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Full Length Article

Multifractal foundations of visually-guided aiming and adaptation to prismatic perturbation

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ABSTRACT

Visually-guided action of tossing to a target allows examining coordination between mechanical information for maintaining posture while throwing and visual information for aiming. Previous research indicates that relationships between visual and mechanical information persist in tossing behavior long enough for mechanical cues to prompt recall of past visual impressions. Multifractal analysis might model the long-term coordinations among movement components as visual information changes. We asked 32 adult participants (6 female, 25 male, one not conforming to gender binary; aged $M = 19.77$, $SD = 0.88$) to complete an aimed-tossing task in three blocks of ten trials each. Block 1 oriented participants to the task. Participants wore right-shifting goggles in Block 2 and removed them for Block 3. Motion-capture suits collected movement data of the head, hips, and hands. According to regression modeling of tossing performance, multifractality at hand and at hips together supported use of visual information, and adaptation to wearing/removing of goggles depended on multifractality across the hips, head, and hands. Vector-autoregression modeling shows that hip multifractality promoted head multifractality but that hand fluctuations drew on head and hip multifractality. We propose that multifractality could be an information substrate whose spread across the movements systems supports the perceptual coordination for the development of dexterity.

1. Introduction

Aiming behavior involves an extension of our haptic capacities of gripping and wielding into what is visually available to us. Hence, the goal of throwing a projectile to a target out of reach recruits the movement system minimally for two subgoals: first, to support ongoing exploration of optical distributions in view and second, to maintain a stable upright posture but extending to the point where the throwing limb releases the projectile. The first subgoal involves visual exploration that is ongoing because either the movement system or the target can move, and the movement system pursues the second subgoal to prevent the unwelcome possibility that the throwing limb could upset the postural balance.

1.1. Mutuality of the subgoals in aimed throwing: Example from the latent aftereffect

The movement system's maintenance of either of these subgoals is likely not independent from maintenance of the other. Movement of the throwing limb plainly takes guidance from visual exploration. Wearing prismatic right-shifting goggles will initially lead to errors because everything in the visual field looks farther to the right than it actually is. So, the movement of the throwing

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limb veers to the right, just where the visual field suggests it should. The visibly-inaccurate trajectory of the projectile prompts the movement system to adapt to this visual change. Initial adaptation to right-shifting goggles, then, involves redirecting throwing movements to the left so as to correct for the visual rightwards shift. Then, when the participant removes the right-shifting goggles, the movement system has built itself the strategy of throwing to the left of what is visually available. Hence, this left-ward error is an initial aftereffect of taking the goggles off after initial adaptation. Adaptations to prismatic distortion and initial aftereffects serve as classic ways to portray how the movement system can use visual information to anchor and, with sudden changes in that visual information, to gradually tailor its movements to changes in visual information.

Less intuitive is the fact that effects of visual impressions appear to linger in the movements of the throwing limb. This latter point follows from research into the "latent" aftereffects in throwing with and then without prismatic right-shifting goggles. Before task context has pressed the movement system into building new relationships among its components, the movement system might only make the right-wards correction when we add the change to the visual field. However, once the participant has experienced the right-shifting goggles, then other, non-visual aspects of that experience can prompt the movement system to make the same correction. For instance, adding a weight to an arm has an immediate downward effect on the direction of throwing movements and actually entails changes in movement at an orthogonal direction. However, if the movement system is wearing a weight on the arm while also wearing right-shifting goggles, then the arm weight alone can become a cue for the movement system to reintroduce those co-ordinations that developed while it was adapting to the right-shifting goggles. Hence, while an arm weight is not a visual stimulus, it can produce movement adaptations that the movement system had learned through recent experience of both the arm weight and the visual-stimulus of the right-shifting goggles. Participants who once wore an arm weight while wearing the goggles appeared to have built a new set of coordinations across visual and mechanical systems above and beyond immediate haptic responses to mechanical stimuli: later reattaching the arm weight alone made participants no longer wearing goggles throw as if they were wearing goggles, and it need only be the application of a once-concurrent haptic perturbation that brings the visually-driven error back (Blau, Stephen, Carello, & Turvey, 2009).

A major entailment of the latent aftereffect is that the many disparate parts of the movement system—the infamous "degrees of freedom" from Bernstein's (1967) articulation of research questions into dexterity—fall into synergies that extend not simply over anatomical space but over time in a task. To review briefly what is more elegantly reviewed elsewhere (Latash, 2008; Turvey & Latash, 1996), Bernstein's degrees of freedom problem addresses the uncertainty that a movement system must surmount whenever it extends outwards into the physical task environment where it can act. The task environment invites possible actions, e.g., a pick-up-able glass on the support surface of a table, a sit-on-able chair (e.g., Gibson, 1979). The movement system needs to translate its intentions (e.g., wanting to take a drink from the glass, wanting to sit down) into actions. No matter what intention the movement system chooses to act on, the major control challenge is the fact that anatomical parts of the movement system vastly outnumber the intentions to act—to say nothing of contingent context-dependent factors that can systematically support, impede, or otherwise modify movement coordination. This imbalance between controllable parts and control intentions leave various parts of the movement system free to vary. Control intentions alone underspecify the movement coordination that results in (hopefully) meeting these intentions, and not all configurations of controllable parts will be successful. Hence the challenge following from the degrees-of-freedom problem is for movement scientists to explain how the movement system collapses the immense uncertainty between intention and successful achievement of that intention. An important strategy has been to articulate hierarchical organization of anatomical parts within synergies, that is, collections of anatomical parts that act together and so reduce the number of dimensions needed for a motor command (Turvey, 2007).

We aim to highlight here that synergies exemplify not just hierarchical organization but hierarchical organizations that change with time. That is, different synergies fall in and out of use depending on the context of available stimulation. Despite the brevity of an action potential in sensory tissues dedicated to a given kind of stimulus energy, the past facts of stimulation persist well beyond the brief action potential and persist even in those tissues that do not respond with the action potential. For instance, arms contain mechanoreceptors and pressure sensors that plainly register the mass and resistance of an arm weight, but this array of sensor cells in the arm is not typically thought to register the changes in optical angles following from wearing prismatic goggles. Sensors cells in the arm and sensor cells in the visual system are separate parts of the anatomy and exist at distant locations in the body, but the demand of a task like aimed throwing presses the movement system into linking them together. The growth of that linkage relies on more immediate linkages, e.g., sensor cells embedded in the same muscle tissue will entrain purely thanks to their mechanical coupling (Kugler & Turvey, 1987), but the individual differences in how movement systems learn to navigate a task and even to transfer their learning suggests that new linkages develop based on individual experiences in a task (de Vries, Withagen, & Zaal, 2015; Kelty-Stephen & Dixon, 2014; Stephen & Hajnal, 2011; Withagen & van Wermeskerken, 2009).

1.2. Multifractal patterning might reveal the coordination of subgoals in aimed throwing

In this work, we propose that multifractal structure in the movement system might reveal insights about the sharing and persistence of information through the movement system. That is, multifractal patterning across the movement system may reveal how the movement system coordinates its disparate parts to maintain both visual exploration and throwing without destabilizing upright posture. Multifractal patterning is a multiplicity of fractal patterns—which etymological breakdown is worth noting if only to turn the larger question "What is multifractality?" into apparently simpler questions "What is fractality?" and "How can there be multiple fractalities?" Neither of these questions, we realize, are actually much simpler, but they can at least focus some further definition.

In order to answer the first question, it is important to consider that all scientists want some way to explain their dependent measures, and these explanations rely on mathematical models that portray the observed dependent measures in a way that provides