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WHOLE-BODY MULTIFRACTAL SYNERGIES SUPPORT COGNITIVE VISUAL WORD SEARCH

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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 1 Introduction

² Grasping a single word that might describe Michael T. Turvey is not just difficult—it is almost comically impossible.
³ His impact demands many words, some seemingly unrelated, bound together only by the remarkable genius with
⁴ which he found and wove connections among them. The breadth of Turvey’s intellectual reach has few true analogs
⁵ in contemporary science. The rigid silos of academia make it difficult for most to embrace the kind of polymathy
⁶ that came naturally to him. Yet Turvey was never interested in polymathy for its own sake; he pursued something
⁷ deeper—an interdisciplinary integrity that united diverse fields, expertise, and ideas. For him, uncovering the hidden

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

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

25 “*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,
 26 as perceiving-acting systems fluent in both affordances and object classification (e.g., Gibson, 1979; Withagen and
 27 Chemero, 2012), somehow hop from dynamical law in affairs like step-on-ability (Warren, 1984) to classifying the
 28 objects. Turvey’s priorities were clear, and he left judicious room for the possibility of a future connection between the
 29 dynamical laws underwriting action and the symbolic constraints of words. He did not want us to worry immediately or
 30 too much about “*How?*”—likely because he knew much work remained to be done in this vein. Thus, unearthing a once-
 31 silly, once-student’s question is not a disrespectful *gotcha*. The present manuscript attempts to return to the question,
 32 even if it is no longer possible to return to the bartender, with some later-developed ideas. We are seeing—always too
 33 late—new possibilities for integrating some of the variegated pieces that Turvey brought to our attention.

34 1.1 The long fractal roots of how words might get into muscles

35 The possible connections we propose here for understanding the grasp of a single word may have only begun to
 36 dawn on Turvey himself relatively late. Yet the roots ran deep and early: Turvey had a distinguished career as a
 37 psycholinguist (Lukatela et al., 1980; Lukatela and Turvey, 1998; Ognjenović et al., 1983; Turvey et al., 2017). He also
 38 began drawing other psycholinguists from the connectionist tradition into questions about dynamical law and emergence
 39 beyond mere computational or symbolic constraints (Van Orden et al., 2003). This latter pull need not have been too
 40 strong—connectionism itself had quite constraints-averse beginnings, favoring cascades and flows that verged on the
 41 anarchic amid the reign of information-processing models (McClelland, 1979). Turvey called some connectionists
 42 back to their grounding values, steering them away from their compromises with traditional information-processing
 43 frameworks to maintain legitimacy within cognitive psychology. These anarchic themes carried forward into Turvey’s
 44 absolutely visionary collaborations with Guy Van Orden and Jay Holden, helping to launch bold new proposals on
 45 how the fractal and power-law evidence that had simmered in the psychological empirical record for decades might
 46 signal the self-organization supporting cognition itself (Holden, 2002; Van Orden and Holden, 2002; Van Orden et al.,
 47 2003, 2005). Turvey and colleagues first identified this fractal patterning in spoken-response times. Kello later recruited
 48 Van Orden and Holden to explore similar patterns in spoken-syllable and spoken-word sequences (Kello et al., 2008).
 49 Revolution felt almost palpable in the air.

50 Suddenly and briefly, Turvey appeared to grasp the connection between our mental handling of individual words and
 51 the fractal patterning of our bodily movements. His work with Rhodes provided preliminary evidence linking power-
 52 law-like scaling in memory recall to power-law-like foraging dynamics, suggesting a deeper, shared organizational
 53 principle across cognitive and ecological domains (Rhodes and Turvey, 2007). Holden then led Van Orden and Turvey
 54 in a remarkable encore, examining power-law and power-law-like distributions in word-reading times (Holden et al.,
 55 2009). This work sparked several follow-up demonstrations of similar patterns across various language-use domains and
 56 populations (Holden and Rajaraman, 2012; Holden et al., 2014). Turvey offered us a glimpse into the entanglement of
 57 memory and visual word recognition with our bodily movement system, cultivating a scale-invariant froth of interactions
 58 across events large and small. The task of so-called “processing” language—one individual word at a time—was no
 59 longer merely an affair written at the scale of discrete symbols, that is, symbols large enough for us to recognize or
 60 write as individual letters (Turvey, 1977b), yet arbitrary enough to frustrate any devotee of natural law (Turvey et al.,
 61 1981). No, for a fleeting moment, Turvey planted the seed for a naturalization of language use—one that promised to
 62 embed the symbolic word within a fluid cascade of dynamics, whose richly nested structure pervaded the body that

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

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

82 1.2 The tensegrity connection called back to the fractal response to words

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

95 Why multifractal and not just fractal? It is worth asking because, to the unfamiliar reader, fractal scaling can seem exotic
 96 enough without asking for the more cumbersome-sounding abundance of *multifractality*. The multifractal tensegrity
 97 hypothesis reflected a line of reasoning that involved at least two steps. The reasoning that tensegrity might be at
 98 least fractal was that the connective tissues supporting the musculoskeletal system functioned through a dynamic
 99 balance of tension and compression elements—an intriguing nuance being that what was tensile at one scale could
 100 manifest as compressive at another and vice versa. The heterogeneity of the bodily form and its boundedness at the
 101 skin had previously prompted suggestions that a single fractal parameter could not do justice to the wider range of
 102 this scale-invariant property. Furthermore, the interactivity across scales held the potential of something more fluidly
 103 cascading. Echoing Pattee's (2001) intuition, what seemed like a rigid compressive constraint at one scale might be
 104 supported by more fluid tension at another. This more fluid interdependence made nonlinear interactivity across scales
 105 a firmer requirement, and the best formalism for carrying this requirement to date is the multiplicative cascade. The
 106 best statistics for estimating the underlying parameters of a cascade are multifractal statistics—a point established by
 107 Mandelbrot (1974; 1982; 2013) and brought home to a psychological audience by Ihlen and Vereijken (2010). The
 108 multifunctionality that had confounded simplistic attempts to characterize motor degrees of freedom (Turvey et al.,
 109 2014) requires a more nuanced characterization than a single scale-invariant parameter to rule the whole system.

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

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

129 **1.3 Aiming the multifractal tensegrity hypothesis at single-word recognition**

130 So, the present work aims at a research question inspired by Turvey's lifelong steadfast work trying to unite such
 131 disparate domains as visual word recognition and the multifractal tensegrity coordination of the movement system. We
 132 do not come to this task completely out of the blue or simply in a fit of mourning. There is prior work documenting
 133 that speech is indeed as multifractal as it should be if a tensegrity structure were producing it (Kelty-Stephen et al.,
 134 2023b), and then, the multifractality of speech appears to be a distinguishing feature of speech supporting the attention
 135 and perception of human listeners (Hasselman, 2015; Ward and Kelty-Stephen, 2018). Multifractal structure of speech
 136 supports spoken word recognition, particularly as human listeners listen to a coherent narrative, even as word recognition
 137 hinges less on individual word features and more on the narrative structure (Bloomfield et al., 2021). What is more, if
 138 the listening task is self-paced and so explicitly requiring fingertap movements to elicit more spoken words, listeners
 139 who bring more multifractality in their fingertap sequences in this speech event appear to have better recognition
 140 memory for the words they have heard in the narrative (Bloomfield et al., 2021). Hence, we have preliminary evidence
 141 consistent with tensegrity-based answers to Turvey's questions about language use on the speech side. We now offer the
 142 latest step, this time towards tensegrity-based answers to questions about the reading side.

143 Grasping a single word may rest in our grasp for the ground, and the multifractal tensegrity hypothesis may help
 144 unlock a scientific view into that relationship. The present work aims to forge the strongest linkage between visual
 145 word recognition and upright postural control. Turvey had long been a champion of the ecological-psychology insight
 146 (e.g., Gibson, 1966, 1979; Riccio and Stoffregen, 1991) that upright posture and vision were intimately connected
 147 (Balasubramiam et al., 2000; Riley et al., 1997, 1998; Turvey, 1977a). Once the multifractal aspects of posture
 148 had begun to show consonance with a tensegrity model of perception (e.g., Ihlen et al., 2013; Morales and Kolaczyk,
 149 2002), Turvey began to show an interest in the multifractality of posture for haptic perception (Palatinus et al., 2014).
 150 Multifractality became a new way for Turvey to understand how the organism might shift its attention, making quick
 151 and agile shifts in using the same tissues to accomplish different perceptual feats.

152 **1.3.1 Postural stance in support of searching for Stroop-incongruent words**

153 To ensure that this research question is worthy of the scholar who inspired it, we aim to clearly articulate how it honors
 154 the complementarity between law and constraint—an idea fundamental to Turvey's ecological-psychological approach
 155 (Pattee, 1974; Turvey, 1992). On the lawful side, multifractal dynamics reflect nonlinear flows unfolding across all scales
 156 without being tied to a native scale of measurement (e.g., Kugler and Turvey, 2015; Warren, 1984). On the constraint
 157 side, enabling constraints shape bodily capacity for movement as well as the task settings that support it (Baggs et al.,
 158 2020; Raja and Anderson, 2021). Our participants stood upright while performing a word-recognition task designed as
 159 a word search. This choice avoids the representational challenges inherent in distinguishing words, non-words, and
 160 pseudowords. At the same time, it still probes single visual word recognition by requiring participants to use word
 161 status and meaning to identify the correct target. A search task also facilitates the exploration of connections between
 162 posture and word recognition because postural constraints, such as stance width, influence search performance (Mitra
 163 and Fraizer, 2004). In particular, we examined postural constraints under four settings: a self-selected comfortable
 164 stance width, a restrained stance in which the participant stands with their back against a vertical surface, a narrow
 165 stance, and a wide stance. This restraint against a surface does not address stance width, but it does appear important in
 166 limiting the exploratory possibilities of postural sway for perceiving structure in the ambient layout of surfaces (Mark
 167 et al., 1990).

168 Beyond the strictly bodily constraints, we must also consider the task constraints. The task we have chosen to probe
 169 visual word recognition might have appealed to Turvey's love of tradition. He sought with Rhodes to probe for fractal
 170 dynamics in the traditional Bousfield and Sedgewick's (1944) paradigm of categorical free recall (Rhodes and Turvey,
 171 2007). Now, we take our multifractal-tensegrity inquiry yet deeper into the psychological canon to Stroop's (1935)

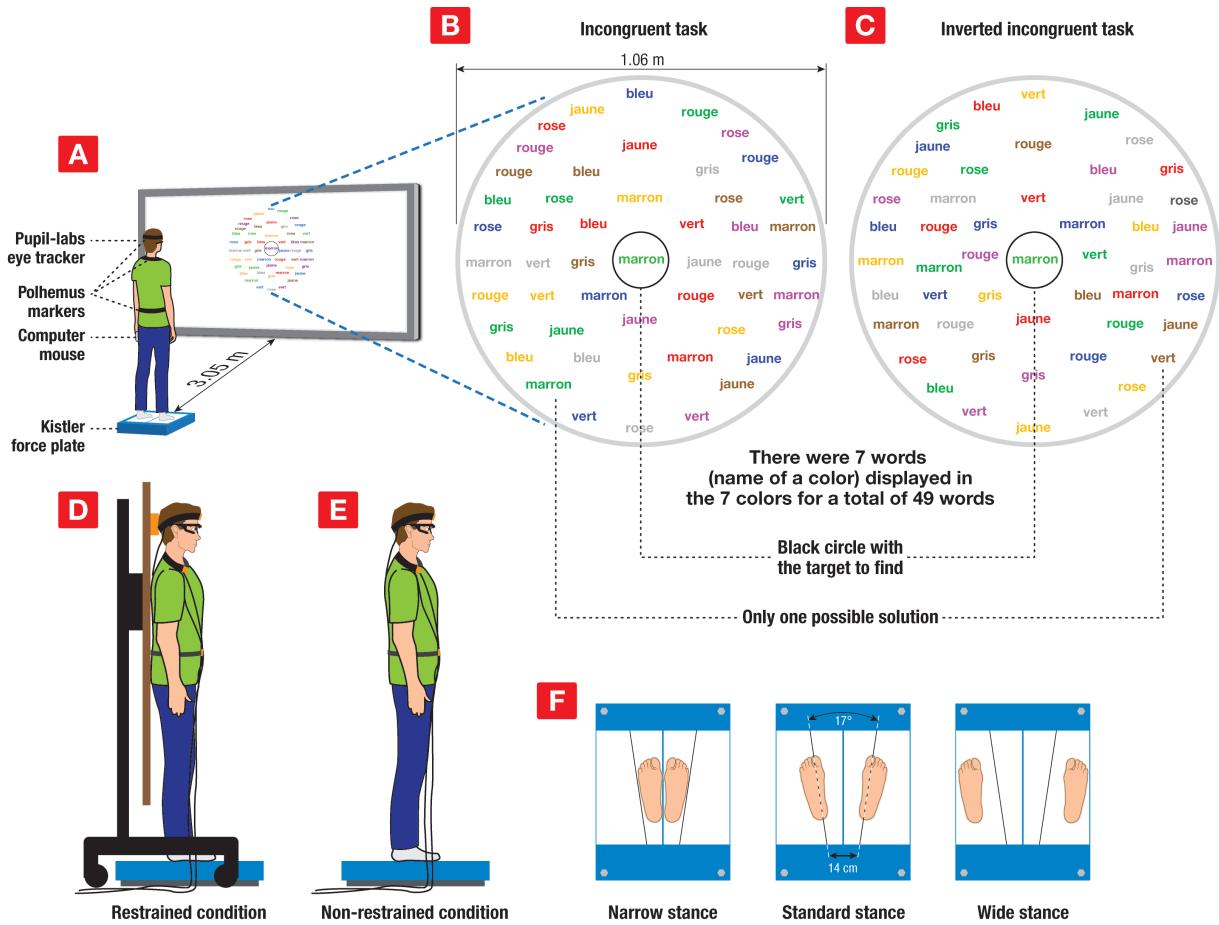


Figure 1: Experimental setup and task conditions. (A) Participants stood on a force plate while performing a visual search task. Eye movements were tracked using an eye tracker, and active markers recorded body motion. A computer mouse was used for target selection. (B) In the incongruent task, participants 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.

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

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

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

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

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

- 222 • Our first hypothesis predicted that successful search performance would be associated with lower multifractal
 223 nonlinearity t_{MF} , measured as the t -statistic comparing the original multifractal spectrum width to that of its linear
 224 surrogates, in center-of-pressure (CoP) displacements (Hypothesis 1).
- 225 • This relationship should be strongest when constraints further restrict movement degrees of freedom, such as a
 226 narrower stance (Hypothesis 2a), a target appearing in a smaller circle (Hypothesis 2b), or their interaction (Hypothesis
 227 2c). It is true that a narrower stance will prompt instability, but that is precisely the sense in which a narrower stance
 228 prompts the postural system to constrain its degrees of freedom. The reduction of multifractal nonlinearity is a
 229 protective response constraining degrees of freedom when posture is less stable.
- 230 • Conversely, when a vertical surface constrains posture, the system must free some degrees of freedom elsewhere to
 231 allow exploration. We, therefore, anticipated a reversal of the earlier relationship: a compensatory rise in multifractal
 232 nonlinearity, indicating that the postural system has expanded its capacity for exploratory movement. In this scenario,
 233 better search performance should coincide with higher multifractal nonlinearity t_{MF} at parts of the body that retain
 234 more freedom to move than the CoP. Specifically, pressing the back against a vertical surface shifts the search-
 235 promoting multifractal fluctuations toward the clavicle, head, or eyes. However, because overall movement is more
 236 restricted, this benefit might only appear for the smallest circle of the visual display (Hypothesis 3).
- 237 • Finally, we expected that searching for an inversion of the priming word's incongruence would promote more
 238 constrained search patterns, likely benefiting from reduced multifractal nonlinearity. However, as suggested above,
 239 the inverted task would also favor better search performance when reductions in multifractal nonlinearity occur
 240 at upper-body anatomical locations within the postural system (Hypothesis 4a). This hypothesis also warranted

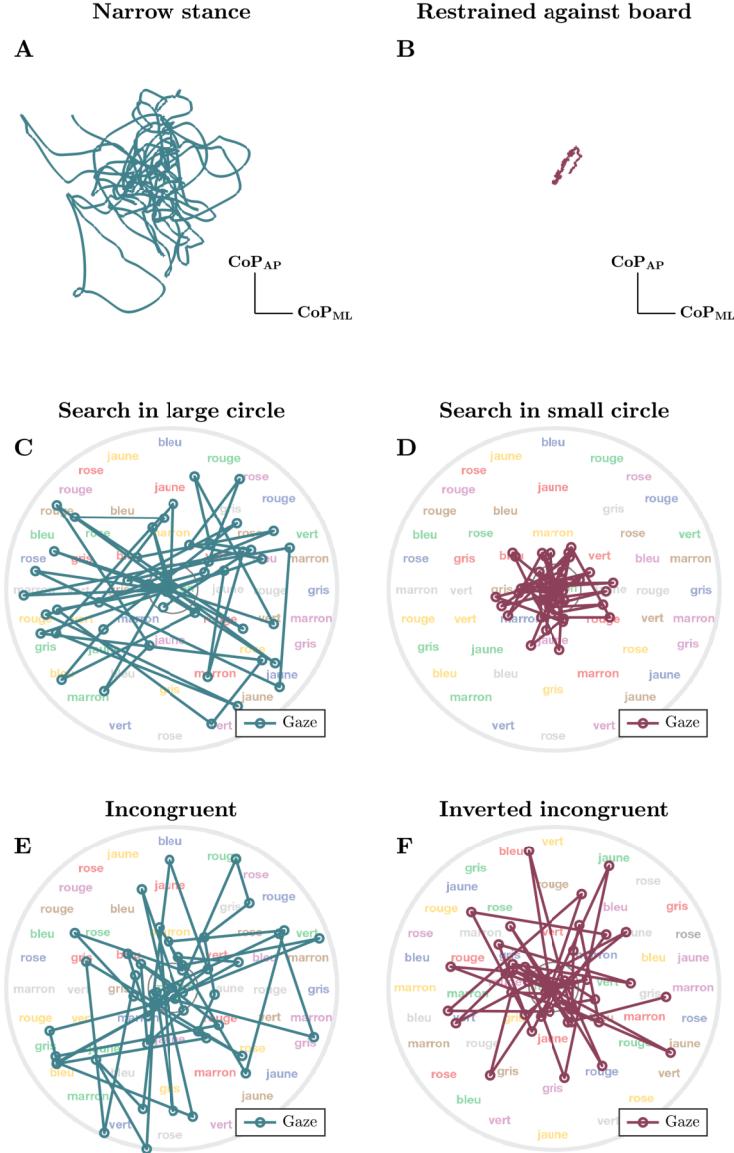


Figure 2: Hypothesis comparisons of postural sway and gaze behavior across postural and task conditions. (A–B) Postural sway in narrow vs. constrained stance: The center of pressure (CoP) trajectory is expected to be more constrained in the restrained condition (B) compared to the narrow stance (A), 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.

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

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

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

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

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

276 2 Methods

277 2.1 Participants

278 Twenty-one healthy students (7 women; $M \pm SD$ age: 22.4 ± 2.2 years; body mass: 66.1 ± 14.0 kg; height:
 279 170.9 ± 8.9 cm from the University of Lille participated in this study. All participants provided their informed written
 280 consent to participation approved by a local ethical committee (Study No. 2021-546-S100). All participants diligently
 281 wore masks and willingly signed a comprehensive document addressing their responsibility in light of the ongoing
 282 COVID-19 pandemic.

283 2.2 Experimental setup and visual search task

284 During the experimental sessions, the participants positioned themselves 3.05 m in front of a large flat display (custom-
 285 made mobile image wall by Antycip, 4 stereo 120 Hz with 4 Canon video-projectors; height: 2 m; width: 4 m;
 286 **Figure 1**). This display presented a circular image (radius: 0.53 m; visual angle: 20° at eye level, directly in front of
 287 the participants. Within this circular image, a central priming word appeared within a small black circle, surrounded by
 288 49 words arranged in three virtual circles (**Figure 1A**). This priming word was a color word printed in an incongruent
 289 color in the spirit of Stroop (1935), for example, the word "blue" written in red. The objective was to use the priming
 290 central word to find a unique target word among the 49 surrounding words consisting of seven color words (that is,
 291 blue, green, red, brown, pink, gray, and yellow), each displayed in one of the seven colors. There were two task
 292 settings: as elaborated below, one task setting involved finding a target word that was the same as the priming word,
 293 printed in the same incongruent color, and the other task setting involved finding an incongruously colored target word
 294 with the inverse incongruence, for example, priming with the word "blue" written in red prompted the participant
 295 to find the word "red" written in blue. The small, medium, and large virtual circles contained 8, 16, and 25 words,
 296 respectively. Subsequent modeling encoded these different virtual circles as the variable *CircleSize* with values

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

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

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

317 2.3 Visual task manipulation

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

337 2.4 Postural manipulation

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

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

352 **2.5 Experimental procedure**

353 The participants participated in eight experimental conditions, with two trials conducted for each condition, which is
 354 16 trials per participant. To maintain consistency, the order of the eight conditions and the sequence of the 16 images
 355 were randomized for each participant. However, the two trials per condition were presented consecutively in a blocked
 356 fashion to prevent frequent changes in the experimental design. The total number of correct searches was recorded in
 357 each trial, serving as a performance measure for each combination of manipulation of visual and postural tasks.

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

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

376 **2.5.1 Dependent measures**

377 The primary dependent measure we sought to statistically model and explain was the total number of correct targets
 378 found N_{found} . We confirmed this by visual inspection of videos of the gaze position during each trial. We standardized
 379 this measure to control for inevitable variations across the concentric circles. The smallest, medium, and largest circle
 380 contained 8, 16, 25 possible targets, so we calculated N_{SFound} as N_{found} , $N_{\text{found}}/2$, and $N_{\text{found}}/3.125$ for the smallest,
 381 medium, and largest circles. We modeled this performance measure regarding the visual and postural task manipulations
 382 and the multifractal nonlinearity of endogenous movement variability. We collected six concurrent measurements
 383 to model how bodily fluctuations and exploration moderated the effect of *InvertedTask* and *PosturalCondition*.
 384 First, we measured the time intervals between consecutive search responses. We summarized these inter-response
 385 intervals with their arithmetic mean IRI_{mean} , expecting that this average response latency would indicate mental
 386 effort or “processing” load for the decision process in interpreting visual stimuli as in previous literature (Parr et al.,
 387 2023). Second, third, and fourth, we measured the 3D position displacement time series of Head, Clavicle (using the
 388 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
 389 and sixth, we measured the CoP displacement time series $x_{\text{CoP}}(t)$ and the 2D gaze displacement time series $x_{\text{gaze}}(t)$
 390 from the coordinates on the force platform and the viewed projector screen, respectively, at 120 Hz. These measures
 391 appeared in subsequent modeling as moderators of the task covariates’ higher-order interaction *PosturalCondition* \times
 392 *Task* \times *CircleSize*. Given our stated interests in testing hypotheses about cascade dynamics in bodily exploration
 393 through operationalization by multifractal nonlinearity t_{MF} , we used Euclidean displacements of consecutive points in
 394 the second through sixth series for estimating the multifractal spectrum and the amount of multifractality attributable to
 395 nonlinear correlations. The inter-response interval series was too short for multifractal analysis, but as noted below,
 396 later modeling drew on IRI_{mean} in formally similar ways as it drew on the multifractal nonlinearity estimates for the
 397 more continuous bodily measurements that are, $t_{\text{MF,head}}$, $t_{\text{MF,clavicle}}$, $t_{\text{MF,trunk}}$, $t_{\text{MF,CoP}}$, and $t_{\text{MF,gaze}}$.

398 **2.5.2 Signal processing**

399 Dexterous postural control relies on a hierarchy of distinct mechanisms operating across multiple temporal and neural
 400 scales. These mechanisms include short-latency reflexes (SLRs), long-latency reflexes (LLRs), and compensatory
 401 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 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 (Duyens 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 α (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 μ -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

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

436 For values of q yielding a strong relationship between Eqs. (5 & 6)—in this study, correlation coefficient $r > 0.95$, the
 437 parametric curve $\{\alpha, f(\alpha)\}$ constitutes the multifractal spectrum, and $\Delta\alpha = \alpha_{\max} - \alpha_{\min}$ constitutes the multifractal
 438 spectrum width. This use of r ensures only estimates of α and f compose the multifractal spectrum when representing
 439 equally strong scaling relationships. We computed the multifractal-spectrum width $\Delta\alpha$ for the Euclidean displacement
 440 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 $x_{\text{gaze}}(t)$.

441 2.6.2 Assessing multifractality due to nonlinearity using surrogate testing

442 To identify whether a nonzero $\Delta\alpha$ reflects multifractality due to cascade-like interactivity, $\Delta\alpha$ for the original time
 443 series is compared to $\Delta\alpha$ for 32 Iterated Amplitude Adjusted Fourier Transform (IAAFT) surrogates (Ihlen, 2012;
 444 Schreiber and Schmitz, 1996). IAAFT randomizes original values time-symmetrically around the autoregressive
 445 structure, generating surrogate time series that randomize phase ordering of the original series' spectral amplitudes
 446 while preserving linear temporal correlations. The one-sample t -statistic (henceforth, t_{MF}) takes the subtractive
 447 difference between $\Delta\alpha$ for the original series and the 32 surrogates, dividing by the standard error of the spectrum width
 448 for the 32 surrogates; the greater the value of t_{MF} , the greater the multifractality in the original series due to nonlinear as
 449 opposed to linear sources. As noted above, we used multifractal-spectrum width $\Delta\alpha$ for $x_{\text{CoP}}(t)$, $x_{\text{head}}(t)$, $x_{\text{clavicle}}(t)$,
 450 $x_{\text{trunk}}(t)$, and $x_{\text{gaze}}(t)$ from the prior step and computed $\Delta\alpha$ as well for phase-randomized linear surrogates of these
 451 time series. The comparison of $\Delta\alpha$ for each original series to 32 of its corresponding surrogate time series allowed
 452 calculating $t_{\text{MF,CoP}}$, $t_{\text{MF,head}}$, $t_{\text{MF,clavicle}}$, $t_{\text{MF,trunk}}$, and $t_{\text{MF,gaze}}$.

453 2.7 Statistical analysis

454 2.7.1 Modeling search performance

455 We used a linear mixed-effect model in R (R Core Team, 2024) using the function `lmer()` from package “lme4” (Bates
 456 et al., 2009) observing an alpha level of 0.05 for significant testing using package “lmerTest” (Kuznetsova et al., 2017).
 457 We used this procedure to model the dependent measure of the circle-standardized correct number of targets found
 458 N_{Found} as a weighted sum of predictors (**Supplementary Dataset S1 & Model S1**). Linear regression modeling
 459 estimated a coefficient b for each predictor, indicating the average change in N_{Found} with a unit increase in the predictor
 460 value, and each coefficient had a corresponding *s.e.* term indicating the variability of the change due to the predictor.
 461 Modeling proceeded through three major steps. First, it began with six families of interaction, respecting the five
 462 estimates of multifractal nonlinearity t_{MF} at each of the five measurement locations on the body $t_{\text{MF,CoP}}$, $t_{\text{MF,head}}$,
 463 $t_{\text{MF,clavicle}}$, $t_{\text{MF,trunk}}$, and $t_{\text{MF,gaze}}$ as well as one estimate of speed through the average inter-response-interval
 464 IRI_{mean} defined as the average of the time intervals between each successive mouse click. We fit interactions of
 465 each of these predictors with the higher order interaction $PosturalCondition \times Task \times CircleSize$. In the second
 466 step, we trimmed all higher-order interactions that failed to meet the $p < 0.05$ benchmark for significance. Third, to
 467 acknowledge the fact that multifractal fluctuations at different measurement locations might interact, we included any
 468 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
 469 ensuring that the final model satisfied the convention of requiring a minimum of 10 observations per predictor (Babyak,
 470 2004; Troutt, 2004).

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

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

476 This model selection strategy prioritizes multifractal nonlinearity over incorporating more straightforward and familiar
 477 measures of variability within the same model. By exploring its interactions across a comprehensive marker set, the
 478 approach provides a nuanced perspective on how multifractal effects propagate across different body parts and depend
 479 on postural width, task complexity, and specific spatial subsets of the search area while also remaining constrained
 480 by the 10-observation-per-predictor limit, leaving little room for additional interactions with conventional variability
 481 measures. Previous research with fewer task parameters has included fluctuation series' mean and standard deviation
 482 (*s.d.*) alongside fractal and multifractal metrics within the same models (Kelty-Stephen and Dixon, 2014; Stephen
 483 et al., 2010; Stephen and Hajnal, 2011). For example, a single model could include *mean* * *Trial* and *t_{MF}* * *Trial*,
 484 allowing the regression model to assess the relative strength of these terms. However, our emphasis on capturing the
 485 rich interactions of multifractal nonlinearity across the extensive task parameters precluded the simultaneous inclusion
 486 of more familiar measures of variability in this modeling approach. However, we ran alternate models demonstrating
 487 that regression modeling performed more effectively using multifractal variability metrics than traditional variability
 488 measures such as *s.d.*. Specifically, we modified our final model to create three alternative versions, each replacing *t_{MF}*
 489 with a different metric. One model substituted Mean for *t_{MF}* in both its main effect and all comparable interactions,
 490 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
 491 values for the *mean* and *s.d.* models were both higher than those for the multifractal-nonlinear model, indicating
 492 weaker model fits: the Mean model had AIC and BIC values 17.147 and 17.147 points higher, respectively, while
 493 the *s.d.* model had values 13.450 and 13.450 points higher, supporting the superior fit of the multifractal-nonlinearity
 494 model (Burnham and Anderson, 2004).

495 The raw multifractal model using $\Delta\alpha$ was comparably stronger than the models dedicated to more traditional measures
 496 of variability, and it had only negligible differences from the multifractal-nonlinearity model. It did have lower AIC and
 497 BIC than the multifractal-nonlinearity model using *t_{MF}* and not $\Delta\alpha$, that is, a marginal difference of 5.152 and 5.152,
 498 respectively. This difference suggests minuscule improvements in the fit of the raw-multifractal model, but we do not
 499 report this model for theoretical and empirical reasons. First, the present work aims to speak specifically to the nonlinear
 500 interactivity across scales of activity in the perceptual system. So, we prefer to address our modeling and remarks
 501 specifically on the nonlinear components of the multifractal results. Besides that primary goal, the interpretability of raw
 502 multifractal spectrum width is classically rife with confusion and ambiguity because, although multifractal geometry
 503 was designed to explain nonlinear dynamical processes, empirical estimates of multifractal spectrum width are sensitive
 504 to linear features of measurements contributing to those estimates (Veneziano et al., 1995). In a sense, although it does
 505 not include any $\Delta\alpha$ terms, our multifractal-nonlinearity model does already control for the linear features because the
 506 multifractal-nonlinearity metric we use *t_{MF}* expresses significant difference from spectrum widths for a set of linear
 507 surrogates. Our second reason for neglecting to pursue the raw-multifractal model is that, besides its theoretical opacity
 508 about nonlinearity, a difference in AIC or BIC less than 6 is insufficient to reject one model for another (Richards,
 509 2005, 2008). So, though the differences greater than 10 between models with multifractal metrics and non-multifractal
 510 metrics is a compelling reason to prefer the multifractal treatments, the empirical differences in AIC and BIC are not
 511 sufficient to outweigh the theoretical reasons for focusing our attention on the multifractal-nonlinearity model.

512 2.7.2 Manipulation check on root-mean-square of gaze fixations

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

522 2.7.3 For testing for any differences in multifractal nonlinearity for Non-Hypothesis 1

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

Table 1: Significant effects from the linear mixed-effects model¹ 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_{Found} .

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_{TC2}</i>	$-8.538 \times 10^0 \pm 1.228 \times 10^0$	-6.953	6.360×10^{-12}
<i>IRI_{mean}</i>	$-2.564 \times 10^0 \pm 2.612 \times 10^{-1}$	-9.813	$< 2.000 \times 10^{-16}$
<i>CircleSize_{small} : IRI_{mean}</i>	$-8.381 \times 10^{-1} \pm 3.687 \times 10^{-1}$	-2.273	0.023
<i>InvertedTask_{TC2} : IRI_{mean}</i>	$1.910 \times 10^0 \pm 2.637 \times 10^{-1}$	7.242	8.960×10^{-13}
<i>InvertedTask_{TC2} : CircleSize_{small}</i>	$-4.784 \times 10^0 \pm 1.416 \times 10^0$	-3.378	0.001
<i>InvertedTask_{TC2} : CircleSize_{small}</i>	$1.012 \times 10^0 \pm 3.719 \times 10^{-1}$	2.722	0.007
<i>IRI_{mean}</i>			
<i>InvertedTask_{TC2}</i>	$3.738 \times 10^0 \pm 1.481 \times 10^0$	2.524	0.012
<i>PosturalCondition_{PCond2}</i>	:		
<i>CircleSize_{small}</i>			
<i>t_{MF,CoP}</i>	$-3.036 \times 10^{-2} \pm 1.544 \times 10^{-2}$	-1.967	0.049
<i>PosturalCondition_{PCond3}</i>	$-7.530 \times 10^{-2} \pm 3.003 \times 10^{-2}$	-2.507	0.012
<i>CircleSize_{small} : t_{MF,CoP}</i>			
<i>PosturalCondition_{PCond2}</i>	$9.235 \times 10^{-3} \pm 3.849 \times 10^{-3}$	2.423	0.016
<i>CircleSize_{small} : t_{MF,head} : t_{MF,clavicle}</i>	$3.145 \times 10^{-2} \pm 1.019 \times 10^{-2}$	3.086	0.002
<i>InvertedTask_{TC2} : t_{MF,CoP}</i>	$-6.696 \times 10^{-2} \pm 3.313 \times 10^{-2}$	-2.021	0.044
<i>InvertedTask_{TC2}</i>	$1.935 \times 10^{-1} \pm 6.769 \times 10^{-2}$	2.858	0.004
<i>PosturalCondition_{PCond2}</i>	:		
<i>CircleSize_{small} : t_{MF,head}</i>			

¹ $N_{\text{Found}} \sim t_{\text{MF,head}} * \text{PosturalCondition} * \text{InvertedTask} * \text{CircleSize} + (t_{\text{MF,head}} * t_{\text{MF,clavicle}}) * (\text{InvertedTask} + \text{CircleSize} + \text{PosturalCondition} * \text{CircleSize}) + t_{\text{MF,CoP}} * (\text{PosturalCondition} * \text{CircleSize} + \text{InvertedTask} + \text{PosturalCondition} + \text{CircleSize}) + (\text{PosturalCondition} * \text{InvertedTask} + \text{CircleSize}) + t_{\text{MF,clavicle}} * (\text{PosturalCondition}) + \text{InvertedTask} * \text{CircleSize} * \text{IRI}_{\text{mean}} + \text{PosturalCondition} * \text{InvertedTask} * \text{CircleSize} + (1|\text{Participant} * \text{CircleSize})$.

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

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

533 3 Results

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

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

540 3.1 Greater difficulty and longer search times for inverted-incongruent targets

541 First, the standardized number of targets found (N_{Found}) was significantly lower in the more difficult inverted-
 542 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_{Found} was also
 543 significantly lower for participants who, on average, exhibited longer intervals between mouse clicks ($b = -2.564 \times$
 544 $10^0 \pm 2.612 \times 10^{-1}, t = -9.813, p < 2.000 \times 10^{-16}$). This result reflects the expected relationship between faster search

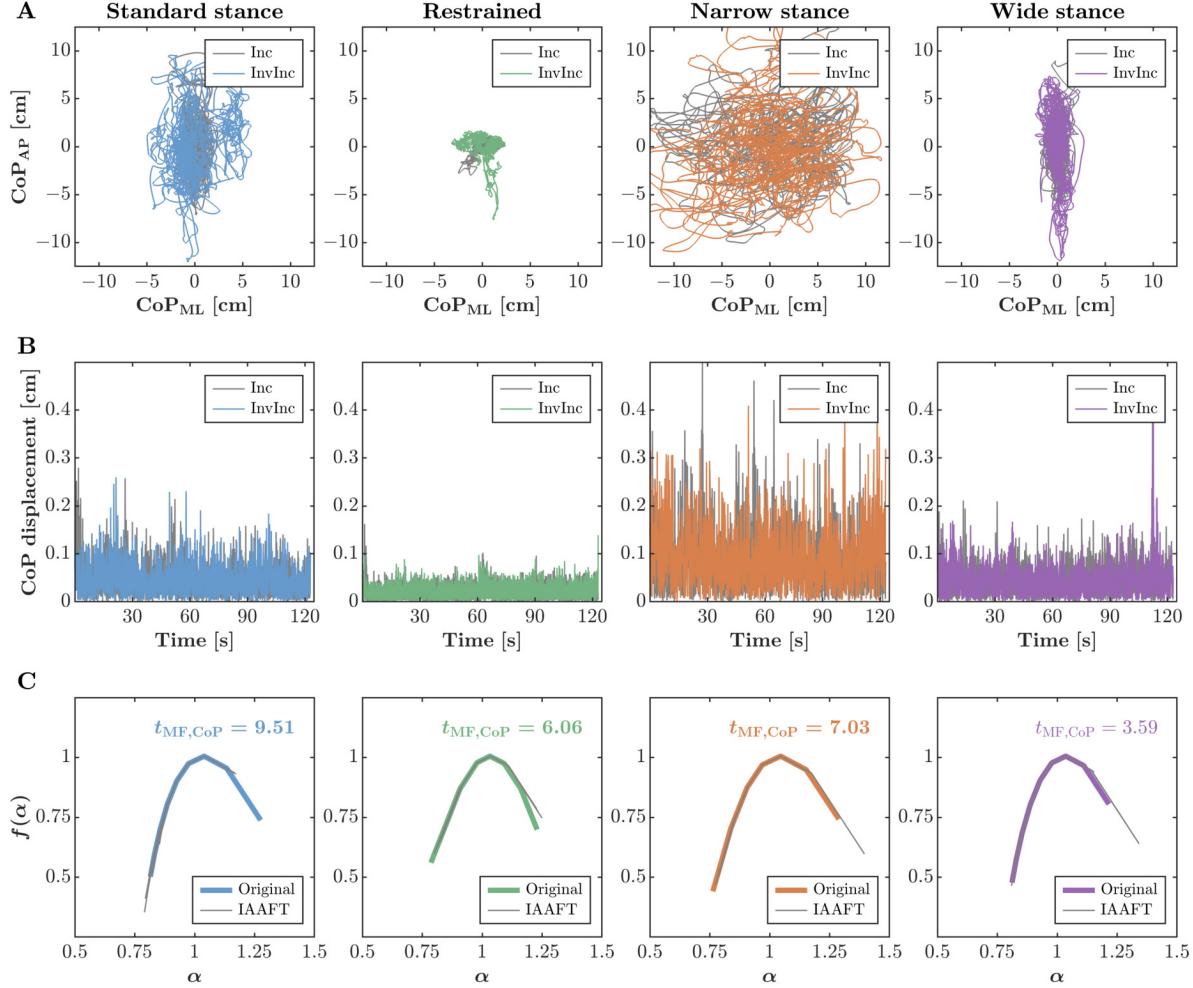


Figure 3: Center of posture (CoP) dynamics under different stance conditions (Standard, Restrained, Narrow, and Wide) for the two search task conditions (Incongruent and Inverted incongruent) for a single participant. (A) CoP trajectories for each stance condition along the anteroposterior (AP) vs. mediolateral (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.

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

548 **3.2 Heightened difficulty in searching for inverted-incongruent targets in the smallest circle, mitigated by**
 549 **narrow stance, and nullified associations with click speed**

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

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

557 **3.3 Multifractal nonlinearities in the postural system drive search performance variations across task settings**

558 **3.3.1 Hypothesis 1: Search in comfortable stance improved with reductions of CoP multifractal nonlinearity**

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

564 **3.3.2 Hypothesis 2: Search in narrow stance improved with reductions of CoP multifractal nonlinearity,
 565 particularly for search in the smallest circle**

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

570 **3.3.3 Hypothesis 3: Search with stance restrained against a vertical surface improved with compensatory
 571 increase in upper-body multifractal nonlinearity**

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

577 **3.3.4 Hypothesis 4: Inverted-incongruent search improved with reductions of upper-body multifractal
 578 nonlinearity**

579 This negative relationship between CoP multifractal nonlinearity and search performance disappeared in the inverted-
 580 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
 581 Hypothesis 4a, better inverted-incongruent search performance co-occurred with reduced multifractal nonlinearity at
 582 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
 583 4b, after we removed four trials in which participants looked off the display and generated *rms* values more than 3
 584 standard deviations from the mean *rms*, our linear mixed-effect model of *rms* returned only a significant effect of
 585 *InvertedTask*. This effect was negative, confirming that the inverted-incongruent task did elicit gaze that returned
 586 more often to the center to consult the priming word ($b = -20.228 \times 10^0 \pm 8.933 \times 10^0, t = 2.264, p = 0.024$);
 587 **Figure 4**). We found no significant effects of *PosturalCondition* or *Trial* or any interaction among these factors.
 588 Compounding the inverted task setting with postural restraint against a vertical surface accentuated these effects: the
 589 inverted-incongruent task with a restrained posture further strengthened the positive relationships between upper-body
 590 multifractal nonlinearity and search performance. Specifically, as predicted by Hypothesis 4c, restraining stance
 591 against the vertical surface led to stronger inverted-incongruent search performance in the small circle with increases in
 592 multifractal nonlinearity at the head, $t_{MF,head}$ alone ($b = 1.935 \times 10^0 \pm 6.769 \times 10^{-1}, t = 2.858, p = 0.004$).

593 **3.3.5 Non-hypothesis 1: Multifractal nonlinearity was often negative, higher for CoP, increased with the wide
 594 stance, and increased only in the upper body in the restrained condition**

595 **Figure 5** presents what initially seems an alarming profile of the t_{MF} values: often negative. The linear mixed-effect
 596 model on t_{MF} values indicated a significant positive effect of the wide stance, suggesting that widening the stance allows
 597 for the release of degrees of freedom while completing search tasks ($b = 2.971 \times 10^0 \pm 1.412 \times 10^0, t = 2.104, p =$
 598 0.036). We also observed significant negative effects on all postural positions except for CoP, indicating that CoP
 599 exhibits significantly greater multifractal nonlinearity compared to the head ($b = -24.804 \times 10^0 \pm 1.412 \times 10^0, t =$
 600 $-17.571, p < 2 \times 10^{-16}$), clavicle ($b = -23.335 \times 10^0 \pm 1.412 \times 10^0, t = -16.530, p < 2 \times 10^{-16}$), and trunk

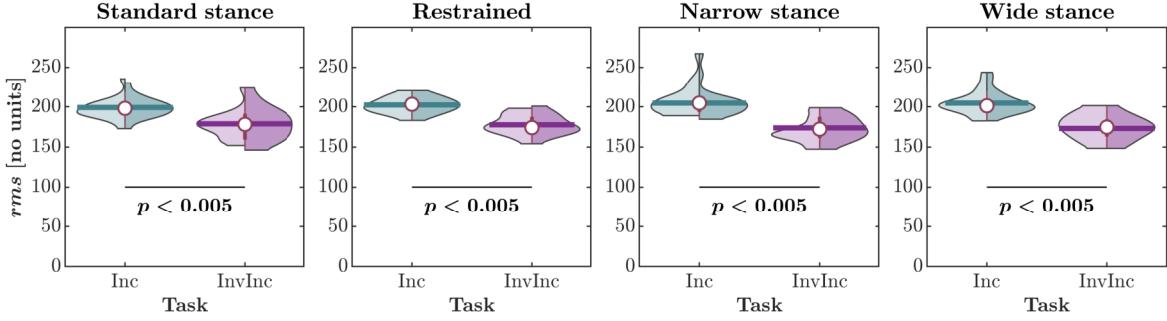


Figure 4: Violin plots showing the root-mean-square (rms) values under different stance conditions (Standard, Restrained, Narrow, and Wide) for the two search task conditions (Incongruent and Inverted incongruent). Each plot displays the distribution of rms values, with white markers indicating the median 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).

601 ($b = -23.300 \times 10^0 \pm 1.412 \times 10^0, t = -16.505, p < 2 \times 10^{-16}$) during the search task. Lastly, restraining
 602 posture against a vertical surface appears to elicit a compensatory increase in multifractal nonlinearity at the head
 603 ($b = 5.496 \times 10^0 \pm 1.996 \times 10^0, t = 2.753, p = 0.006$) and at the clavicle ($b = 4.509 \times 10^0 \pm 1.996 \times 10^0, t =$
 604 $2.258, p = 0.024$).

605 4 Discussion

606 We tested four hypotheses in a task that human participants completed by visually searching for Stroop-like color words
 607 printed in an incongruent color among concentric circles while standing upright (see **Figure 1**). **Figure 3** depicts the
 608 diversity of postural outcomes during different stances: standard stance, restrained, narrow stance, and wide stance. The
 609 multifractal signatures of CoP showed general support for the idea that The hypotheses addressed the possibility that
 610 successful visual word search might be sensitive to how the manipulated postural and task constraints interacted with
 611 the endogenous signatures of tensegrity-like multifractal nonlinearity in the upright posture. The first hypothesis was
 612 that search performance with a comfortable stance would improve with reductions in CoP multifractal nonlinearity,
 613 signifying a constraint of degrees of freedom to focus attention. The second hypothesis was that search performance
 614 might improve with a further reduction in CoP multifractal nonlinearity, particularly with a narrow stance (Hypothesis
 615 2a), for targets in the smallest circle (Hypothesis 2b), and for the interaction of the narrow stance with the smallest-circle
 616 targets (Hypothesis 2c). The third and fourth hypotheses addressed how experimental postural and task constraints
 617 could highlight the association of multifractal nonlinearity with single-word recognition at relatively upper-body points
 618 in the postural system. The third hypothesis was that search performance would improve in narrower circles when
 619 upper-body multifractal nonlinearity increased to compensate for the surface-restrained stance. The fourth hypothesis
 620 was that search performance for the inversion of the priming Stroop-type incongruence would improve with reduced
 621 multifractal nonlinearity (e.g., as in Hypothesis 1) farther up in the postural system than at the CoP (Hypothesis 4a). A
 622 manipulation check confirmed that, yes, the inverted-incongruent search involved constraint of the point of eye gaze
 623 towards the center, promoting less rms (Hypothesis 4b). However, we predicted that a surface-restrained stance would
 624 show the same improvement in inverted-incongruent search with compensatory increases in upper-body multifractal
 625 nonlinearity as in non-inverted search (Hypothesis 4c). Results supported all of the hypotheses except for Hypotheses
 626 2a and 2b (see **Table 1**).

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

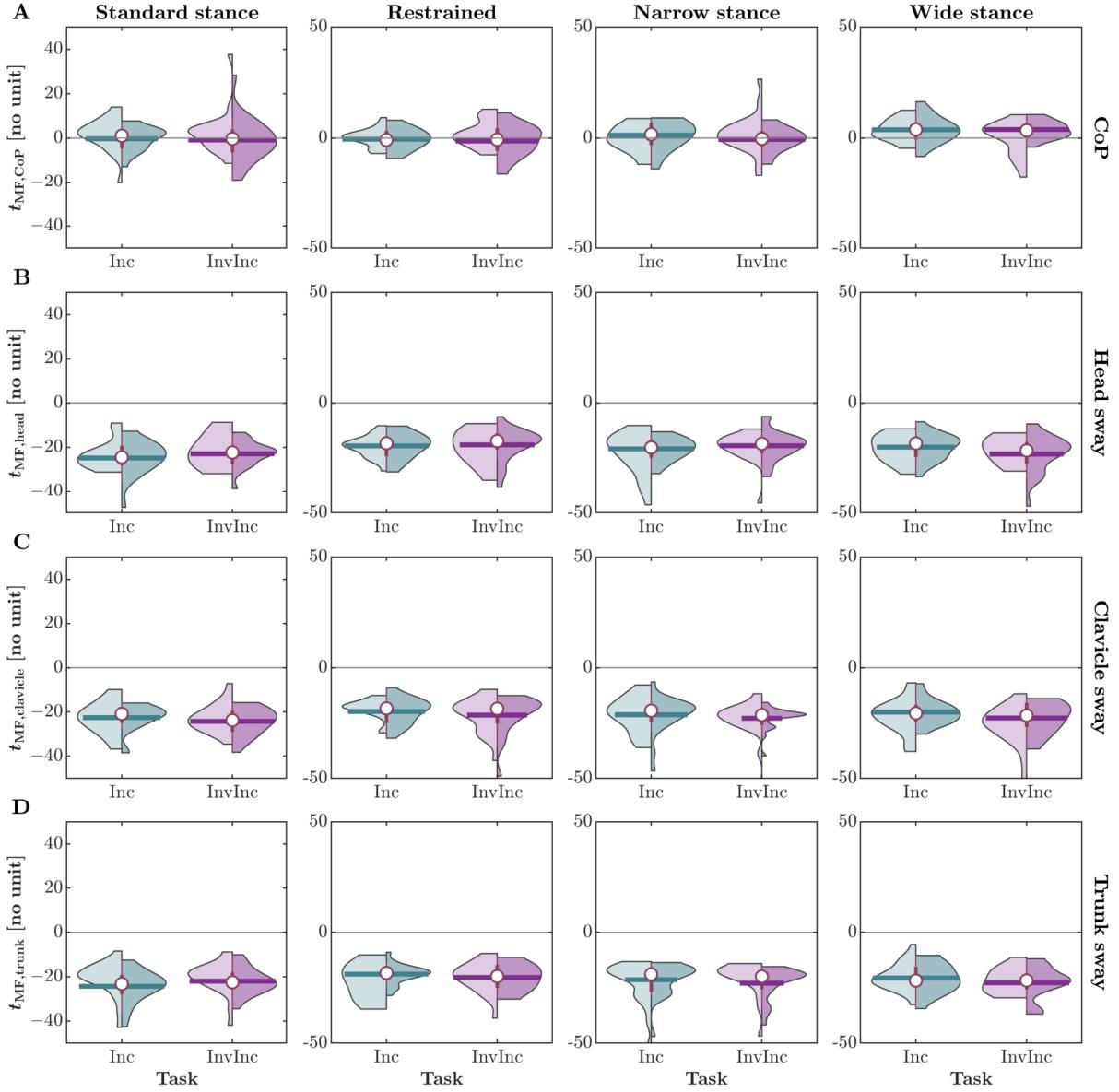


Figure 5: Violin plots showing the multifractal nonlinearity (t_{MF}) values for CoP and head, clavicle, and trunk sway under different stance conditions (Standard, Restrained, Narrow, and Wide) for the two search task conditions (Incongruent and Inverted incongruent). Each plot displays the distribution 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).

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

646 movement coordination principles. If nonlinearity only amplified variability, there would be no meaningful analog
 647 between multifractal tensegrity and Bernstein's (1996) foundational framework on movement coordination as a problem
 648 of degrees of freedom. And let us be clear: Turvey sought to preserve this analogy (Profeta and Turvey, 2018; Turvey,
 649 2007; Turvey and Fonseca, 2009, 2014).

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

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

676 4.1 Steps toward a tensegrity-based view of single-word reading

677 We can summarize our findings as follows. Visual-word recognition may rely on the same postural-sway dynamics
 678 that support visual perception more broadly (Riccio and Stoffregen, 1991; Balasubramaniam et al., 2000). Postural
 679 control involves both the release and the constraint of postural degrees of freedom. Focusing visual attention on a
 680 display full of words requires drawing inward degrees of freedom that stabilize the stance and maintain visual contact
 681 with a display of potential targets. We propose that the bodywide multifractal tensegrity hypothesis (Turvey et al.,
 682 2014)—suggesting that multifractality arises from nonlinear interactions—may provide a useful lens for examining
 683 the release of degrees of freedom. The constraint of degrees of freedom necessary to maintain a stable stance or focus
 684 appears to co-occur with a reduction in multifractal nonlinearity. This relationship was previously observed in postural
 685 control during upright standing (Kelty-Stephen, 2018; Kelty-Stephen et al., 2021), and now it appears to hold for stance
 686 during visual word search. The constraints on posture and the distance of the target word from the centrally located
 687 prime can accentuate this relationship. Neither constraint alone necessarily ensures the successful search for a single
 688 word, as effective recognition relies on a broader system of interactions. The organism-wide focus on single-word
 689 recognition depends on multifractal tensegrity to coordinate nonlinear interactions, with experimental manipulations
 690 that constrain both mechanical and visual aspects further highlighting the link between accurate search performance
 691 and reduced multifractal nonlinearity.

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

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

707 **4.2 Limitations and future directions: Seeking an explanation of perception-action first and multifractality as a
 708 distant second**

709 Important limitations on the present work can highlight the future directions that this work might inform. First,
 710 single-word recognition is a scant tip of the iceberg, and searching for an individual word is a narrow subdomain of
 711 how we use words—all the more narrow for only addressing color words. Future work should press the application
 712 of the multifractal tensegrity hypothesis in reading behaviors more broadly, for example, to narrative text as well as
 713 to word-recognition situations in the built world that we all navigate through. Additionally, expanding the scope of
 714 inquiry to include linguistic contexts that involve ambiguity, metaphor, and syntactic complexity could provide deeper
 715 insights into the interaction between cognitive dynamics and reading behavior. It would be worth revisiting the classical
 716 lexical-decision paradigms from the other side of the ecological/cognitive divide. Deploying even non-ecological
 717 tasks is not a typical penchant of ecological psychologists, but it would only strengthen the ecological, psychological
 718 program if we could deflate the representationalist account of its most cherished psycholinguistic paradigms. Beyond
 719 any fears of a pitched battle across this divide, traditional information-processing perspectives on single-word reading
 720 are hungry for formalisms that might explain and predict some of the slipperiness in language use (e.g., Magnuson,
 721 2007). Non-ecological psychologists are realizing the nonlinearities and impredicativities in their psycholinguistic work,
 722 addressing the multifunctionalities of individual components and processes in often the same terms (e.g., “pleiotropy”
 723 and “nondeterminism”) that Turvey and colleagues invoked when showcasing the difficulty of simple mappings between
 724 components and functions (Johnston and Turvey, 1980; Kugler and Turvey, 2015; Turvey et al., 1982). Second, an
 725 upright stance is a limiting case, even with the experimental application of constraints to catch the postural system
 726 in circumstances that might not occur very often in everyday life. We should hope to develop multifractal-tensegrity
 727 models of reading in more diverse postures (e.g., seated and walking) to encompass the greater range of enabling
 728 constraints from movement. Third, this research warrants a natural and necessary extension to dyadic and group
 729 communication, using either speech or written symbols to collaboratively solve problems together in some of the
 730 exciting and innovative paradigms developed by some of Turvey’s most linguistically inclined students (Galantucci,
 731 2005; Shockley et al., 2003).

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

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

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

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

768 4.3 Connecting the clues from Turvey and potentially lighting a path forward for ecological psychology

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

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

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

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

822 **Supplementary material**

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

825

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

828

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

830

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

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

835

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

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850 **Author contributions statement**

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

856 **Competing interests**

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

859 **Data availability**

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

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