Proprioceptive Position Inference as Velocity Integration

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Abstract

We investigate proprioceptively guided inference of hand position and velocity during movement using a virtual reality (VR) experiment. Participants performed a paced continuous movement task, with visual feedback limited to a brief interval after movement onset. We demonstrate that brief visual offsets induce semi-persistent deviations in movement paths, suggesting that inferred hand position is heavily influenced by the integration of proprioceptively sensed velocity over time. To further explore this, we present a generative model based on Bayesian sensory integration and compare the movement characteristics of three distinct model versions to human data. Our findings show that combining velocity integration with position sampling produces movement patterns that closely resemble human behaviour, highlighting the importance of velocity-based integration in proprioceptive inference.

Keywords: Multi-sensory integration; motor control; vision; proprioception; Bayesian sensory integration

Introduction

When reaching for an object we may use both vision and proprioception in order to guide our hand to a target. It has been shown that if slightly incorrect visual feedback of hand movement is provided for a brief time, then the reaching movement will tend to be adjusted, to account for and move relative to this visual offset (Körding & Wolpert, 2004). Furthermore, it has been shown that whether visual feedback of hand location is available or not before movement onset influences the magnitude and variability of end-point errors (Desmurget, Rossetti, Jordan, Meckler, & Prablanc, 1997; Rossetti, Stelmach, Desmurget, Prablanc, & Jeannerod, 1994), with this effect being increased for longer delays since visual feedback of hand location was removed (Elliott, 1988; Elliott & Calvert, 1990). Additionally, it has been demonstrated that pre-movement errors in perceived starting location are correlated with end-point errors (Vindras, Desmurget, Prablanc, & Viviani, 1998). These findings together indicate that proprioceptively guided movements seem to be executed relative to a previously estimated effector position, taking into account both vision and proprioception - as visual feedback of the hand is removed, the visual information of hand position appears to be gradually discounted over time.

One way to account for these movement error patterns in situations with manipulated or removed visual feedback of hand position would be to assume that a significant portion of inferring hand position from proprioception is done by integrating sensed velocity over time, rather than directly sensing position. This assumption has physiological support in that the type Ia afferent muscle spindles, one of the primary and most well-studied proprioceptive sensors, have firing patterns that are correlated to changes in muscle length (and its derivatives), rather than absolute length (Proske & Gandevia, 2012).

This study explores this proposal using a VR experiment requiring participants to track a target following a circular path. 1 second of offset visual feedback of hand position was provided shortly after movement onset. We compare these results to a simple generative Bayesian model, sampling either the hand's position, velocity, or both. This highlights the importance of considering the base input to which the agent has access, as each permutation produces distinct movement patterns.

Theoretical Models of Proprioceptive Inference

In order to perform a reaching movement, where both end-point position and velocity are controlled, an agent must estimate both of these parameters. Due to these two parameters' interdependence as they evolve over time, it is possible to estimate one, if only the other is directly available as an input.

To estimate velocity the agent may consider its current and previous positions, calculating a derivative of the change in position over the course of a movement, and, conversely, it is possible to estimate the change in position over the course of a movement by integrating the velocity over time.

A notable difference in the above-described primitive models is that in the second version, it is only possible to estimate changes in position over time, rather than absolute position. It should be noted that these two models of inference should not be considered mutually exclusive, but should be seen as a framework within which we can investigate the modes of proprioceptive inference during movement.

Bayesian Generative Models

We simulated 3 distinct Bayesian agents in order to compare the resulting movement patterns and types of errors with those observed in human data. The agent samples its proprioceptive and visual (when available) senses and adjusts its acceleration to move towards an always-visible target. Its proprioception is varied as follows:

- Position-based (P): The agent can only directly sample its proprioceptive *position* and estimate its velocity by comparing current to past sensed positions.
- Velocity-based (V): The agent can only directly sample proprioceptive *velocity* and estimate its position by integrating velocity and adding to previously estimated positions.
- Combined (PV): The agent can sample both position- and velocity-based proprioception, combining both approaches.

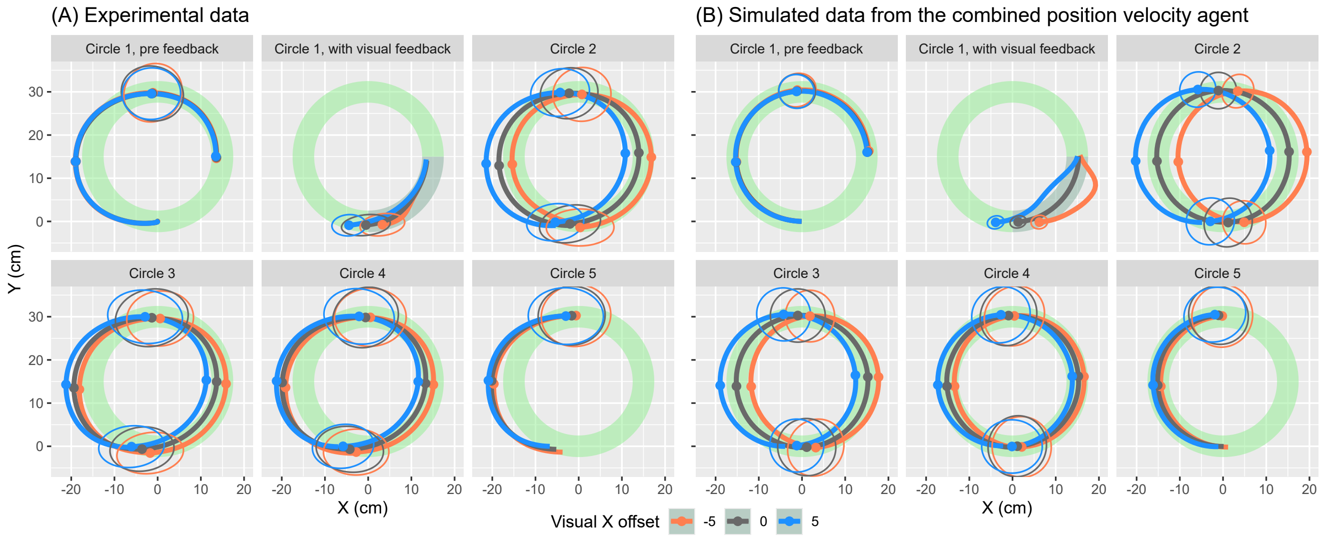

Figure 1: Panel A shows experimental data (mean movement paths for 22 participants) while panel B shows simulated data for the combined position-velocity agent. The wide green circle shows the path of the pacer target (moving in a clockwise direction), which participants were tasked to track. Grey, blue and orange lines show the mean movement path during each visual condition. Ellipses show the mean distribution of 95% of trials at that point in the movement (within-participant in panel A).

Experimental setup

The participants (N = 22) were seated at a table and outfitted with a VR headset. The right VR controller was inserted in a 3D-printed grip with a flat base with a felt slider, such that it could slide with minimal friction on the tabletop, which was tracked into VR. The task consisted of a continuous tracking task, consisting of attempting to follow a displayed target sphere moving a circle (the radius of the circular path was 15 cm, 4 seconds per full circle, each trial consisting of 4.5 revolutions). Visual feedback of the controller position was cut off at trial initiation, with 1 second of visual feedback provided during the last second of the first circle. Visual feedback was correct or offset 5 cm to the left or the right (20 reps. per cond. was completed).

The Bayesian agents were programmed to complete the same task (500 trials per. cond).

Results

The results of the VR task (fig. 1A) show a tendency of participants to initially adjust for and move relative to the presented (offset) visual feedback, with this offset gradually decreasing over time such that both offset paths have mostly converged to the non-offset path by the end of circle 5.

The combined PV Bayesian agent (fig. 1B) matched the tendency to initially adjust for the offset visual feedback and to eventually converge gradually back towards the non-offset movement path.

In contrast, the P-only agent will almost immediately discount visual feedback when it is no longer available, while the V-only agent will adjust for visual feedback, but fails to discount it over time (neither plotted).

Concluding discussion

Together these results support the interpretation that inferring hand position from proprioception is heavily influenced by a velocity integration over time. Additionally, the observation that offset movement paths do eventually converge back to the non-offset path does indicate that some direct information regarding absolute hand position is also inferred from proprioception - the fact that it takes a relatively long time to converge back indicates that this sensed position is assigned a relatively low precision, as compared to both visual inference of hand position, as well as the proposed velocity-integrated estimation of position.

Code availability

`https://github.com/skjoldan000/ccn_bsi`

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