

Juggling on the Moon: Adaptation of complex motor skills to simulated low-gravity enabled changes in tempo

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Many commonly used rhythmic timing tasks can be easily varied in tempo, revealing important scaling laws of timing behavior and aiding learning. In contrast, it is more challenging to vary the tempo of real-world physical tasks like three-ball juggling. To address this, our collaborators have developed a realistic VR visuo-haptic simulation of juggling under reduced gravity using a novel force-generating input device to realistically simulate the physics and proprioception of ball throwing and catching (Kambara et al, *Proc IDW*, 2022). The setup enables the experimental modification of juggling tempo in a way that is not possible in physical settings. Our prior work has shown that juggling training in reduced gravity can enhance skill acquisition in novices, potentially by facilitating the learning of bimanual motor sequencing. (Cho et al., *IEEE VRW*, 2025). Here we shift focus to expert jugglers adapting to slow tempo juggling to test hypotheses about temporal scaling in motor control: proportional scaling vs. constant hold time (which relate to the continuous vs. discrete timing duality in the rhythmic timing literature). We measured motor kinematics (hand trajectories and timing of ball catches and throws) in relation to ball trajectory to describe how these scale with juggling tempo manipulated by changing simulated gravity. Our initial results (though n=2) are that a third alternative is suggested: jugglers attempt to increase tempo in low gravity by using shorter throws. This behavior may reflect VR-specific constraints, such as narrower field of view and less realistic proprioceptive feedback, prompting design improvements including pacing stimuli and visual apex targets to encourage slower juggling. This behavioral foundation supports planned neural studies of temporal scaling of neural dynamics using new methods for movement artifact rejection (Kim et al., *Sensors*, 2023; *J Neur Meth*, 2025).

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