- 1109 Riley, M., Balasubramaniam, R., Mitra, S., and Turvey, M. (1998). Visual influences on center of pressure dynamics in  
1110 upright posture. *Ecological Psychology*, 10(2):65–91. [https://doi.org/10.1207/s15326969eco1002\\_1](https://doi.org/10.1207/s15326969eco1002_1).
- 1111 Riley, M. A., Mitra, S., Stoffregen, T. A., and Turvey, M. T. (1997). Influences of body lean and vision on unperturbed  
1112 postural sway. *Motor Control*, 1(3):229–246. <https://doi.org/10.1123/mcj.1.3.229>.
- 1113 Rosenbaum, D., Mama, Y., and Algom, D. (2017). Stand by your stroop: Standing up enhances selective attention and  
1114 cognitive control. *Psychological Science*, 28(12):1864–1867. <https://doi.org/10.1177/0956797617721270>.
- 1115 Santos, M. J., Kanekar, N., and Aruin, A. S. (2010a). The role of anticipatory postural adjustments in compensatory  
1116 control of posture: 1. Electromyographic analysis. *Journal of Electromyography and Kinesiology*, 20(3):388–397.  
1117 <https://doi.org/10.1016/j.jelekin.2009.06.006>.
- 1118 Santos, M. J., Kanekar, N., and Aruin, A. S. (2010b). The role of anticipatory postural adjustments in compensatory  
1119 control of posture: 2. Biomechanical analysis. *Journal of Electromyography and Kinesiology*, 20(3):398–405.  
1120 <https://doi.org/10.1016/j.jelekin.2010.01.002>.
- 1121 Schieppati, M., Nardone, A., Siliotto, R., and Grasso, M. (1990). Early and late stretch responses of human foot  
1122 muscles induced by perturbation of stance. *Experimental Brain Research*, 105:411–422. <https://doi.org/10.1007/BF00233041>.
- 1124 Schreiber, T. and Schmitz, A. (1996). Improved surrogate data for nonlinearity tests. *Physical Review Letters*, 77(4):635.  
1125 <https://doi.org/10.1103/PhysRevLett.77.635>.
- 1126 Shemmell, J., Krutky, M. A., and Perreault, E. J. (2010). Stretch sensitive reflexes as an adaptive mechanism  
1127 for maintaining limb stability. *Clinical Neurophysiology*, 121(10):1680–1689. <https://doi.org/10.1016/j.clinph.2010.02.166>.
- 1129 Shimba, S., Kawashima, N., Ohta, Y., Yamamoto, S.-I., and Nakazawa, K. (2010). Enhanced stretch reflex excitability  
1130 in the soleus muscle during passive standing posture in humans. *Journal of Electromyography and Kinesiology*,  
1131 20(3):406–412. <https://doi.org/10.1016/j.jelekin.2009.04.003>.
- 1132 Shippen, M. E., Houchins, D. E., Crites, S. A., Derzis, N. C., and Patterson, D. (2010). An examination of  
1133 the basic reading skills of incarcerated males. *Adult Learning*, 21(3–4):4–12. <https://doi.org/10.1177/104515951002100301>.
- 1135 Shockley, K., Santana, M.-V., and Fowler, C. A. (2003). Mutual interpersonal postural constraints are involved in  
1136 cooperative conversation. *Journal of Experimental Psychology: Human Perception and Performance*, 29(2):326–332.  
1137 <https://doi.org/10.1037/0096-1523.29.2.326>.
- 1138 Slobounov, S., Hallett, M., Stanhope, S., and Shibasaki, H. (2005). Role of cerebral cortex in human postural control: An  
1139 EEG study. *Clinical Neurophysiology*, 116(2):315–323. <https://doi.org/10.1016/j.clinph.2004.09.007>.
- 1140 Smith, K. C., Davoli, C. C., Knapp, W. H., and Abrams, R. A. (2019). Standing enhances cognitive control and  
1141 alters visual search. *Attention, Perception, & Psychophysics*, 81:2320–2329. <https://doi.org/10.3758/s13414-019-01723-6>.
- 1143 Soteropoulos, D. S. and Baker, S. N. (2020). Long-latency responses to a mechanical perturbation of the index finger  
1144 have a spinal component. *Journal of Neuroscience*, 40(20):3933–3948. <https://doi.org/10.1523/JNEUROSCI.1901-19.2020>.
- 1146 Soto, O., Valls-Solé, J., Shanahan, P., and Rothwell, J. (2006). Reduction of intracortical inhibition in soleus muscle  
1147 during postural activity. *Journal of Neurophysiology*, 96(4):1711–1717. <https://doi.org/10.1152/jn.00133.2006>.
- 1149 Stephen, D. G., Arzamarski, R., and Michaels, C. F. (2010). The role of fractality in perceptual learning: Exploration  
1150 in dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance*, 36(5):1161–1173.  
1151 <https://doi.org/10.1037/a0019219>.
- 1152 Stephen, D. G. and Hajnal, A. (2011). Transfer of calibration between hand and foot: Functional equivalence  
1153 and fractal fluctuations. *Attention, Perception, & Psychophysics*, 73:1302–1328. <https://doi.org/10.3758/s13414-011-0142-6>.
- 1155 Stephen, D. G., Hsu, W.-H., Young, D., Saltzman, E. L., Holt, K. G., Newman, D. J., Weinberg, M., Wood, R. J.,  
1156 Nagpal, R., and Goldfield, E. C. (2012). Multifractal fluctuations in joint angles during infant spontaneous kicking  
1157 reveal multiplicativity-driven coordination. *Chaos, Solitons & Fractals*, 45(9-10):1201–1219. <https://doi.org/10.1016/j.chaos.2012.06.005>.
- 1159 Stoffregen, T. A., Mantel, B., and Bardy, B. G. (2017). The senses considered as one perceptual system. *Ecological  
1160 Psychology*, 29(3):165–197. <https://doi.org/10.1080/10407413.2017.1331116>.

- 1161 Stoffregen, T. A. and Riccio, G. E. (1988). An ecological theory of orientation and the vestibular system. *Psychological*  
1162 *Review*, 95(1):3–14. <https://psycnet.apa.org/doi/10.1037/0033-295X.95.1.3>.
- 1163 Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, 18(6):643–  
1164 662. <https://doi.org/10.1037/h0054651>.
- 1165 Taube, W., Schubert, M., Gruber, M., Beck, S., Faist, M., and Gollhofer, A. (2006). Direct corticospinal pathways  
1166 contribute to neuromuscular control of perturbed stance. *Journal of Applied Physiology*, 101(2):420–429. <https://doi.org/10.1152/japplphysiol.01447.2005>.
- 1167 Theiler, J., Eubank, S., Longtin, A., Galdrikian, B., and Farmer, J. D. (1992). Testing for nonlinearity in time series:  
1168 The method of surrogate data. *Physica D: Nonlinear Phenomena*, 58(1-4):77–94. [https://doi.org/10.1016/0167-2789\(92\)90102-S](https://doi.org/10.1016/0167-2789(92)90102-S).
- 1169 Treisman, A. and Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12(1):97–136.  
1170 [https://doi.org/10.1016/0010-0285\(80\)90005-5](https://doi.org/10.1016/0010-0285(80)90005-5).
- 1171 Troutt, M. D. (2004). Regression, 10k rule of thumb for. *Encyclopedia of Statistical Sciences*.
- 1172 Turvey, M. (1977a). Contrasting orientations to the theory of visual information processing. *Psychological Review*,  
1173 84(1):67–88. <https://doi.org/10.1037/0033-295X.84.1.67>.
- 1174 Turvey, M. and Carello, C. (2011). Obtaining information by dynamic (effortful) touching. *Philosophical Transactions of*  
1175 *the Royal Society B: Biological Sciences*, 366(1581):3123–3132. <https://doi.org/10.1098/rstb.2011.0159>.
- 1176 Turvey, M. T. (1977b). Preliminaries to a theory of action with reference to vision. In Shaw, R. and Bransford, J.,  
1177 editors, *Perceiving, Acting, and Knowing*, pages 253–257. Lawrence Erlbaum Associates, Hillsdale, NJ.
- 1178 Turvey, M. T. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*,  
1179 4(3):173–187. [https://doi.org/10.1207/s15326969eco0403\\_3](https://doi.org/10.1207/s15326969eco0403_3).
- 1180 Turvey, M. T. (2007). Action and perception at the level of synergies. *Human Movement Science*, 26(4):657–697.  
1181 <https://doi.org/10.1016/j.humov.2007.04.002>.
- 1182 Turvey, M. T., Feldman, L. B., and Lukatela, G. (2017). The Serbo-Croatian orthography constrains the reader to a  
1183 phonologically analytic strategy. In *Orthographies and Reading*, pages 81–90. Routledge, New York, NY.
- 1184 Turvey, M. T., Fitch, H. L., and Tuller, B. (1982). The bernstein perspective: I. The problems of degrees of freedom and  
1185 context-conditioned variability. In Turvey, M. T., Fitch, H. L., and Tuller, B., editors, *Human Motor Behavior*, pages  
1186 239–252. Psychology Press, London, UK.
- 1187 Turvey, M. T., Fitch, H. L., and Tuller, B. (2014). The bernstein perspective: I. The problems of degrees of freedom and  
1188 context-conditioned variability. In Turvey, M. T., Fitch, H. L., and Tuller, B., editors, *Human Motor Behavior*, pages  
1189 239–252. Psychology Press, London, UK.
- 1190 Turvey, M. T. and Fonseca, S. (2009). Nature of motor control: Perspectives and issues. In Sternad, D., editor, *Progress*  
1191 *in Motor control: A Multidisciplinary Perspective*, pages 93–123. Springer, Boston, MA. [https://doi.org/10.1007/978-0-387-77064-2\\_6](https://doi.org/10.1007/978-0-387-77064-2_6).
- 1192 Turvey, M. T. and Fonseca, S. T. (2014). The medium of haptic perception: A tensegrity hypothesis. *Journal of Motor*  
1193 *Behavior*, 46(3):143–187. <https://doi.org/10.1080/00222895.2013.798252>.
- 1194 Turvey, M. T. and Moreno, M. A. (2006). Physical metaphors for the mental lexicon. *The Mental Lexicon*, 1(1):7–33.  
1195 <https://doi.org/10.1075/ml.1.1.04tur>.
- 1196 Turvey, M. T., Shaw, R. E., Reed, E. S., and Mace, W. M. (1981). Ecological laws of perceiving and acting: In reply to  
1197 Fodor and Pylyshyn (1981). *Cognition*, 9(3):237–304. [https://doi.org/10.1016/0010-0277\(81\)90002-0](https://doi.org/10.1016/0010-0277(81)90002-0).
- 1198 Van Orden, G. C. and Holden, J. G. (2002). Intentional contents and self-control. *Ecological Psychology*, 14(1-2):87–  
1199 109. <https://doi.org/10.1080/10407413.2003.9652753>.
- 1200 Van Orden, G. C., Holden, J. G., and Turvey, M. T. (2003). Self-organization of cognitive performance. *Journal of*  
1201 *Experimental Psychology: General*, 132(3):331–350. <https://doi.org/10.1037/0096-3445.132.3.331>.
- 1202 Van Orden, G. C., Holden, J. G., and Turvey, M. T. (2005). Human cognition and  $1/f$  scaling. *Journal of Experimental*  
1203 *Psychology: General*, 134(1):117–350. <https://doi.org/10.1037/0096-3445.134.1.117>.
- 1204 Veneziano, D., Moglen, G. E., and Bras, R. L. (1995). Multifractal analysis: Pitfalls of standard procedures and  
1205 alternatives. *Physical Review E*, 52(2):1387. <https://doi.org/10.1103/PhysRevE.52.1387>.
- 1206 Ward, R. M. and Kelty-Stephen, D. G. (2018). Bringing the nonlinearity of the movement system to gestural theories of  
1207 language use: Multifractal structure of spoken English supports the compensation for coarticulation in human speech  
1208 perception. *Frontiers in Physiology*, 9:1152. <https://doi.org/10.3389/fphys.2018.01152>.

- 1212 Warren, W. H. (1984). Perceiving affordances: Visual guidance of stair climbing. *Journal of Experimental Psychology:*  
1213 *Human Perception and Performance*, 10(5):683–703. <https://doi.org/10.1037/0096-1523.10.5.683>.
- 1214 Withagen, R. and Chemero, A. (2012). Affordances and classification: On the significance of a sidebar in James Gibson’s  
1215 last book. *Philosophical Psychology*, 25(4):521–537. <https://doi.org/10.1080/09515089.2011.579424>.
- 1216 Woollacott, M. H. and Nashner, L. M. (1982). Inhibition of the achilles tendon reflex by antagonist long-latency postural  
1217 responses in humans. *Experimental Neurology*, 75(2):420–439. [https://doi.org/10.1016/0014-4886\(82\)](https://doi.org/10.1016/0014-4886(82)90171-6)  
1218 90171–6.
- 1219 Worgan, S. and Moore, R. (2010). Speech as the perception of affordances. *Ecological Psychology*, 22(4):327–343.  
1220 <https://doi.org/10.1080/10407413.2010.517125>.