A Hard-Real-Time Juggling Simulator to Shape Human Sensitivity to Cues and Coordination of Muscles

Date of Report: Sept 30, 2018

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1. Narrative

Introduction

Many virtual reality tasks incorporate auditory and haptic (or touch) feedback, in addition to visual displays of spatial information. Non-visual feedback modalities such as the former increase realism; but they may have an ancillary benefit of increasing human motor performance and learning. One task for which this has been exhibited is paddle juggling, or vertically bouncing a ball off of a rigid elastic planar surface. For the objective of hitting the ball toward a target height, visual feedback is sufficient. Yet, previous studies have shown that non-visual feedback----specifically haptic---both is sufficient in the absence of vision to maintain stable ball accuracy[1], and is capable of complementing vision to lengthen the duration that human jugglers can sustain such spatial accuracy[2]. The purpose of my research supported by the Link Fellowship in Modeling, Simulation, and Training was to better understand the roles of visual and non-visual feedback (defined as haptic or audio cues); particularly how they relatively contribute to the human nervous system's processing of sensory information from the task, and to its subsequent action selection mechanisms for juggling.

To perform this research, I developed a hard-real-time virtual reality paddle-juggling simulator, in which participants juggled a ball in virtual reality by moving the handle of a haptic paddle[3]. The goal was explicitly spatial; namely, to bounce the ball to a given target height. However, audio and haptic cues were presented at ball-paddle collision events via a simultaneous buzzer beep and force impulse to the hand through the haptic paddle handle.

To achieve the target performance in this juggling task, the human operator must coordinate his or her arm muscles so that the paddle strikes the ball at an appropriate velocity and acceleration. Given the spatial goal and the improvement of accuracy that has been noted to accompany the introduction of non-visual feedback, the original hypothesis was that the brain interprets non-visual cues such as touch and sound as an ancillary measure of ball position. In other words, because non-visual cues occur at collision events, they signify the timing of these collisions, which can be mapped inversely to previous ball height by a simple model of ball kinematics that the brain knows both through basic knowledge of physics and through practice on this particular system[4,5,6].

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[1] Sternad D, Duarte M, Katsumata H, and Schaal S. Bouncing a ball: tuning into dynamic stability. *J Exp Psychol-Hum Percept Perform*, 27(5):1163-1184, 2001.

[2] Ankarali MM, Sen HT, De A, Okamura AM, and Cowan NJ. Haptic feedback enhances rhythmic motor control by reducing variability, not improving convergence rate. *J Neurophysiol*, 111(6):1286-1299, 2014.

[3] Okamura AM, Richard C, Cutkosky MR. Feeling is believing: using a force-feedback joystick to teach dynamic systems. *J Eng Educ*, 91(3): 345-349, 2002.

[4] Ankarali et al., ibid.

[5] Nickl RW. Spatial and Timing Regulation of Upper-Limb Movements in Rhythmic Tasks. PhD thesis, Johns Hopkins University, Baltimore, MD, 2018.

To test this hypothesis, I exploited the hard-real-time nature of the simulator to perturb both visual and non-visual feedback, and to measure the resulting response of the human's arm movements. While the ball flight and ball-paddle impacts were simulated using an accurate physics engine, feedback was restricted to the ball peaks (visual ball flash), and to the ball-paddle collision events only (haptic + audio pulse). That is, the information about performance was restricted to a small window about ball apex position, and to the ball-paddle contact point, in keeping with information that is sufficient for skilled ball juggling. Visual perturbations were applied by displaying the ball higher or lower than the position dictated by the physics engine. Because audio and haptic feedback was not spatial, these non-visual cues were perturbed by advancing or delaying their times of incidence.

Results

In experiments run on over 20 unique participants, we observed that jugglers responded to visual or non-visual feedback in characteristic ways. Visual information is used for spatial control. Jugglers hit the ball in the opposite direction it was perturbed (anti-phase to perturbations); this is consistent with the notion that the human brain interprets these perturbations as spatial errors, and recognizes that it must guide arm movements to cancel these perturbations to achieve target performance. However, non-visual information---rather than enhancing spatial accuracy directly---is used actively by the human brain for action timing. When non-visual information was perturbed by precisely delaying or advancing the timing of the audio and haptic cues, humans responded by delaying or advancing the timing of their hand swing (specifically, peak velocity and timing of hand descent initiation). Critically, none of the participants were aware they were being perturbed (determined by indirect questioning).

Thus, the visual perturbation---ball spatial response may be said to be mediated by the brain's "spatial controller" and the timing perturbation---hand timing response behavior by the brain's "timing controller". By performing model selection and model fitting techniques on perturbed data, I established that the brain processes visual and non-visual cues with different dynamics and timescales. Namely, the dynamics of visual control were history-dependent and influenced by the most recent visual error, and that observed in the previous cycle (proportional-integral). The dynamics of timing control appear to be regulated by the most current haptic + audio feedback only (proportional law). These control laws have interesting parallels to control behavior of other tasks. The visual controller is analogous to what has been observed in the spatial control of discrete movements such as reaching. The timing controller is similar to models of metronome entrainment found in the tapping / synchronization literature.

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[6] Nickl RW, Ankarali MM, and Cowan NJ. The separable roles of visual and non-visual feedback in rhythmic arm movement control. Under review at the Journal of Neurophysiology

Significance and impact

Altogether, these results suggest that whenever humans perform immersive virtual reality tasks, the brain may solve complimentary problems that affect how it regulates muscular coordination: accuracy control and action-feedback synchronization. Rather than simply contributing to realism, nonvisual cues such as sound and force impulses have an important functional role in control, as pacemakers to aid the human nervous system in initiating and timing of movements.

The response of humans to non-spatial perturbations is mathematically equivalent to a control process where the brain perceives the perturbation as an error in its internal estimate of time. This finding is consistent with an interpretation that the brain's internal estimate of time is inaccurate, and that the brain assumes external cues as ground truth and uses them as a clock with which to reset its movement timing[7].

Where might this lead?

The work I completed with the Link Fellowship in Simulation and Training both contributes to the knowledge of complementary control between spatial and timing regulation, but also the role of auditory and haptic feedback to the latter process. In other words, audio and haptic cues not only increase the realism of the task, but appear to give humans specific information to help them prepare and time their movements.

The specific manipulation of nonvisual cues as a tactic for task learning---to "coach" humans about when and how to initiate movements—is an interesting area worthy of further study in more extensive experiments. From a more basic scientific standpoint, two fundamental questions are how humans process these cues at a biological level, and how generalizable these effects are across the broader spectrum of tasks.

The biological effects of non-visual feedback can be studied at the cognitive level by measuring the electrophysiology of the brain, and at the level of musculoskeletal coordination by measuring the electrical signaling at neuromuscular junction by electromyography. The former issue was the subject of a commentary I published (see Section 2), while the latter was explored in a limited number of subjects after the main work of my thesis was completed.

The juggling experiments conducted on my simulator focus on a specific type of rhythmic movement involving coordination of the wrist, forearm, and shoulder. In a broader sense, tasks are classified as discrete, rhythmic, or a combination of both. Another future direction would be study movement preparation in other tasks that are not rhythmic (i.e. segmented, or point-to-point tasks), and how non-visual feedback modalities contribute to those also, as a further test of generalizability across task classes.

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[7] Lamperski A, Cowan NJ. Optimal control with noisy time. *IEEE Trans Autom Control*, 61(2):319-333, 2016.

2. How did the fellowship make a difference?

The Link Fellowship was crucial in allowing me to further develop my research on the simulator I developed. First, it enabled me to conduct more experiments that would not have been possible otherwise. The addition of further experiments gave further insight into how generalizable the effects of visual and nonvisual cues are across the population of young adults, and also improved the statistical rigor of my results. In turn, I was enabled to present my work at the largest neuroscience conference in the world, and to prepare a cohesive manuscript that was submitted and is currently under review for publication in a respected journal that has a wide neuroscience and engineering readership.

An equally great benefit that the Link Foundation Fellowship provided me was the flexibility to explore my developing interests in how humans respond to virtual reality tasks and learning interventions at a more physiological level. I have had the opportunity to begin working with electrophysiological data from muscular (electromyographic, or EMG) and scalp (electroencephalographic, or EEG) activity to begin to understand how learning and sensory feedback affect both the peripheral nervous system and the brain. During my Link Fellowship tenure, I independently wrote a commentary on a study in monkeys of how neurons in the brain respond to timekeeping tasks that likely engage the "timing" controller I found in my research. This commentary was published in the highly respected Journal of Neuroscience and highlighted on social media. Without the Link Foundation's support, it is very likely that none of these experiences would have been feasible.

3. Future Plans

I defended my thesis in February 2018 and graduated in June 2018. I will be continuing my research career as a Postdoctoral scholar at Johns Hopkins Medical Institutions beginning Fall 2018, where, I will be studying topics including the brain's physiological dynamics during learning, and the impact of brain stimulation during the learning of dexterous tasks, using virtual reality and other tasks.

4. Publications, Presentations, and Other Outputs.

Thesis

Nickl RW. Spatial and Timing Regulation of Upper-Limb Movements in Rhythmic Tasks. PhD thesis, Johns Hopkins University, Baltimore, MD, 2018

Publications

Nickl RW, Ankarali MM, and Cowan NJ. The separable roles of visual and non-visual feedback in rhythmic arm movement control. Under review at the Journal of Neurophysiology

Nickl RW. The medial premotor cortex as a bridge from internal timekeeping to action The Journal of Neuroscience 37(37), 8860-8862, 2017

Abstracts / Poster Presentations

Nickl RW, Ankarali MM, and Cowan NJ. Complementary roles of spatial- and timing-based control during rhythmic arm movements. Society for Neuroscience annual meeting. Washington, DC, 2017.

Nickl RW and Cowan NJ. Proportional—integral control in paddle juggling. Omega Psi Cognitive Science Society regional conference. Baltimore, MD. April 2017.