Atypical biological kinematics are represented during observational practice

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Abstract

The present study investigated the effect of stimulus-response compatibility on the representation of atypical biological kinematics during observational practice. A *compatible group* observed an atypical model that moved rightwards, whereas an *incompatible group* observed an atypical model that moved leftwards. Both groups were instructed to observe the model with the intention to later reproduce the movement trajectory. This was examined in a post-test where participants were asked to move rightwards with a kinematic profile that matched the atypical kinematics. Compared to a *control group* that did not engage in practice, and irrespective of whether the stimulus was observed in a spatially compatible or incompatible orientation, participants from both experimental groups reproduced velocity profiles that were comparable, and similar to the atypical biological kinematics. Bayesian analysis indicated equality between the two experimental groups, thus suggesting comparable sensorimotor processing. Therefore, by rotating the *incompatible* stimulus by 180 degrees during observational practice, the current study has isolated the processing and representation of atypical biological kinematics to the underlying sensorimotor processes, rather than spatial encoding of peak velocity via processes associated with stimulus-response compatibility.

Key words: biological kinematics; spatial compatibility

Public Significance Statement

Humans show a remarkable capacity to learn a variety of motor skills such as using chopsticks, or riding a bicycle. This study looked at how individuals learned from merely observing a movement. This form of learning is called observational practice, and requires an individual to watch a movement only for a number of times during practice. Even though individuals did not physically perform the movement in practice, they successfully copied

how (e.g., speed and acceleration) the movement was performed in a post-observation-test. This finding has implications for understanding the best way to facilitate the development of motor skills in the general population, and people that have certain neurodevelopmental conditions (e.g., autism).

Introduction

When interacting with their environment, and with others, humans are often required to learn novel movements. One route via which humans engage in sensorimotor learning is known as observational practice, and occurs when a person repeatedly watches a model before reproducing the observed action. The efficacy of observational practice has been demonstrated experimentally in a number of studies; for example, compared to control groups without an opportunity to learn, observational practice groups acquired knowledge of a sequence of finger movements having merely watched a model perform the sequence of movements (Bird & Heyes, 2005; Bird, Osman, Saggerson & Heyes, 2005; Osman, Bird & Heyes, 2005). In addition to leading to the acquisition of the observed motor behaviour, observational practice also produces similar adaptation in the cortical sensorimotor system (i.e., action-observation network; Cross, Kraemer, Hamilton, Kelley, & Grafton, 2009). These findings show that even though the peripheral motor system is not engaged in the observed motor task during observational practice (e.g., the relevant limb is at rest), a sensorimotor representation of the action is developed by engaging a common-coding system linking perception and action (Brass & Heyes, 2005; Jeannerod, 1994; Prinz, 1997).

Direct activation of the sensorimotor system during the observation of actions is said to be underpinned by processes preferentially tuned to biological motion (Press, 2011). As well as facilitating socio-cognitive functioning during interactions between people (Cook, Blakemore, & Press, 2013; Press, Cook, Blakemore, & Kilner, 2011), biological tuning is important for the acquisition of novel motor actions during observational practice (Bird & Heyes, 2005). We have confirmed biological tuning across a series of behavioural studies where participants observe a series of model stimuli that depict typical or atypical human biological kinematics (Hayes, Dutoy, Elliott, Gowen, & Bennett, 2016; Hayes, Elliott, & Bennett, 2010, 2013; Hayes, Roberts, Elliott, & Bennett, 2014; Hayes, Timmis, & Bennett,

2009; Roberts, Bennett, Elliott, & Hayes, 2015). Typical kinematics had a movement profile where peak velocity occurred at approximately 50% of the trajectory, which is consistent with goal-directed upper-limb aiming movements (Elliott et al., 2010). Atypical kinematics were novel, and displayed peaks occurring at 18% (Hayes et al., 2016) or 77% (Hayes et al., 2014) of the movement trajectory. From a theoretical perspective, the presentation of atypical kinematics is fundamental for understanding the contribution of low-level sensorimotor processes during observational practice. For example, if a model is presented that has typical kinematics it cannot be ruled out that imitation is based on a representation of the movement speed, as opposed to a representation of the underlying biological motion kinematics. In the former case, the feedforward contribution to motor execution would have been associated with rescaling a pre-existing motor representation of a familiar and meaningful movement based on higher-order semantic processes (Rumiati et al., 2005). In contrast, imitation of atypical kinematics cannot be solved by merely recruiting an existing sensorimotor representation; the sensorimotor system needs to be configured during observational practice based on a representation of the observed kinematics.

Although this previous work demonstrated biological specificity, it did not control for the influence of spatial stimulus-response (S-R) compatibility (Heyes, Bird, Johnson, & Haggard, 2005). Therefore, it remains a possibility that the spatial position of peak velocity could have been encoded during action observation rather than the movement kinematics *per se* (Hommel & Lippa, 1995). To better locate processing of biological motion within sensorimotor processes, S-R compatibility can be controlled by arranging the stimulus and response in an orthogonal (e.g., stimulus hand vertical; responding hand horizontal) orientation. Indeed, using these techniques during studies of automatic imitation, which recruits similar sensorimotor processes as observational practice (Heyes, 2011), motor responses are facilitated in compatible compared to incompatible trials, thus confirming

direct activation of motor representations during action-observation which is not confounded by spatial S-R compatibility (Bertenthal, Longo & Kosobud, 2006; Catmur & Heyes, 2011; Heyes et al., 2005; Press, Bird, Walsh, & Heyes, 2008).

Based on this methodology, we investigated S-R compatibility on the reproduction of atypical biological kinematics following observational practice. Participants in a *compatible group* and *incompatible group* observed a model (a single dot) with the intention to reproduce the movement trajectory following observational practice. For the *compatible group* the model was observed moving in a left to right direction on a monitor, whereas the *incompatible group* observed the model moving in a right to left direction. A control group did not engage in observational practice. In a post-test, the experimental groups were both instructed to reproduce the modelled movement(s) in a left to right direction. If the reproduction of atypical biological kinematics is underpinned by direct activation of sensorimotor processes, we expect comparable post-test performance between the two experimental groups. If, however, reproduction is mediated by S-R compatibility associated with spatial orientation, the *compatible group* should perform more accurately than the *incompatible group*. Finally, we expect an advantage of observational practice for both experimental groups compared to the control group when reproducing atypical biological kinematics.

Methods

Participants

Sixty participants (44 males; 16 females; mean age of 22 years) with normal, or corrected to normal vision, were provided with an information sheet and consented to be a volunteer in the study. Participants were randomly assigned to a *compatible group*,

incompatible group, and *control group*. The study was designed in accordance with the 1964 Declaration of Helsinki and approved by the local research ethics committee.

Apparatus and Stimuli

Participants sat facing a 21-inch CRT monitor (Iiyama Vision Master 505) operating with a resolution of 1280 x 1024 pixels and a refresh rate of 85 Hz, located on a table at a viewing distance of 555 mm. The monitor was connected to a PC (HP Compaq 8000 Elite), which also recorded input of a hand-held stylus on a graphics tablet (Wacom Intuos Pro XL). Experimental stimuli were generated using COGENT toolbox (developed by John Romaya at the Laboratory of Neurobiology at the Wellcome Department of Imaging Neuroscience) and implemented by MATLAB (Mathworks Inc.).

Two non-human agent models were created by a human volunteer performing *typical* (used in pre-test) and *atypical* (used in the observational practice phase) horizontal movements using a hand-held stylus on a graphics tablet (Figure 1.A). The stylus movement was represented as a white-dot (diameter = 6 mm) on the computer monitor, and traversed from the left-hand start-position (red-dot, diameter = 12 mm) to the right-hand end-position located at an amplitude of 200 mm. The total movement duration was exactly 1700 ms. For both models, raw position data were first filtered using a low pass 4th order autoregressive filter with an 8 Hz cut-off. Data were then differentiated using a three-point central difference algorithm to obtain velocity. The *typical* model reflected an exemplar trial, and thus displayed a typical (Elliott et al., 2010; Flash & Hogan, 1985) bell-shaped velocity profile (dashed trace in Figure 1.B) with a peak of 0.19 mm/ms that occurred at 44% of the movement duration. For the *atypical* model (black trace in Figure 1.B), peak velocity was 0.33 mm/ms and occurred at 18% of the movement duration. The method of using a human volunteer to generate both models was important because it ensured the kinematics were

biological and reproducible by participants (Hayes et al., 2016). This did result in movement deviation in the x and y axes, however the latter was minimal (i.e., perpendicular deviation) as confirmed by a root mean square error of 0.9 mm for the *atypical* model and 1.55 mm for the *typical* model.

Figure 1.

Procedure

The experiment consisted of a pre-test, observational practice phase, and a post-test. In the pre-test, the control group received exactly the same instructions as the experimental groups, which were to watch the monitor and focus on watching how the model moved. Following an observation, all participants were instructed to imitate how the model moved by using the stylus on the tablet. All participants observed the *typical* model, however no specific information was provided to the groups regarding the nature of model, nor was feedback regarding imitation performance provided. The pre-test procedure familiarised participants with the spatiotemporal relationship between the stylus movement on the graphics tablet and cursor movement on the screen, and quantified baseline motor behaviour associated with performing typical goal-directed movements.

The observational practice phase consisted of 30 consecutive action-observation trials (Figure 1.A). The *compatible group* observed the *atypical* model as it moved rightwards, while the *incompatible group* observed the same *atypical* model, but moving leftwards. Having reversed the direction of motion, peak velocity still occurred at 18% of the movement duration. Both experimental groups were instructed to observe the model with the intention to execute a movement in the post-test that reproduced the *atypical* movement trajectory (Hayes et al., 2014). As per the pre-test, the experimental groups received no specific information regarding the nature of modelled kinematics, nor was feedback regarding imitation

performance provided. The control group observed a blank screen for a duration equal to the observational practice phase (Figure 1.A).

In the post-test, the experimental groups performed 10 trials that required them to recall and execute a movement that reproduced the profile of the observed *atypical* model. Importantly, all movements commenced from a start-position located at a left-side start-position and ended on the right-side of the screen. The *control group* executed a movement as per the pre-test. No feedback regarding imitation performance was provided to any group.

Data Reduction

The analysis was focused on the primary movement (i.e., x-axis data) and did not take into account minimal deviation in perpendicular axis (i.e., RMSE < 1.5 mm), which was most likely an incidental result of anatomical constraints rather than intentional imitation (Hayes et al., 2016). First, we identified the start and end of the movement within the x-axis position data. The start was defined as the moment the centre of the cursor moved beyond the perimeter of the start-position circle, and the end equated to the moment the participant clicked the upper-button on the stylus. Next, for each trial the position data were filtered using a low pass 4th order autoregressive filter with an 8 Hz cut-off. Data were then differentiated using a three-point central difference algorithm to obtain velocity. Finally, we extracted *percentage-time-to-peak-velocity* from each trial.

Data Analysis

The effect of observational practice on motor performance was examined by comparing *percentage-time-to-peak-velocity* at post-test as a function of group. To minimise the impact of initial group differences resulting from random assignment, and to statistically control for the baseline effects from imitating the typical model that is not the primary interest of the analysis, the pre-test data was used as a covariate (ANCOVA). Post hoc

pairwise comparisons were conducted using Bonferroni corrections. Alpha was set at $p < 0.05$, and partial eta squared (η_p^2) expressed the size of the effect. In addition, and to account for issues with null hypothesis statistical testing (Jarosz & Wiley, 2014; Masson, 2011; Rouder, 2014; Wagenmakers, 2007), we used the BayesFactor package (Morey & Rouder, 2015) using RStudio v. 1.0.44 to run three separate Bayesian ANCOVAs. This involved calculating Bayes factors (BF_{01}) to estimate the posterior probability through an odds ratio for the null/alternative hypothesis (a value of 1 means they are equally likely; larger values indicate more evidence for the null; smaller values indicate more evidence for the alternative).

Results

ANCOVA indicated a significant main effect of group for *percentage-time-to-peak-velocity* [F (2,56) = 7.871, p = 0.001, η_p^2 = 0.219]. Post hoc tests indicated the percentage peak velocities reproduced by the *compatible* (M = 28%) and *incompatible* (M = 31%) groups were comparable ($t = 0.97$, $p > 0.05$; BF_{01} = 2.25). The exemplar data presented in Figure 2.B illustrates how the two experimental groups reproduced peak velocity that occurred early in the movement trajectory, in a similar manner to the atypical model (Figure 1.B). The difference in *percentage-time-to-peak-velocity* between the *compatible group* and the *control group* was 12 units (t = 3.84, p = 0.001; BF_{01} = 0.004), and 9 units between the *incompatible group* and the *control group* (t = 2.73, p = 0.025; BF_{01} = 0.03). Notably, the occurrence of *percentage-time-to-peak-velocity* for the control group (M = 40%) was towards the midpoint of the trajectory (Figure 2.B), and thus similar to the typical model (Figure 1.B).

Figure 2.

Discussion

We investigated the influence of spatial S-R compatibility on the reproduction of atypical biological kinematics following observational practice. Irrespective of compatibility, post-test performance of the experimental groups was comparable, with *percentage-time-to-peak-velocity* occurring early in the movement trajectory, in a manner similar to the observed atypical model. This was supported by the Bayesian statistics that indicated insufficient evidence to accept the experimental hypothesis that the compatible and incompatible groups would differ. The *control group* was not comparable to the experimental groups, with Bayes analysis indicating strong evidence (Jarosz & Wiley, 2014; Raftery, 1995) for the alternative hypothesis (groups being dissimilar) compared to the null hypothesis (groups being similar). Peak velocity occurred towards the midpoint of the movement trajectory, which is similar to the typical model and the pre-existing sensorimotor repertoire, and reflective of the constraints of the task.

The finding from the *compatible group* supports previous work (Hayes et al., 2014) that showed atypical kinematics are represented during observational practice. As before, we suggest this occurs within a mechanism that activates sensorimotor processes. However, to control for the influence of spatial S-R compatibility (Hommel & Lippa, 1995), here we also presented an *incompatible* stimulus that was rotated through 180 degrees. The fact that the *incompatible group* reproduced the *atypical* kinematics when physically recalling (from memory) and executing the movement in the opposite left-to-right direction, strengthens our suggestion that sensorimotor adaptation across observational practice occurs via lower-level processes linking visual and motor representations (Catmur, Walsh, & Heyes, 2007; Catmur & Heyes, 2011; Cook, Bird, Catmur, Press & Heyes, 2014). Indeed, there is a possibility participants represented a kinematic landmark during observational practice, such as the

position that peak velocity occurs (e.g., spatial position relative to the monitor frame), however this is a less parsimonious explanation that would require a spatial translation through 180 degrees to reproduce an accurate *atypical* trajectory in the left-to-right direction at post-test.

In addition to low-level sensorimotor processes underlying our adaptation effects, we acknowledge that complimentary higher-order processes may have been involved. Specifically, visual attention and intention could have modulated the lower-level processing of the *atypical* kinematics following the explicit instructions given to participants to observe the model with the intention to execute a movement in the post-test that reproduced the same *atypical* movement trajectory (Hayes et al., 2014). Also, having perceived that the *atypical* model had a particular acceleration profile that differed from the *typical* model observed in the pre-test, and/or their own pre-existing sensorimotor repertoire, it follows that across observational practice inductive processes could have adapted and refined the developing sensorimotor representation (Turnham, Braun, & Wolpert, 2011). Indeed, because the *atypical* practice trials were presented in blocked order, sensorimotor experience and expectation gained from *trial n* would likely influence parameterisation and processing of sensorimotor feedback on *trial n+1* (Tenenbaum, Griffiths, & Kemp, 2006; Turnham, et al., 2011).

To conclude, we have confirmed that *atypical* biological kinematics associated with an observed novel action are represented and reproduced following observational practice. Although we have previously shown this effect (Hayes et al., 2014; Hayes et al., 2016; Andrew et al., 2016), the current data and Bayesian analyses extend theoretical knowledge of the processes underlying observational practice by implementing a methodology that controls movement direction of a model during action-observation, and thus spatial compatibility.

This method better isolates the representation of *atypica*l kinematics to sensorimotor processes rather than spatial encoding.

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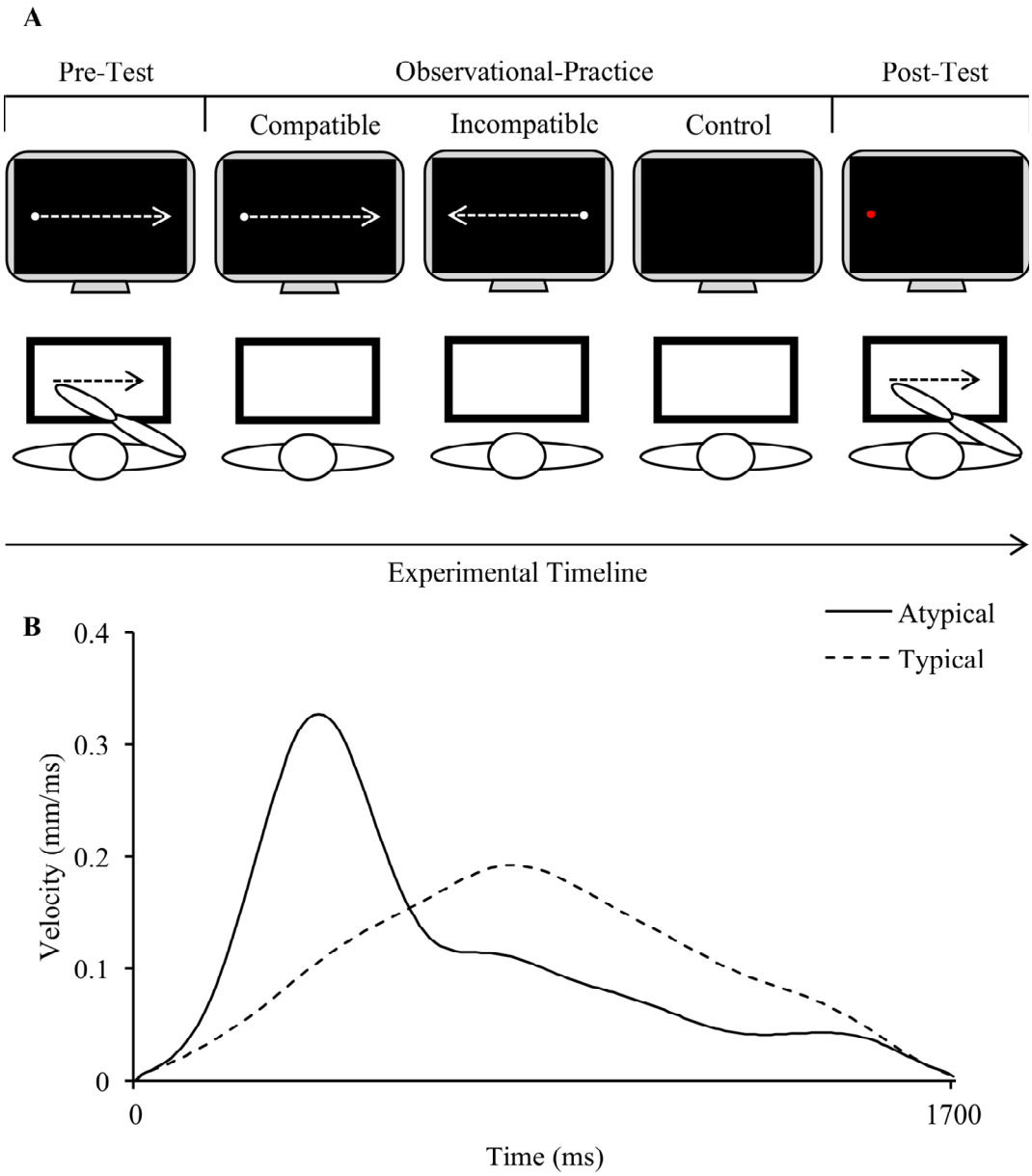

Figure 1. (A) A schematic representation of the experimental design as a function of phase and group. The black outlined rectangle represents a graphics tablet. The white circle displayed on the CRT monitor represents the model. The single-segment movement is depicted by the arrow (i.e., from the start-position to the end-position). (B) Displacement time-series displaying typical (dashed trace) and atypical (black trace) velocity models.

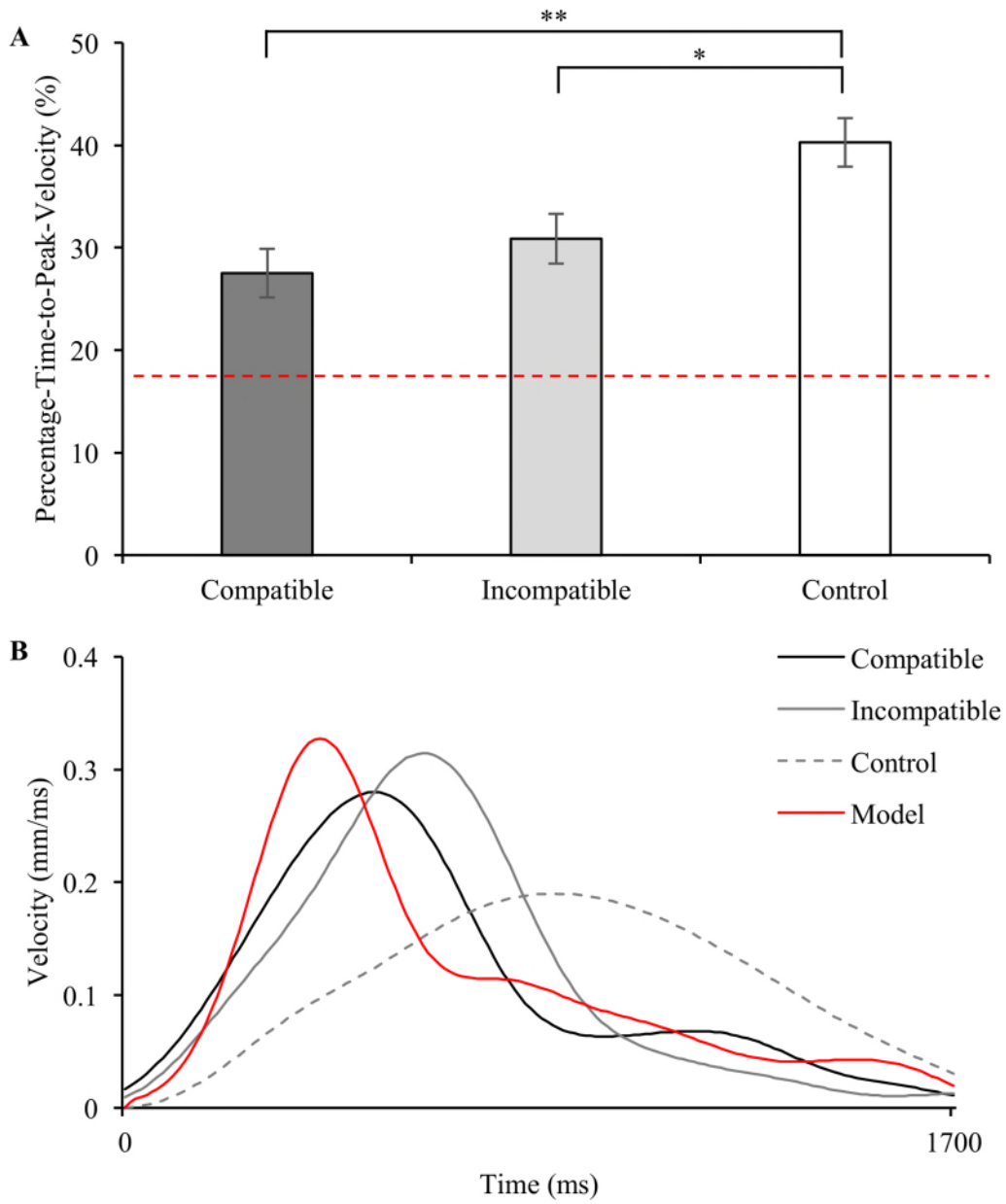

Figure 2. (A) Percentage-time-to-peak-velocity for the post-test (error bars represent standard error of the mean) presented as a function of group. Dashed line represents the atypical model. ** $p < 0.01$; * $p < 0.05$. (B) Exemplar velocity traces of trial performance in the post-test for the compatible (black trace), incompatible (dark-grey trace), and control (dashed trace) groups, as well as the model (red trace).