Motion trajectory information and agency influence motor learning during observational practice

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ABSTRACT

Fundamental to performing actions is the acquisition of motor behaviours. We examined if motor learning, through observational practice, occurs by viewing an agent displaying naturalistic or constant velocity, and whether motion trajectory, as opposed to end-state, information is required. We also investigated if observational practice is sensitive to belief regarding the origin of an agent. Participants had to learn a novel movement sequence timing task, which required upper-limb movements to a series of targets within a pre-specified absolute and relative time goal. Experiment 1 showed learning after viewing naturalistic and constant velocity, but not end-state information. For Experiment 2, in addition to learning the movement sequence, participants observed a series of movement stimuli that were either the trained or new sequences and asked to rate their confidence on whether the observed sequence was the same or different to observational practice. The results indicated that agency belief modulates how naturalistic and constant velocity is coded. This indicated that the processes associated with belief are part of an interpretative predictive coding system where the association between belief and observed motion is determined. When motion is constant velocity, or believed to be computer-generated, coding occurs through top-down processes. When motion is naturalistic velocity, and believed to be human-generated, it is most likely coded by gaining access to bottom-up sensorimotor processes in the action-observation network.

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1. Introduction

Fundamental to performing goal-directed actions is precise spatio-temporal parameterisation, movement sequencing and sequence knowledge. The representation and acquisition of these processes occurs during observational practice (Bird & Heyes, 2005; Vogt, 1995). This visuomotor learning takes place during a training period of pure stimulus observation. As such, no overt physical practice is performed during training, resulting in a learner not receiving response-produced feedback (reafference). This process is said to occur within the action-observation network [AON] (Cross, Kraemer, Hamilton, Kelley & Grafton, 2009), where neurons respond in a similar manner during observation and execution (Fadiga, Fogassi, Pavesi & Rizzolatti, 1995). Linked to this network is the superior temporal sulcus which provides input to the fronto-parietal cortices (Grossman et al., 2000) where the spatial-temporal characteristics (i.e., kinematics) and action-goal (Hamilton, 2008; Iacoboni, 2005) of the observed stimulus are processed.

The processing of kinematics is partly based on the perception of biological motion, as indicated by a motor interference effect during interpersonal execution-observation (Kilner, Paulignan & Blakemore, 2003). Here, then, participants exhibited increased variability in an intended movement whilst observing an incongruent movement performed by a human (naturalistic velocity; biological motion), not a robot (constant velocity; nonbiological motion), model. In this context, it is important to note that naturalistic velocity is different to constant velocity because it contains task specific changes in acceleration based on human anatomy and the external constraints (gravity; direction; target size) associated with a particular task. These factors combined underpin a velocity profile that is bell-shaped (Flash & Hogan, 1985), which is reflective of typical goal-directed aiming movements. Thus, motor interference is suggested to occur from the automatic activation of motor codes that directly respond to the naturalistic velocity characteristics of the observed biological motion (Blakemore & Frith, 2005). This automatic activation is commonly referred to as bottom-up processing, which involves the preferential treatment of information directly available via the stimulation of sensory receptors (Teufel, Fletcher & Davis, 2010), and is linked to the fronto-parietal mirror region where stimuli consistent with these biological laws of motion are processed (Casile et al., 2010; Dayan et al., 2007). Indeed, it is the coding of this biological motion

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that is also suggested to drive automatic imitation (Brass, Bekkering & Prinz, 2001), voluntary imitation (Wild, Poliakoff, Jerrison & Gowen, 2010) and observational practice (Hayes, Roberts, Elliott & Bennett, 2014; Hayes, Timmis & Bennett, 2009).

Although there has been reported differences in contagion when viewing biological and nonbiological motion, the AON also is activated by (Cross et al., 2011; Gazzola, Rizzolatti, Wicker & Keysers, 2007; Ramsey & Hamilton, 2010) and adapts to (Press, Gillmeister & Heyes, 2007) nonbiological motion. In the case of motor contagion, interference occurs when a non-human agent (a ball) displays both naturalistic and constant velocity motion (Kilner, Hamilton & Blakemore, 2007). Unlike naturalistic velocity, which is suggested to directly generate contagion via the automatic activation of motor codes, constant velocity displayed via a non-human agent is suggested to be processed by individuals forming an interpretation, or predicting, the agency, and action goal, based on prior knowledge (Kilner et al., 2007; Stanley, Gowen & Miall, 2007, 2010). This effect can be explained by modulation through top-down processes. 'Top-down' processing depends on an observer's knowledge and expectation of a situation (Teufel et al., 2010), and may be underpinned by contextual factors such as motion trajectory (Tremoulet & Feldman, 2000), belief (Stanley et al., 2007) and social context (Hogeveen & Obhi, 2013). Another top-down process that influences motion coding is goal interpretation and assignment (Bekkering, Wohlschläger & Gattis, 2000) whereby an end-state goal organises the motor response during imitation. For example, an end-state goal (grasping the right ear) might be achieved using a motor response (right-arm) that differs from the observed movement (left-arm). Furthermore, there is some suggestion that the aforementioned motor interference effects are influenced by the perceived end-state goal (Stanley et al., 2007), as well as information contained within the movement trajectory (Kilner et al., 2007).

The consensus therefore is that the AON involves regions that perform specialised processing, with the contribution being dependent on the nature of the observed stimulus and interpretation of agency (Liepelt & Brass, 2010; Press, Gillmeister & Heyes, 2006; Stanley et al., 2007; Stenzel et al., 2012). To date these factors have been studied during interpersonal execution-observation, voluntary imitation and automatic imitation tasks where visual information is processed in combination with efferent and afferent sensory information from the peripheral motor system. This sensorimotor experience underpins enhanced action perception in experts (Calvo-Merino, Glaser, Grezes, Passingham & Haggard, 2005), and facilitates response times during action-observation (Catmur, Walsh & Heyes, 2007). It is therefore important to understand if the coding of biological and nonbiological stimulus motion information occurs during observational practice in the absence of reafference.

2. Experiment 1

To examine biological (naturalistic velocity) and nonbiological (constant velocity) motion trajectory information during observational practice we had participants acquire a 5 segment movement sequence timing task. The goal was to learn how to perform the absolute, and relative, timing parameters associated with the sequence. Absolute time is the total time required to successfully perform the 5 segments. Relative timing is the proportion of time required to successfully perform each segment within the sequence. Because the goal was to learn the timing parameters, we displayed the spatial position of the 5 segment end-points on the computer monitor. By keeping the spatial locations constant, participants in the experimental conditions observed a non-human agent (a white cursor) perform the 5 segment movement sequence with a motion trajectory that displayed naturalistic or constant velocity.

Given the AON is activated by naturalistic and constant velocity it is not possible to make specific predictions regarding the learning effects after observing these two motion trajectories. However, any additional

benefit of observing naturalistic velocity motion over constant velocity would depend on the relative contribution of bottom-up and top-down coding processes during observational practice. We do predict however those participants exposed to motion trajectory information will learn the sequence timing more accurately than the control participants who did not perform observational practice. Finally, to further examine the effects of motion trajectory information, we used a third control model (end-state model) that displayed the relative, and absolute, timing parameters, but here motion trajectory information was removed so that the model appeared as a sequence of 5 flashes presented at the spatial segment end-points. If motion trajectory information is processed during observational practice the groups that observed naturalistic and constant velocity will learn timing parameters more accurately than those who observed the end-state control model.

2.1. Method

2.1.1. Participants

Data were recorded from forty-eight volunteers (aged 18 to 21 years; three participants were removed from the analyses due to missing data from technical errors). All participants had normal or corrected-to-normal vision, and gave informed consent. The experiment was approved by the local ethics committee.

2.1.2. Experimental procedures

The apparatus was the same as that used in our lab for a previous experiment (Hayes, Elliott & Bennett, 2013). The current experiment had a pre-test, observational practice phase and post-test (Fig. 1A). Before the pre-test, all volunteers received information regarding the spatial layout of the movement sequence pattern and the two timing goals (Fig. 1B). Here, participants were informed that they were required to successfully navigate a mouse so that a cursor moved between each of the predefined target end-points. In the event of a spatial error involving the cursor not reaching a target, an error message was displayed on the monitor and the participant was required to repeat the trial. Also, by keeping the spatial segment end-points controlled the volunteers were instructed the primary goal was to learn the absolute time goal and the relative time goal. The absolute time goal required participants to control the mouse so that the cursor left the start position, passed through five segments and terminated (pressing the right mouse button) within the final target (Fig. 1B) in a time of 4625 ms. The relative timing goal required participants to perform the absolute time goal by ensuring the segment proportions met the criterion structure: 13% (segment 1; 601 ms), 32% (segment 2; 1480 ms), 14% (segment 3; 648 ms), 17% (segment 4; 786 ms) and 24% (segment 5; 1110 ms).

We created three models: biological motion, nonbiological motion, and end-state. A biological motion model was created by an experimenter who practised the sequence until the criterion time goals were performed accurately. The time-series data from a representative trial were used to generate the model. These data were then presented on the monitor, and as such displayed both vertical (y-axis) (black trace; Fig. 2A) and horizontal (x-axis) (black trace; Fig. 2B) motion. This was important in order to ensure high fidelity replication of biological motion, which does not typically comprise movement in a single axis.

A nonbiological motion model displaying constant velocity within each segment was generated using the amplitude and time constraints. The displacement time-series data for the model had the same time goals but included motion only in the primary direction (e.g., y-axis of segment 1) (grey trace; Fig. 2A), and thus without any deviations in the perpendicular axis (e.g., x-axis of segment 1) (grey trace; Fig. 2B). Therefore, the nonbiological model comprised both biologically implausible velocity and spatial trajectory. An end-state model was created that had the same time parameters, but only displayed the single-point light as it entered and left each target (a series of flashes). The flashes were displayed for 35 ms to provide visual information about