Action imitation via trajectory-based or posture-based planning

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Abstract

Movement imitation is a significant daily activity involved in social interaction and motor learning. Although imitation remains poorly understood, recent research suggests that it may be achieved in two distinct ways. In posture-based imitation, movements reproduce how the body should look and feel, and are sensitive to the relative positioning of body parts. In trajectory imitation, movements mimic the spatiotemporal motion path of the end effector. We hypothesized that people can imitate via either mechanism. If true, we would expect to see a switch cost when individuals change from one mechanism to the other. To test this, twenty-five healthy young adults performed a sequential multitasking imitation task. Participants were first instructed to pay attention to the limb postures or the hand path of a video-recorded model. They next performed an intervening motor task that was neutral, congruent, or incongruent with the instructed imitation type. Finally, participants imitated the modeled movement. Spatiotemporal imitation accuracy was greatest after a neutral intervening task, and worst after posture matching. When the primary task involved imitating trajectories, we observed a switch cost: movements following the posture-matching intervening task were less consistent with baseline (neutral) performance, suggesting performance was disrupted by the incongruence. Incongruent primary and intervening tasks also reduced cross-subject consistency. Such effects were not observed when imitating limb postures. In summary, we observed a partial dissociation between posture matching and trajectory imitation as a result of instructions and intervening tasks that is nevertheless consistent with the existence of two computationally distinct imitation mechanisms.

Keywords: Posture matching imitation, trajectory imitation, task-switching

1. Introduction

The capacity to imitate another individual's actions is critical to many daily social interactions, and is a key component of motor learning and recovery. For instance, reaching up to return a high-five, learning ballet, or rehabilitation of functional movement after stroke can all involve observing and imitating another's movements. Despite the prevalence of imitation in our day-to-day lives, there is no consensus regarding how humans imitate. Two proposed mechanisms include imitation via matching limb postures, and imitation via matching motion trajectories. However, as these mechanisms have thus far not been studied in the context of a single experiment, it unknown whether individuals can and do imitate using both of these methods.

A large body of prior research suggests that we imitate movements by matching the postural configurations of our own limbs to the limb configurations of the individual-to-be-imitated [1,2]. When performing a high-five, for instance, one might seek to match the shoulder-elbow-forearm-hand positioning of the other person in order to successfully complete the required response. That is, imitation by posture matching involves a body-dependent process of generating goal representations specifying how the limbs should look and feel while performing the action [3]. Indeed, one well-supported theory proposes that, in general, we plan movements with the intent to achieve desired postures [4,5]. Much of the evidence for posture-based imitation stems from research in individuals with limb apraxia, a disorder that commonly results from stroke lesions to the left hemisphere. People with apraxia experience difficulties with imitating gestures [6,7] [1,2] – especially when the relative positions of body parts is critical [8] – despite having otherwise intact motor control. Apraxia is often thought to be related to an inability to form a spatial-configural representation of the body [9], effects which can be observed when individuals imitate postural configurations with their own body or by positioning the limbs of a mannequin [10]. In fact, imitation impairments in these patients have been found to correlate with impairments of the “body schema” [6,11], a representation supporting the ability to represent the spatial relationships between body parts [12,13]. This relationship between imitation deficits and impaired body schema representations in patients with apraxia has been cited as evidence supporting the idea that imitation can occur by matching limb postures.

Recently, we proposed another mechanism for imitation that instead involves matching the dynamic trajectory of the end-effector [14]. To imitate a high-five using this method, an individual may specify their desired movement in terms of an arcing motion of the hand to mirror the motion trajectory of the other individual’s hand. In this case, the configuration of the individual limb segments to achieve this trajectory are not directly specified as in posture-matching imitation, but are simply those most amenable to producing the desired hand motion. Thus trajectory imitation is body-independent, as it requires only specifying the motion path of the hand in space [15]. Indeed, when observing others in preparation for imitation, individuals often focus primarily on the end-effector [16]. Our recent study demonstrated that individuals with apraxia are impaired at imitating motion trajectories even when they are presented with no associated body-posture information [14]. In that study, participants with left-hemisphere stroke and neurotypical controls were asked to imitate motion trajectories cued by a human model or via the movement of a cursor. While neurotypical controls could successfully imitate the movement regardless of how they were cued, imitation performance in participants with stroke was equally impaired in both conditions, revealing that it is not necessary to observe body-configuration information when imitating. However, while suggestive, the previous study did not definitively demonstrate that participants were planning motion trajectories during imitation (i.e., they could have specified their motor plans in terms of postural configurations that satisfy the desired trajectory). As such, the previous study leaves open the question of whether people actually directly plan imitative movements by specifying end-effector trajectories; i.e., whether people actually imitate using both mechanisms.

While in many cases imitating postures and trajectories will result in the same gross behavior, some situations seem likely to favor the use of one mechanism over the other. For instance, when learning classical ballet, a student must focus on matching the correct arm, torso, and leg positions of the teacher, which results in enhanced posture matching imitation abilities over years of training [17–19]. On the other hand, when reaching around obstacles the primary concern is to control the trajectory of the hand [15]. Some previous research has even suggested that an observed action may be represented in terms of both postural forms and motion trajectories [20]; this may be possible as different neuroanatomic structures have been associated with posture matching (left inferior parietal lobe) and trajectory imitation (left dorsolateral premotor cortex) [7,14]. Thus we hypothesized that individuals should able to use either proposed imitation mechanism depending on the specific task goals.

To test this hypothesis, we manipulated the goal of an imitation task by changing the task instructions. Task instructions have been previously shown to strongly modulate how individuals complete a given task. A large body of prior research, for example, has shown that instructions can modulate where people focus their attention while completing various activities, consequently affecting task success. Across a variety of motor activities (from balance and jumping to tennis and golf), instructions to focus on internal features such as how an individual's body is moving (e.g., arm postures during a tennis swing) tends to result in worse performance compared to instructions directing focus toward external features associated with how the environment is affected by the movement (e.g., the motion of the racket and ball) (for reviews, see [21–25]. Thus task instructions can have a surprisingly strong effect on the way in which people perform motor tasks, and suggest the importance of attending to body-independent motion trajectories when body position is not explicitly critical (for a similar effect in stroke patients, see [26]).

Here, we used an instruction manipulation to encourage neurotypical individuals to focus on either imitating postures or trajectories in the same paradigm with the same stimuli. To assess whether participants used both forms of imitation as instructed, we employed a sequential multitasking paradigm designed to create interference in the form of a switch cost associated with transitioning from one mechanism to the other. Often observed in cognitive tasks, switch costs can also impair motor planning [27]. Switch cost effects occur in the sequential multitasking paradigm when an intervening task inserted in the midst of a primary task relies on distinct computational processes [28,29], requiring a large “switch” between tasks and subsequently impairing performance of the primary task. Sequential multitasking paradigms have often been used in action observation studies to assess memory for whether an action has been previously observed or not (for a review, see [30]), showing that memory for static postures and dynamic full movements rely on distinct working memory processes [31]; however, sequential multitasking paradigms have not yet been applied to imitation.

In the current study, participants first observed a meaningless upper arm movement demonstrated by a model on video and were instructed that they would either have to match body postures or match hand trajectories. Participants then completed an intervening task that was designed to be either congruent (no switch cost), incongruent (inducing a switch cost), or neutral with respect to the primary imitation task instructions. We assessed accuracy of movement and timing between the participant and the model, and additionally conducted *post hoc* analyses comparing participant's movement consistency in the congruent and incongruent conditions against their own performance in the neutral condition, as well as with the other participants' performance in the same condition. We predicted that in all cases, performing incongruent primary and intervening tasks (e.g., trajectory imitation instructions and the posture-matching intervening task) would induce a larger performance decrement compared to performing congruent primary and intervening tasks (e.g., trajectory imitation instructions and the trajectory intervening task). Such findings would provide evidence in support the existence of two computationally distinct means of imitating – by matching postures or copying trajectories – and suggest that individuals are able to employ either mechanism depending on the task goals.

2. Methods

2.1 Participants

We recruited participants from Salus University through email solicitation with recruitment procedures approved by the Salus Institutional Review Board. Participants were graduate students or faculty in a healthcare field, such as Occupational Therapy or Optometry. Twenty-five young adults completed the experiment across two sessions (22 female). The average age was 25.0 years (*SD*=4.8, range 22 to 41 years). Participants were right-handed, had full range of motion of the arm, normal or corrected-to-normal vision, and no known neurological disorders. All participants provided written informed consent with procedures approved by the Einstein Healthcare Network Institutional Review Board. Participants completed two sessions; the first session lasted approximately 1.5 hours, and the second session occurred a minimum of one week later and lasted approximately 1 hour. Participants were compensated $15 per hour for their time.

2.2 Materials

For the imitation experiment, participants were seated in a stationary chair 176 cm in front of a 42.5” 4K LG monitor (refresh rate, 60 Hz) mounted on the wall directly in front of the chair, where videos of an actor or static images were displayed using custom experiment scripts written in C++ (https://github.com/CML-lab/DualTaskImitation).

Movement kinematics were recorded using a magnetic motion tracking system (TrakSTAR, Northern Digital Inc., Ontario, CA) with a wide-range transmitter (range, 6 feet) and 4 standard (8mm) sensors. Sensors were placed on the top of the right hand near the wrist, the right elbow joint, and on each shoulder. Movement was recorded at an effective sampling rate of 420 Hz. A piece of tape on the participant’s right thigh, near the knee, served to indicate a home position where the participant should return his or her hand between movements.

Following the imitation experiment, participants were seated at a desk in front of a desktop computer (23.8” Acer R240HY widescreen monitor, 60 Hz refresh rate) and completed a computerized Corsi Block Tapping Task in the Psychology Experiment Building Language (PEBL; http://pebl.sourceforge.net/battery.html).

2.3 Procedure

The imitation experiment consisted of a sequential multitasking paradigm [28,29] in which participants were asked to watch videos of an actor generating a movement with what appeared to be his left arm, complete an intervening task, then imitate the movement they had watched using their right arm (i.e., imitating as if the movement was observed in a mirror, which is considered a more automatic and natural form of imitation; [32,33]; see Figure 1). Movements of the actor were in fact recorded using the actor's right arm to ensure greater comparability to the participants' own movements; videos were then mirror-reversed to make it appear as if the actor was using his left arm. For the imitation portion of the task, movements consisted of two or more static postures (with a ~1 second hold at each posture) with dynamic transitions between those postures, and were designed to have no obvious meaning associated with the movement. For example, one movement would consist of lifting the arm off the lap and bending it into a raised "L" shape out to the side (posture 1), a brief pause, extending the arm out to the side to a low diagonal (transition to posture 2), a brief pause, and then returning the arm to the lap (see Figure 2). Postures and transitions involved motion about the shoulder and elbow, but did not include flexion/extension at the wrist or movement of the fingers; the hand remained in a fist throughout the motion. Movements were selected to range in difficulty based on whether they included 1 or 2 dynamic transitions (2 or 3 static postures, respectively), with the transition movements being either straight or curved. After watching the movement and completing an intervening task (see below), participants were instructed to wait until the go cue, in which the word "Imitate!" was displayed on the screen along with an auditory tone, to begin imitating. The go cue appeared 500 ms after the end of the intervening task. If participants moved before the go cue (detected as movement of the hand more than 5 cm from the home position), the trial restarted.

On each day (Fig. 1b), participants were given a specific set of instructions for the entire session about what movement features to focus on during imitation (see Instructions manipulation below). They then completed 4 imitation-only practice trials in which they watched a video of the model performing the movement, and were immediately instructed to imitate the observed movement with no intervening task present. Next, participants completed 3 blocks in each session, one for each of the 3 intervening tasks described below. Each block began with 10 familiarization trials of the intervening task to be performed in that block. This was followed by 4 combined practice trials, where they first watched the model movement without moving their hand, completed the same intervening task they had just practiced, then performed their imitation of the model movement upon seeing a go cue. Finally, participants completed 20 test trials (analogous to the combined practice trials) to finish the block, and received a brief (~30 seconds) break before beginning the next block. Following the completion of all blocks in the session, participants completed the Corsi task.

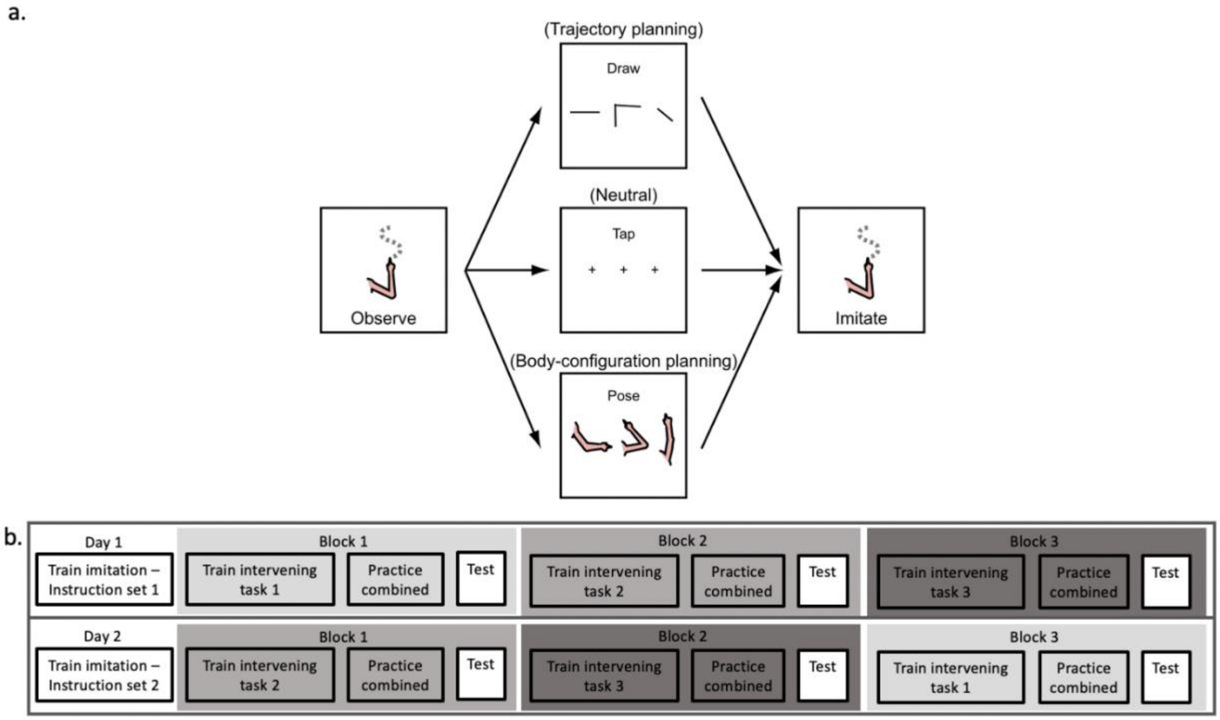

Figure 1. Overview of experimental paradigm.

2.3.1 Primary task: Instruction manipulation. The primary task (PT) was to imitate gestures. Instructions were used to manipulate the focus of attention during imitation on either limb postures or end-effector trajectories. That is, participants received a different set of instructions in each session (order counterbalanced between subjects). For each instruction, the practice videos were edited to emphasize the relevant set of instructions. In the Posture Matching instructions (Posture Matching PT), the experimenter instructed participants to: “Pay attention to the position of the body parts—for example, how the elbow, shoulder, and wrist are positioned.” In the practice videos, when the model reached each static posture, the movement was momentarily paused and straight red lines appeared on the model’s forearm and upper arm to encourage participants to pay attention to the positions of the body parts relative to each other (Fig. 2, top panel). In the Trajectory instructions (Trajectory PT), the experimenter instructed participants to “Pay attention to the path that the hand takes through space.” In the practice videos, the model’s hand was encircled by a red circle that followed the movement of the hand; upon completion of the movement, the full path of the movement was displayed as a red line on the screen to encourage participants to attend to the path of the end effector (Fig. 2, bottom panel). The experimenter also verbally reminded participants to either “focus on the position of the body parts” or to “pay attention to the path the hand takes through space” at 7 points during each session: prior to the instruction-only practice videos at the very beginning of the session, prior to the combined practice trials (one for each of the three intervening tasks described below), and prior to the test trials for each intervening task. In all cases, participants were instructed to imitate the movement at the same speed as the model.

Figure 2. Snapshots of Instruction videos. The top panel is an example of the instruction video provided in the Posture Matching PT. Participants watched the model perform a two-posture movement, pausing at each position. Emphasis lines appeared to draw attention to the position of the body parts (wrist, elbow, shoulder). The bottom panel is an example of the instruction video provided in the Trajectory PT. Participants watched the model perform a two segmented movement with the circle tracking the movement of the hand (bottom left and bottom middle). Upon reaching the end position, a "trace" of the movement appeared, which represented the path the hand took through space (bottom right). Emphasis lines were only present during the initial four practices on each day of testing. Photos of author M. Isaacs used with the author's permission.

In order to minimize learning effects, we randomized the order of the movements within easy (the first 8 trials, consisting of 2 static postures each) and hard (the second 12 trials, consisting of 3 static postures each) trials between blocks so that participants did not view the movements in the same order each time. We also created forward and reversed videos of each movement, which contained equivalent kinematic information but allowed us to minimize the number of repeated exposures to the exact same movements. Reversed videos were generated by running time backwards in the videos. Participants saw either the forward or the reversed videos in the first session (paired with either Posture Matching or Trajectory PTs), and then the other set of videos in the second session, paired with the other set of instructions. We hypothesized that the direction of movement would not significantly influence imitation accuracy. For trials where the video was reversed, we also inverted time in the kinematic recordings from the participants such that in our analyses the recorded gestures from all trials and all participants were compared to the kinematics of the forward-in-time model movement. Note that the model kinematics were the exact kinematics recorded from the model during filming of the movement videos for this experiment, using the same trakSTAR and placement of trackers.

2.3.2 Intervening tasks. We included three intervening tasks (IT), which were manipulated within-subjects. The order of ITs was randomized and counterbalanced between participants and between sessions. These tasks were meant to evoke processing interference with the primary imitation task; as such one task was related to planning limb postures and a second was related to planning trajectories. The third task served as a control for the working memory demands associated with remembering the PT while performing an IT. In these three ITs, participants were required to produce a movement once every 1200 ms in time with a metronome for 6 iterations before returning their finger to the home position.

In the Posture Matching IT, participants were asked to reproduce three body postures presented in pictures on the screen, from left to right, in time with the metronome (see Figure 3). In the Trajectory IT, participants saw three meaningless shapes on the screen, and were asked to extend their right arm directly in front of them and draw the shapes in the air using their whole arm in time with the metronome. Examples of these shapes include a straight horizontal line, a rotated “L”, and a diagonal line. Drawing movements were to begin at the dot in each image (see Figure 3).

To control for working memory demands associated with the delay that the intervening tasks created between watching the action and performing the imitation, we included a neutral intervening task in which participants saw 3 fixation crosses presented side by side on the screen and simply had to tap their hand on their thigh in time with the metronome – a motor response that does not preferentially invoke the planning of either body configurations or trajectories. Fixation crosses were used to provide an analogous amount of visual cuing information across conditions. When tapping, participants were instructed to slide their hand up their leg away from the home position, and keep the heel of their hand on their leg.

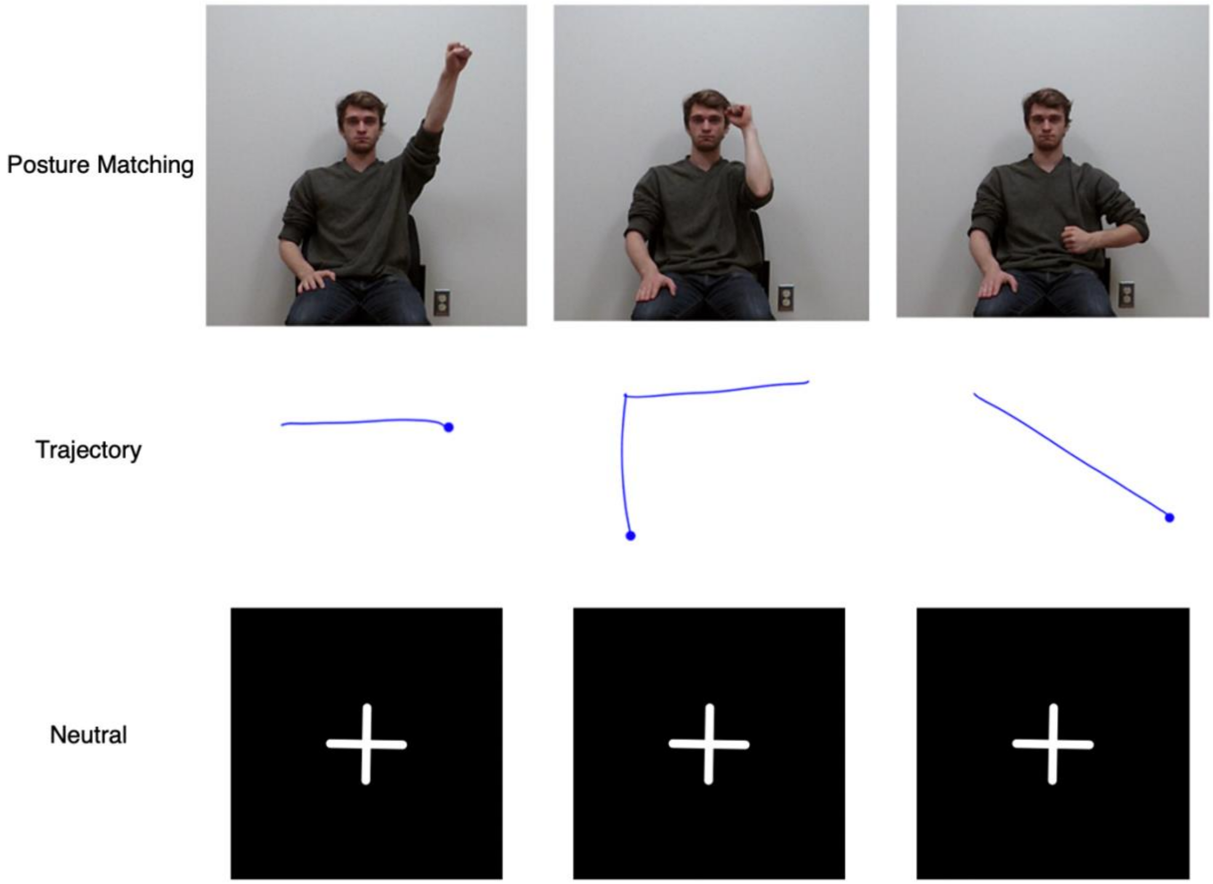

Figure 3. Intervening Tasks. Participants completed each of three ITs for both sets of Instructions. In the Posture Matching IT (top row), participants matched the arm positions in the photographs of the model from left to right in time with a metronome that presented a tone once every 1200 ms. They heard 6 tones and were asked to match the postures from left to right twice through. Posture Matching IT is congruent with Posture Matching PT, but incongruent from Trajectory PT. In the Trajectory IT (middle row), participants raised their hand in front of them into the air and drew the shapes one at a time from left to right in time with the metronome. They completed the row of shapes twice for 6 metronome tones. We instructed participants to start the drawing movement at the circle on each shape. The Trajectory IT is congruent with Trajectory PT, but incongruent from Posture Matching PT. In the Neutral IT (bottom row), participants tapped their hand on their upper leg in time with the metronome, 6 times. We expected the Neutral IT to be unrelated to either Posture Matching or Trajectory PT and to serve as a control for working memory demands. Photos of author M. Isaacs used with the author's permission.

2.3.3 Corsi task. As our task required individuals to hold a multi-segment movement in mind while performing an IT, we wanted to control for potential individual differences in spatial working memory abilities. To assess spatial working memory, participants completed a standard computerized Corsi block tapping task at the end of each session. Participants viewed a layout of nine blue squares on a black background. Blocks briefly turned yellow one at a time in sequence, and after the last block in the sequence returned to blue, participants were instructed to reproduce the sequence by clicking on the boxes in the same order. Participants first completed 3 practice trials, then began the experimental trials. Sequences progressed in difficulty starting with 3 blocks. If participants correctly reproduced at least one of the two sequences at that length, the sequence became longer. When participants failed both attempts, the task ended. The maximum number of blocks correctly reproduced was used as that individual's Corsi block span. For each individual, we took the average of their two Corsi span assessments. The average Corsi span across individuals was 6.68 (*SD*=1.11, range 5 to 9).

2.4 Data Analysis

Kinematic data were analyzed in Matlab using custom scripts. Movement start and end were automatically identified according to a velocity threshold of 5 cm/s. These points were verified by visual inspection and manually adjusted if necessary by one researcher, then they were independently confirmed by a second researcher. The start of each movement was identified as the point at which participants initiated a movement away from the first static posture, and the end of each movement was the point at which participants arrived at the final static posture; that is, we only included the "core" portion of the movement from the first to the last target postures, excluding motion to and from the home position. As a preliminary analysis, we counted the number of movement segments executed on each trial using the same velocity threshold method to mark the movement segments. Segment-count errors were identified when there were more than or fewer than the correct number of movement segments generated during that trial. We observed a greater likelihood of producing movement segment errors after the Posture Matching or Trajectory ITs compared to the Neutral IT, suggesting that the Neutral IT was indeed "neutral" with respect to the primary imitation task[1].

2.4.1 Primary task performance. Accuracy in the primary task (imitation performance) was measured by quantifying the degree of dissimilarity between the participant's kinematics and the model's kinematics (analysis 1). We also performed two *post hoc* analyses to assess within-subjects' and between-subjects' consistency of movement. We compared the participant's kinematics in one condition to their own kinematics for the same movement in another condition (analysis 2), and the participant's kinematics on a given movement compared to the kinematics

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[1] Segment-count errors comprised 3.33% of the data. Neither Instruction ($\chi^2(3)=.97$, $p=0.8$) nor the Instruction*Intervening Task interaction ($\chi^2(2)=0.78$, $p=0.7$) had a significant effect on segment-count error trials according to a binomial generalized linear model, but Intervening Task explained significant variance in the data ($\chi^2(4)=15.50$, $p=0.004$). Both Posture Matching ($z = -3.26$, $p=0.003$) and Trajectory ($z = -3.18$, $p=0.004$) ITs increased the likelihood of a segment-count error compared to the Neutral IT, but there was no difference between Posture Matching and Trajectory ITs ($z = 0.08$, $p=0.9$).

of the other participants for that same movement, for each condition (analysis 3). For these three analyses we used a Procrustes Distance (PD) metric, which is a measure of dissimilarity between two geometric shapes after accounting for any affine transformations (i.e., translation, rotation, and scaling) [34]. A larger PD indicates greater dissimilarity, or error, compared to the referent.

To describe the motion of the entire arm throughout the movement, we projected all data into a coordinate system defined by the orientation of the participant's body in space (where x points to the participant's right, y points forward, and z points up). We then developed a novel method of summarizing the configuration of the arm by treating the arm as a plane rotating in 3D space, with its origin at the shoulder, y axis directed along the shoulder-elbow vector, z axis directed along the normal to the plane, and containing the elbow-hand vector (Figure 4). We calculated the instantaneous orientation of the plane as a quaternion relative to the body-centered coordinate frame. Two additional angles were needed to define arm orientation fully; these consisted of the elbow angle (the angle from the shoulder-elbow to the elbow-hand vector), and the roll angle of the hand within the plane (reflecting pronation/supination of the forearm, defined as the angle between the normal to the hand sensor and the normal to the plane). These latter two angles were normalized by 360 degrees to put them on a comparable scale to the arm-plane quaternion. This six-element vector was computed at every time step, and the entire high-dimensional trajectory was then time-normalized to have 200 equally spaced points. Finally, we compared this time-normalized arm representation against a similarly constructed one for the model. For this comparison we used a modification of the PD algorithm in which movements could be scaled differently in each dimension, as it improved the quality of the fits [35].

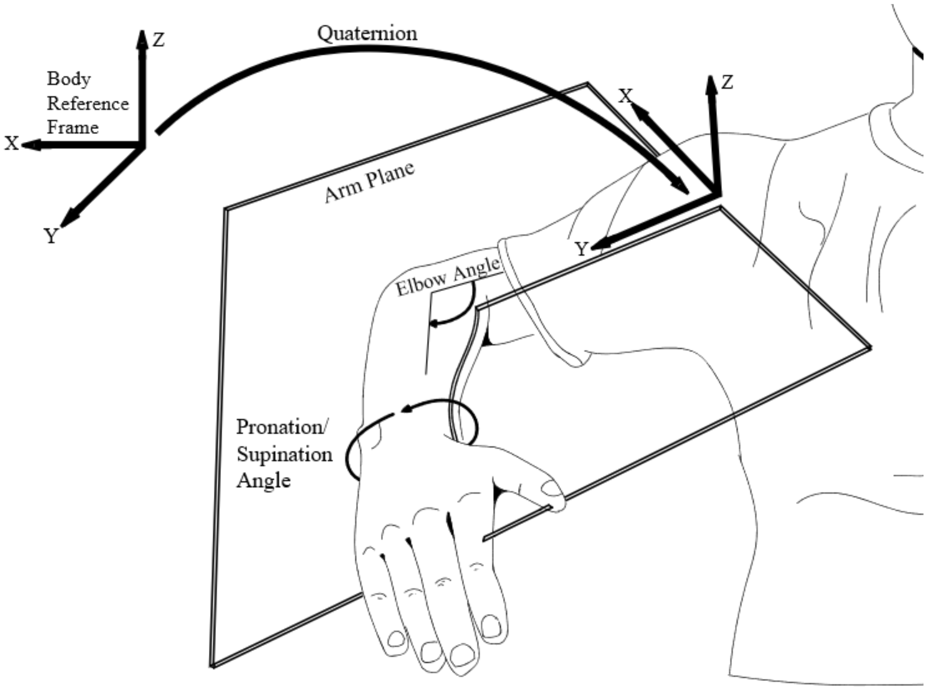

Figure 4. Arm configuration at each time step was described using six values: a quaternion that described the rotation of the axes of an "arm plane" (defined as the plane containing the shoulder-elbow and elbow-wrist vectors) relative to a body-centered reference frame (4 values); the angle of the elbow within the arm plane (1 value); and the pronation/supination angle of the forearm (1 value). The latter two angles were normalized by 360 degrees to be of a similar scale as the individual elements of the quaternion.

PD measures are typically bounded between 0 and 1, where 1 reflects maximal dissimilarity [34,36]. However, when the algorithm is modified to allow each dimension to scale differently as suggested by Rohlf and Slice [35], PD values may exceed 1. Nevertheless, even in such cases PD values remain relatively constrained to the range 0-1 such that PD values greater than 1 reflect unusually large behavioral outliers; we therefore removed these outliers in our analyses. This resulted in the removal of 0.03% of our data (8 trials) for our primary analyses, 0.3% of the data for our first *post hoc* analysis (69 trials), and 0.03% of the data for our second *post hoc* analysis (123 trials).

2.4.2 Movement time. As participants were instructed to imitate movement speed as well as spatial position, we also assessed temporal accuracy errors. Timing errors were computed as the absolute difference between the time taken for the participant and the model to produce a given movement. Larger values indicate a greater difference between participant and model movement times, suggesting more timing dissimilarity.

2.4.3 Statistical analysis. All statistical analyses were performed in R [37]. We used the *lme4* package [38] to fit generalized linear mixed effects models, with significant effects of interest identified by calculating likelihood ratio tests between models with and without the factor of interest. Because the PD data are bounded and non-normally distributed, we used a generalized linear model with a log link to analyze imitation accuracy. For the Movement Time data, we used a square root link, which normalized the data to resemble a more normal distribution. Because of experimenter or technical error, 86 of 3000 trials (2.87%) were missing. Our hypothesized models included fixed effects of Instruction (2 levels), Intervening Task (3 levels), and the Instruction*Intervening Task interaction (2x3), along with a random effect of Participant. We also checked for an effect of instruction Order and video Direction (forward or reverse) in our models; we hypothesized *a priori* that neither of these factors would have a significant impact on our data. Finally, we tested whether performance was influenced by spatial working memory span. For all statistical models, we performed pairwise contrasts with the *emmeans* package [39] using a Tukey adjustment for multiple comparisons.

3. Results

3.1 Imitation is disrupted by an imitation-related intervening task

In our first analysis we compared participants' imitation to the model to assess the extent of spatial dissimilarity using the Procrustes Distance algorithm. We first checked if there were any effects of video Direction and instruction Order. As hypothesized there was no significant effect of Direction ($\chi^2(1)=0.38$, $p=0.5$) or Order ($\chi^2(1)=0.38$, $p=0.5$), so we removed these terms from the model. The resulting model suggested a trending effect of Intervening Task ($\chi^2(4)=8.60$, $p=0.07$) but no effect of Instruction ($\chi^2(3)=0.97$, $p=0.8$). There was also no significant interaction ($\chi^2(2)=0.92$, $p=0.6$). Planned pairwise contrasts revealed that imitation following the Neutral IT was significantly more accurate (lower PD) compared to imitation following the Posture Matching IT ($z=-2.97$, $p=0.008$; see Figure 4). PD following the Trajectory IT did not differ significantly from Neutral ($z=-1.91$, $p=0.1$) or Posture Matching ($z=1.06$, $p=0.5$) ITs. Adding average Corsi block span to the model did not improve model fit ($\chi^2(1)=1.29$, $p=0.3$), suggesting that imitation accuracy was not significantly related to spatial working memory. See Table 1 for means in each condition.

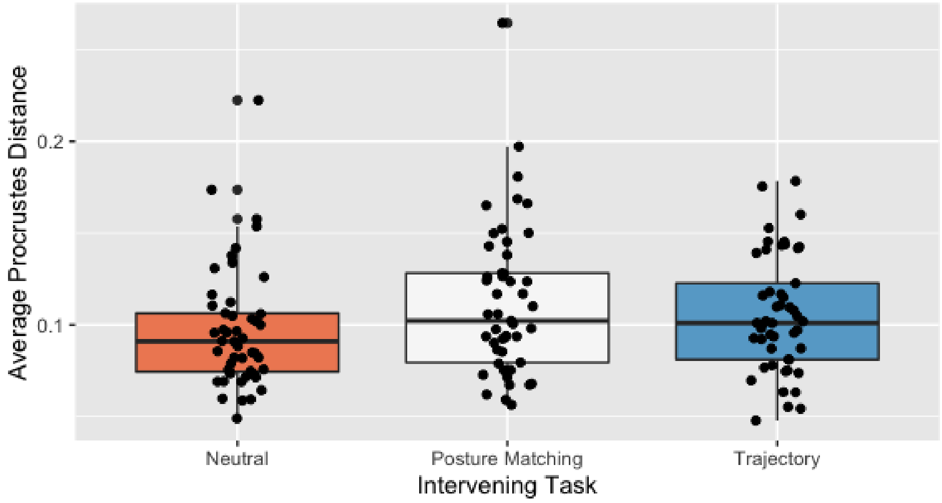

Figure 5. Boxplot of participant's average PD across the 20 trials in each condition.

Table 1. Average imitation performance compared to the model.

	Posture Matching Primary Task			Trajectory Primary Task		
Intervening Task	Posture Matching	Trajectory	Neutral	Posture Matching	Trajectory	Neutral
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*

PD	.111 (.137)	.103 (.119)	.099 (.122)	.114 (.145)	.108 (.130)	.096 (.128)
Movement Time	.831 (.623)	.777 (.608)	.724 (.594)	.844 (.625)	.785 (.614)	.696 (.564)

Note.

Participants were also instructed to imitate movement timing (movement speeds and static posture hold times) as well as position; thus we additionally examined how well participants were able to imitate total movement time by comparing the absolute difference between the time taken for the participant and the model to produce a given movement (Fig. 5). Larger values indicate a greater timing dissimilarity (i.e., more error) between participant and model movement times.

We first checked if there were any effects of video Direction and instruction Order. There was a significant effect of Direction ($\chi^2(1)=50.29$, $p<0.0001$) but not of Order ($\chi^2(1)=0.85$, $p=0.4$). We therefore retained Direction as a nuisance variable in our analysis. Using this model, we observed a significant effect of Intervening Task ($\chi^2(4)=25.57$, $p<0.001$), but no significant effects of Instruction ($\chi^2(3)=0.82$, $p=0.8$), nor was there an Instruction*Intervening Task interaction ($\chi^2(2)=0.81$, $p=0.7$). Planned pairwise contrasts revealed that imitation movement time errors following the Neutral IT were significantly smaller than Movement Time errors following the Posture Matching ($t=-7.29$, $p<0.0001$) and Trajectory ITs ($t=-4.16$, $p=0.0001$). Movement time errors following the Posture Matching IT were significantly larger than following the Trajectory IT ($t=3.13$, $p=0.005$). See Table 1 for means. These data reveal that individuals were more accurate at imitating movement timing following the Neutral IT than the two interference conditions, and moreover that imitating movement time was more accurate after Trajectory than Posture Matching ITs. Taken together with measures of spatial imitation accuracy, these results suggest that in general, having to perform an intervening task related to either of the hypothesized mechanisms supporting imitation is disruptive to the ability to reproduce both spatial and temporal movement features. We also note that the Trajectory IT may be a little less disruptive compared to the Posture Matching IT.

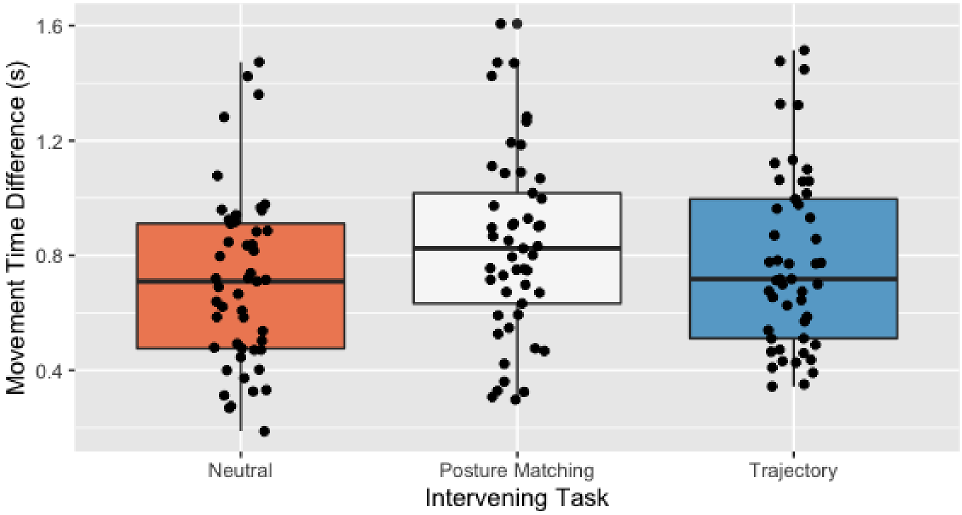

Figure 6. Boxplot of participant mean movement time errors in each condition.

3.2 Post hoc analyses

3.2.1 Within-subjects consistency reveals a switch cost for imitating trajectories

In the prior analysis, we assessed how accurately people imitated in contrast to the ideal (model) movement. While we did not observe the expected interaction between primary and intervening tasks, this may have been due to a large amount of noise or variance unrelated to our manipulations. That is, because it may be challenging in general to exactly reproduce the kinematics of an observed model, our measure of accuracy compared to the model may not have been sufficiently sensitive to detect any additional behavioral variance arising from the IT manipulation. Thus as an additional, potentially more sensitive measure of imitation performance, we also examined the ability for any given individual to repeatedly produce the same movement consistently in all conditions. In other words, the disruption induced by an intervening task might be better detected by comparing each participant's performance for a given movement shape and condition to their own performance of the same movement shape in a different condition (i.e., a measure of variance versus a measure of bias). Specifically, since the same set of movements were imitated in every block, and because in our prior analyses we confirmed that the Neutral condition is least disruptive of imitation accuracy, we calculated a PD value that represented a participant's performance dissimilarity following the Posture Matching and Neutral ITs, and following the Trajectory and Neutral ITs, within each Primary Task instruction condition. A higher PD value indicates less imitation consistency with reference to the neutral condition, suggestive of greater disruption due to the IT.

We again ran a generalized linear mixed effects model with fixed effects of Instruction (Posture Matching or Trajectory) and Intervening Task Comparison (Posture Matching vs. Neutral or Trajectory vs. Neutral) as well as the Instruction X Intervening Task Comparison interaction. There was no significant effect of Order ($\chi^2(1)=0.98$, $p=0.3$) but there was a significant effect of video Direction ($\chi^2(1)=5.33$, $p=0.02$). We dropped Order and retained Direction as a nuisance variable in the model. With this model, there was no significant effect of Instruction ($\chi^2(2)=4.95$, $p=0.08$), and no significant effect of Intervening Task ($\chi^2(2)=4.94$, $p=0.08$), but there was a significant interaction ($\chi^2(1)=4.52$, $p=0.03$). Planned contrasts revealed a significant difference between Intervening Task comparison types for the Trajectory PT ($z=1.97$, $p=0.049$) but not for the Posture Matching PT ($z=-1.01$, $p=0.3$). As depicted in Figure 6, for the Trajectory PT, there was greater consistency between performance following a Neutral IT and Trajectory IT than there was between performance following a Neutral IT and Posture Matching IT. In other words, the combination of Trajectory PT and Trajectory IT resulted in performance that was relatively less disrupted (i.e., more consistent with performance following the Neutral IT) compared to other combinations. This effect was present regardless of the spatial working memory span of individual participants: adding Corsi block span to the model did not improve model fit ($\chi^2(1)=0.41$, $p=0.5$). In summary, we observe a switch cost effect due to Intervening Task within the Trajectory PT, but not within the Posture Matching PT. That is, the goal of what participants are trying to imitate affects how consistent individuals are across repeated imitation attempts, and moreover, participants typically imitate less consistently when the intervening task is incongruent with the instruction type (at least for Trajectory instructions).

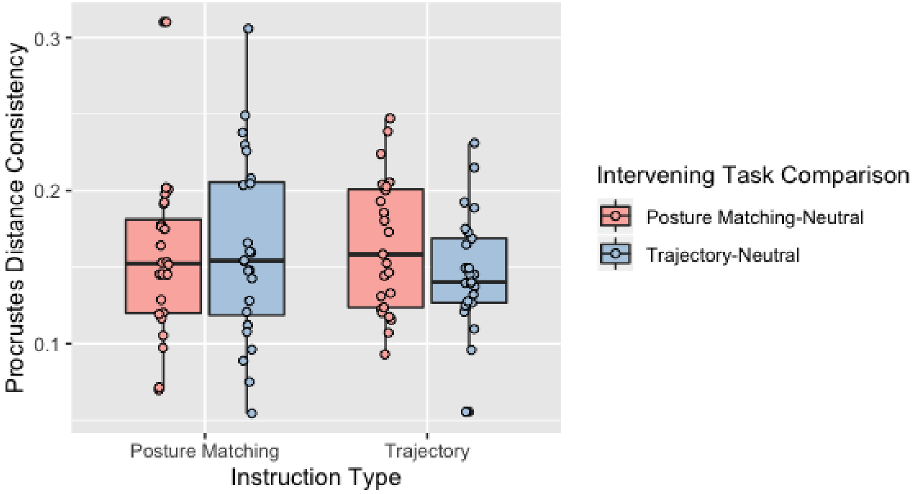

Figure 7. Boxplot of Procrustes Distance results for imitation consistency. A larger number indicates more dissimilarity within an individual comparing imitation following one of the interfering intervening tasks to the Neutral IT.

3.2.2 Switch costs reduce cross-subject consistency

Finally, as an additional *post-hoc* exploratory analysis we asked how consistently participants performed with respect to each other. This analysis allowed us to examine whether a particular combination of instruction type and intervening task resulted in less consistent behavior across individuals (i.e., more disrupted imitation leading to greater inter-subject variability), which could again suggest the presence of a switch cost. For this analysis, we calculated a PD value for every participant compared to every other participant on each trial within a specific PT and IT condition (e.g., Participant 1's imitation of movement 1 in the

Posture Matching PT + Posture Matching IT condition compared to participants 2-25 for that same movement and condition). We ran a generalized linear model to assess for effects of Instruction, Intervening Task, and the Instruction*Intervening Task interaction on between-subjects' consistency. Based on this model, we observed significant effects of Instruction ($\chi^2(3)=11.27$, $p=0.01$), Intervening Task ($\chi^2(4)=144.52$, $p<0.0001$), and the interaction ($\chi^2(2)=8.26$, $p=0.016$). Planned contrasts again revealed a task switching effect when the primary task was to imitate Trajectories. Critically, for the Trajectory PT, PDs after the Posture Matching IT were higher than PDs after the Trajectory IT ($z=3.31$, $p=0.003$). This same task switching effect was not observed for the Posture Matching PT ($z=-0.64$, $p=0.8$) (See Fig. 8). We also noted that for both instruction types, PDs after the Neutral IT were significantly lower than PDs after either the Posture Matching IT (Trajectory PT: $z=-8.29$, $p<0.0001$; Posture Matching PT: $z=-7.11$, $p<0.0001$) or the Trajectory IT (Trajectory PT: $z=-4.99$, $p<0.0001$; Posture Matching PT: $z=-7.74$, $p<0.0001$), again demonstrating that the neutral IT was least disruptive in general and therefore resulted in the greatest performance consistency across individuals. These results, combined with the within-subjects consistency findings above, are consistent with our hypothesis that participants exhibit greater imitation performance decrements (i.e., larger switch costs) when the instructions and intervening task are incongruent, particularly when imitating trajectories.

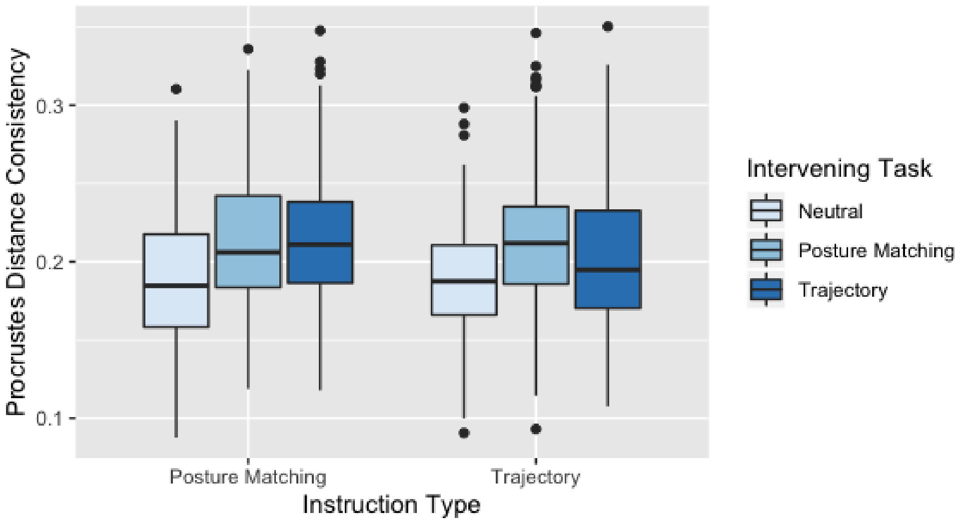

Figure 8. Boxplot of the average PD of the 20 trials in each condition for every subject pairing. A point represents a subject pairing (e.g., subject 1 and 4) and how consistent their performance was across the trials in that condition.

4. Discussion

In the current study we aimed to test whether individuals could imitate via either posture matching or trajectory mechanisms using a sequential multitasking paradigm. We reasoned that if people can imitate using both mechanisms, we should observe a cost when switching from one mechanism to the other, such as when performing an intervening task that requires a different processing mechanism compared to the primary task. Our primary task was to imitate gestures by attending to either the limb postures or path of the hand of the model. In tandem, participants also completed one of three motor intervening tasks: two that were congruent/incongruent with the instructions and designed to potentially create interference, and one that served as a neutral baseline. In our primary analysis, we saw no overall effect of the primary task, but did observe that the neutral intervening task was least disruptive to imitation as suggested by better spatiotemporal imitation accuracy (i.e., lower spatial dissimilarity and smaller movement timing errors) when comparing individuals' behavior against the model. Once we better controlled for individual subjects' variability by measuring within-subjects consistency, however, we were able to observe a task switching effect in the trajectory primary task condition. Specifically, when participants had to complete a posture-matching intervening task that was incongruent with the primary trajectory imitation task, their performance was less consistent with their own baseline performance. Finally, in our analysis of consistency between subjects, we also observed a task-switching effect for trajectory imitation such that consistency decreased when the intervening task was posture based, and thus incongruent with the primary imitation task. These effects were unrelated to any potential individual differences in spatial working memory as assessed by Corsi span (for similar lack of working memory effect, see [40]). Each result is discussed below in turn. Together these results suggest that switching between trajectory and posture matching imitation tasks is computationally burdensome and induces a switch cost, supporting our hypothesis that people can imitate via either of these two distinct methods.

In our primary analysis of spatiotemporal accuracy compared to the model, our results were only partially consistent with our hypothesis. While we expected an interaction between primary and intervening tasks that would provide evidence of a switch cost, we only observed an effect of intervening task. The posture matching and trajectory intervening tasks were intended to be cognitively and motorically disruptive of the primary task, whereas the neutral intervening task was intentionally designed to obviate these spatio-motor and cognitive demands. Our results suggest that indeed, performance of the primary imitation task following the neutral intervening task was most similar to the model, regardless of the task instructions. In contrast, the posture matching and trajectory intervening tasks both elicited a "cost" compared to the neutral intervening task in the form of decreased spatiotemporal accuracy, suggesting that these intervening tasks were indeed disruptive of imitation. Additionally, imitation following the trajectory intervening task was more temporally accurate than imitation following the posture matching intervening task. While this same pattern was not observed for spatial accuracy, this result suggests that the trajectory intervening task may be a little less disruptive compared to matching postures.

In our first *post hoc* analysis we then compared participant's performance in each intervening task to their own baseline (neutral) performance. Unlike in our measures of imitation accuracy, this measure of consistency yielded clear evidence of a switch cost when the primary task was to imitate trajectories. Switching to a posture matching intervening task elicited a "cost" that impaired performance of the primary task. We suspect that the reason this effect may not have been observed in our original accuracy measures is because we were actually measuring two kinds of errors in that case: errors related to imitation more generally, and errors related to potential disruptions by the intervening task. The former source of error could arise from needing to attend to and perform a mirror mapping of the model's movement to one's own body, maintain the components of the movement in working memory, and execute the movement – each of which would introduce "noise" that would be relatively independent of the specific imitation condition. By comparing each person's performance to their own "baseline" performance (i.e., by assessing movement consistency), we could account for these sources of error and instead more directly examine specific disruptions arising from the intervening task. Thus by adopting a within-subjects analysis, we were better able to detect a task-switching effect in the form of a switch cost when participants had to switch between trajectory imitation and a posture matching intervening task [28].

Intriguingly, we observed similar effects when examining between-subjects consistency in our second *post hoc* analysis, such that consistency across participants decreased when switching between incongruent tasks. Although seemingly counterintuitive, we propose that in contrast to the previous within-subjects analysis that sought to remove variability from one individual to the next, this analysis relied upon that variability. That is, we used the variance across individuals following the neutral intervening task as a baseline level of variance in our population, and assessed whether the intervening task introduced additional between-subjects variability over and above that baseline. We again saw that incongruent imitation tasks elicited a task-switching cost resulting in less consistency between individuals, while congruent imitation tasks led to greater consistency (at least for the trajectory primary task). Moreover, when taken alongside our finding of temporal imitation accuracy, this suggests that imitating trajectories may be an overall easier form of imitation as people tend to produce more accurate movements and are more similar to each other, consistent with the notion that planning trajectories may be less computationally burdensome [15]. However, this result is curious given that trajectory plans do not constrain the position of the limb segments, and yet our consistency measures examine similarity across arm configurations. We speculate that requiring individuals to focus on the greater number of degrees of freedom required to control all the joints may actually impair movement accuracy (particularly if different individuals emphasized control of different joints), in line with prior studies [22].

Our findings are consistent with prior research that has posited the existence of at least two distinct ways to imitate, with evidence for both posture matching [1,2,7] and trajectory matching [14] mechanisms. These two dissociated processes are hypothesized to emphasize different aspects of the movement-to-be-imitated: posture matching requires the ability to represent how the body should look and feel during performance of the movement, whereas trajectory matching instead requires the ability to represent how the end-effector motion should look in a body-independent manner. As these are both useful but distinct means of imitating movements, we hypothesized that people may be able to make use of both mechanisms. Our current study is the first to our knowledge to directly compare these two mechanisms in the same paradigm (and using the same stimuli) to determine whether people can indeed imitate in both ways. There are clearly conditions in which body posture and joint angles are critical to imitation success, such as in learning ballet or modern dance [17–19], or in the static posture imitation tasks that are often used with clinical neurological populations to test for apraxia (e.g., [1,2,10]). However, a trajectory-matching method of imitation may be more ubiquitous, as the action need not be contingent on body-specific properties. Thus this mechanism may not only support imitation using a different effector, but also imitation between species who have different effectors (a human and a dolphin), or species that differ vastly in size and proportion (a human and a monkey; [41]).

Trajectories are also a more computationally compact way of representing a movement, as they need only specify spatiotemporal parameters of the end-effector rather than information about all of the joints. Indeed, our timing data are consistent with this claim that trajectory imitation may be less computationally burdensome. Furthermore, a combined trajectory primary/intervening task resulted in the closest performance to an individual’s own baseline performance, suggesting that this combination has a lower computational burden compared to combinations of primary/intervening tasks that include posture-matching. These findings are also consistent with prior research demonstrating that focusing on external, body-independent movement features (potentially akin to end-effector trajectories) is less attentionally demanding and yields greater movement automaticity compared to focusing on internal body-based movement features (e.g., [25,42]). Finally, we note that trajectory representations seem to be readily accommodated by existing theories of motor command generation [15,43,44]. Thus, while it seems that individuals are capable of imitating by matching postures or copying trajectories, future research will be necessary to further explore the conditions under which each method of imitation is most accurate and least computationally costly.

In our primary imitation task, aside from the instructions everything about the actual movements-to-be-imitated was exactly the same between conditions; our use of visual emphasis lines to direct attention to postures or trajectories was only present during practice trials. Our findings therefore suggest that in accordance with the primary task, participants were attending to different features of the movement during observation and specifying their motor commands in a way that was unique to those particular movement features. These results are concordant with research on internal and external focus of attention, which similarly demonstrate that task instructions can influence (and improve) motor behavior [22,24,42]. Our results also suggest that where individuals attend when observing a movement is important for how that behavior is produced. Prior research has suggested that attention during imitation may be focused on the end-effector or the arm posture [41,16]. While our study did not allow us to ascertain what participants were actually looking at during movement observation, it would be interesting for future studies with eye tracking methods to assess differences in visual behaviors in the different imitation conditions. One might hypothesize, for instance, that fixations will be directed towards the end effector when imitating trajectories and toward other joint segments when imitating postures (although the location of fixations does not seem to greatly affect general imitation ability; [45]).

It is important to note an asymmetry in our results, in that we observed a switch cost when participants were instructed to imitate trajectories but not when instructed to imitate postures. Interestingly, this partial dissociation is consistent with another action observation study that demonstrated interference from an intervening task only in one condition [31]. We speculate that this asymmetry could have arisen for two potential reasons. The first is that there is an inherent asymmetry between the control of postures and the control of trajectories: in trajectory matching, multiple postures can be associated with a given trajectory, but in posture matching, only one trajectory can be associated with a set of postures. In other words, when imitating end-effector trajectories, due to redundant degrees of freedom at the joints it is possible to produce the same trajectory using different arm postures. Hence an intervening task that biases the use of different joint configurations is more likely to influence exactly how the arm is configured (analogous to how observed kinematics unintentionally bias one's movement; [46,47]), and may thus introduce imitation errors when movements are compared at the level of arm configurations as we do here. That is, the constrained joint positions required to complete the posture matching intervening task could carry over into the trajectory primary task, disrupting performance. In contrast, moving one's arm to achieve specific postures necessarily constrains the trajectory of the end-effector (i.e., if one generates a series of postures, only one resulting trajectory of the end-effector is possible). As such, when the primary task was posture matching, there was a limit to how much a trajectory intervening task could bias future behavior since the trajectory produced in the primary imitation task was inherently constrained by the intended postures. Hence even if trajectories are not explicitly planned when the goal is to match postures, it may not be possible to observe a switch cost as long as nothing disrupts the representation of the desired postures themselves. This inherent asymmetry in how movements are controlled may be reflected in our findings.

The second potential explanation for the observed switch cost only when participants were instructed to imitate trajectories (which is not mutually exclusive with the first explanation) is that the posture-matching primary and intervening tasks were much more similar compared to the trajectory primary and intervening tasks. Specifically, both the posture matching primary and intervening task presented images of an actor to be imitated (i.e., they were both clearly imitation tasks), while the trajectory intervening task involved only viewing and tracing abstract shapes with no body information present. Thus in some sense, the trajectory intervening task could be considered less of an imitation task compared to the posture matching intervening task. If the trajectory intervening task invoked a different set of computations than those required during imitation more broadly, it could explain why the trajectory intervening task was potentially less disruptive of imitation performance relative to the other three conditions. That is, there may be an inherent asymmetry in the similarity between primary and intervening tasks.

As we note above, the effectiveness or tendency to imitate via posture or trajectory matching is likely contingent on the task. In our paradigm we attempted to constrain the type of imitation used by participants in each condition using task instructions, but it is interesting to consider what type of imitation people would choose to use by default depending on the particular movement or context (and whether that preference changes across repeated exposure or practice). Nevertheless, evidence for the ability to employ two distinct methods of imitation is exciting because it suggests that imitation can be modulated depending on the demands of the task and how that task is delineated, indicating that it may be possible to modulate imitation impairments in individuals with apraxia by manipulating the focus of the task. In particular, an individual who is differentially impaired in using these two planning mechanisms could potentially be taught to strategically utilize the relatively intact planning mechanism in order to achieve the desired movement outcome. This is particularly intriguing as these two mechanisms are thought to be supported by different brain regions [1,6,7,14], such that lesions (e.g., as a result of stroke) could differentially spare one mechanism over the other. We are currently exploring this idea in a similar experiment with patients.

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