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Running Head: MODEL VARIABILITY AND OBSERVATIONAL LEARNING

The Effect of Modeled Absolute Timing Variability and Relative Timing Variability on Observational Learning

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Abstract

There is much evidence to suggest that skill learning is enhanced by skill observation. Recent research on this phenomenon indicates a benefit of observing variable/erred demonstrations. In this study, we explore whether it is variability within the relative organization or absolute parameterization of a movement that facilitates skill learning through observation. To do so, participants were randomly allocated into groups that observed a model with no variability, absolute timing variability, relative timing variability, or variability in both absolute and relative timing. All participants performed a four-segment movement pattern with specific absolute and relative timing goals prior to and following the observational intervention, as well as in a 24hr retention test and transfers tests that featured new relative and absolute timing goals. Absolute timing error indicated that all groups initially acquired the absolute timing, maintained their performance at 24hr retention, and exhibited performance deterioration in both transfer tests. Relative timing error revealed that the observation of no variability and relative timing variability produced greater performance at the post-test, 24hr retention and relative timing transfer tests, but for the no variability group, deteriorated at absolute timing transfer test. The results suggest that the learning of absolute timing following observation unfolds irrespective of model variability. However, the learning of relative timing benefits from holding the absolute features constant, while the observation of no variability partially fails in transfer. We suggest learning by observing no variability and variable/erred models unfolds via similar neural mechanisms, although the latter benefits from the additional coding of information pertaining to movements that require a correction.

Keywords: observational learning; relative timing; absolute timing; variability

Introduction

Behavioural data has shown that observing demonstrations of a novel motor skill can facilitate the learning of that skill (Ashford, Bennett & Davids, 2006; Hayes, Elliott & Bennett, 2013; Larssen, Ong & Hodges, 2012; Ste-Marie, Law, Rymal, Jenny, Hall & McCullagh, 2012). This finding is most often explained by the shared neural resources that are responsible for the coding of observed and executed actions (Jeannerod, 2001; Vogt & Thomaschke, 2007). Indeed, neuro-imaging studies have revealed that many of the same cortical regions that are active during motor planning and execution, namely, the inferior frontal gyrus (IFG), inferior parietal cortex (IPL) and ventral premotor cortex (vPM), are also active during action-observation (Buccino et al., 2001; Cross, Kraemer, Hamilton, Kelley & Grafton, 2009; Dushanova & Donoghue, 2010; Higuchi, Holle, Roberts, Eickhoff & Vogt, 2012; Rizzolatti & Craighero, 2004). Moreover, these common cortical regions are sensitive to the observation of the precise spatio-temporal dynamics of human movement (Gangitano, Mottaghy & Pascual-Leone, 2001; Sartori, Bucchioni & Castiello, 2012) with a resolution that reflects processing of individual muscles (Alaerts, Swinnen & Winderoth, 2011; Alaerts, Senot, Swinnen, Craighero, Wenderoth & Fadiga, 2010).

Interestingly, research has also consistently shown that observation-based learning is not only mediated through demonstrations that present the hallmark consistency and accuracy of expert performance (Al-Abood, Davids, & Bennett, 2001; Bandura, 1986; Blandin, Lhuisset, & Proteau, 1999; Buchanan & Dean, 2010; 2014; Hodges, Chua, & Franks, 2003), but also by way of demonstrations that contain the error and variability inherent to novice performances (Black & Wright, 2000; Blandin & Proteau, 2000; ; Blandin, Lhuisset, & Proteau, 1999; Buchanan & Dean, 2010; Buchanan, Ryu, Zihlman, & Wright, 2008; Hayes, Hodges, Huys, & Williams, 2007). The findings associated with the observation of an expert model support the idea that these demonstrations provide learners with a perceptual representation of the correctly performed movement, which in turn serves as a standard of reference against which their own performances can be compared (Bandura, 1986; Sheffield, 1961). This is a notion that is also consistent with current accounts of motor control that include a role for anticipatory processing whereby response-associated visual feedback is compared against internal models of sensory expectations (Elliott, Hansen, Grierson, Lyons, Bennett & Hayes, 2010). Alternatively, observation of novice models is purported to help learners make sense of the range of errors that can surround a motor task. That is, learning involves coming to understand the association between different movement patterns and their outcomes relative to the goal (Adams, 1986), such that the observation of novice performances presents the relationship between errors and their consequences. This information is important to learners as they come to generate strategies for executing movements that are designed to alleviate the costs of a potential error (Elliott, Hansen, Mendoza & Tremblay 2004; Lyons, Hansen, Hurding & Elliott, 2006; Grierson, Gonzalez & Elliott, 2008; Grierson & Elliott, 2009). Notably, learning appears to be best facilitated when observation includes a combination of both novice and expert performance demonstrations (Andrieux & Proteau, 2013; Rohbanfard & Proteau, 2011).

Incidentally, the positive impact of observing errors has called into question the straight one-to-one subthreshold activation of motor neurons during action-observation as a complete explanation for the observational learning phenomenon (e.g., Buccino et al., 2001; Cross et al., 2009; Higuchi et al., 2012). Indeed, a recent study from Buckingham and colleagues (Buckingham, Wong, Tang, Gribble & Goodale, 2014) has shown that the corticospinal excitability elicited during the observation of variable motor errors was modulated by the subsequent learning or parameterization of required forces rather than the observed movement kinematics. That is, the observation of motor errors, as indicated by greater grip force rates for large- compared to small-sized objects that were the same weight, resulted in comparatively similar corticospinal responses during cortical stimulation. In other words, the neural codes responsible for the observation and execution of object-lifting were contingent upon the implicit understanding of the force parameters required to execute the task rather than the motor parameters manifesting in error. In addition, the behavioural data collected after the observation of variable motor errors reflected a similar outcome as the neurophysiological data with a more limited size-weight bias, and thus reduced motor error, compared to the observation of consistent error-free trials. Thus, it appears our understanding of the behavioural and neural underpinnings of learning through observation may be greatly benefitted from investigations of mixed or variable models consisting of at least some error.

With this in mind, it is relevant to consider what aspects of learning are benefitted most by the observation of variable or erred models, along with the precise features of observed movements that require variability in order to uphold a learning advantage. Indeed, the current consensus of observing a combination of mixed models for the enhancement of learning may operate at a number of different levels including the coordination of relative motion features (e.g., segmental timing of movements) and/or the parameterization of the absolute movement dynamics (e.g., combined timing or force specification) (Scully & Newell, 1985; see also Shea & Wulf, 2005). To date, evidence has shown that the observation of a mixed combination of expert and novice models results in better relative and absolute timing at immediate and delayed (24 hr) retention tests, as well as enhancing the ability to transfer to a novel absolute timing pattern (Rohbanfard & Proteau, 2011). In a similar vein, it has been shown that the enhanced retention of relative and absolute timing following variable model observation is contingent upon a period of physical practice

(Andrieux & Proteau, 2013). Meanwhile, the observation of variable/erred trials helps the observer to accurately parameterize force during novel object manipulation (Buckingham et al., 2014) and force-field pattern (Brown, Wilson, Obhi & Gribble, 2010) tasks. Taken together, there is some evidence that variable model observation can enhance either relative and/or absolute features of a skill, although it remains to be seen what affect varying these corresponding features within observation has on overall skill development.

Accordingly, the aim of the current study was to examine the characteristic features of variability or performance error that were required in order to enhance motor learning. More specifically, we investigated the effect of varying relative and absolute timing on the learning of corresponding features of a skill. To this end, we challenged participants to learn specific relative- and absolute-timing of a four-segment movement pattern through the observation of demonstrations that were characterized by degrees of error in relative and absolute timing performance. The models featured either accurate absolute and relative timing with no error, constant accuracy in absolute timing but variable error in relative timing, constant accuracy in relative timing but variable error in absolute timing, or variable error in absolute and relative timing. The learners were tested on their ability to generate the criterion time in immediate and retention post-observation tests, and also in tests that required them to transfer to new absolute and relative timing goals.

In accordance with previous literature (for e.g., Al-Abood et al., 2001; Blandin & Proteau, 2000; Buchanan et al., 2008; Buchanan & Dean, 2010; 2014; Hayes et al., 2007; Hodges et al., 2003), we hypothesized that participants would learn both relative and absolute timing features following the observation of accurate absolute and relative timing with no errors. Of even greater interest was the impact that the observation of performances containing relative timing errors and/or absolute timing errors had on the learning of the relative timing and absolute timing. In general, we anticipated the learning of absolute and relative features to be even greater following the observation of demonstrations that included errors within these relevant or corresponding features. That is, the learning of absolute timing would be benefited most by the observation of models consisting of variable error in absolute timing, and the learning of relative timing would be benefitted most from models of variable error in relative timing. Lastly, we explored the degree to which the absolute and relative timing could be transferred to new absolute and relative timing goals. If the variability of model demonstrations enhances the detection and amendment of errors (Andrieux & Proteau, 2013; Blandin & Proteau, 2000), over and above constant accurate models consisting of no error, then we may predict the variability of observed absolute and relative features to promote transfer to novel absolute and relative timing patterns, respectively.

Materials and Methods

Participants

Forty volunteers (*21 males, 19 females, mean age = 23.72 ± 2.86*) were recruited to take part in the study. All participants were free of any upper limb injuries or neurological disorders, had normal or corrected-to-normal vision, and were self-reported right-handers. Consent was obtained from each of the participants and the study was conducted in accordance with the guidelines set out by the McMaster University Research Ethics Board and the Declaration of Helsinki (2013).

Apparatus and Task

Stimuli were presented on a computer monitor (57 cm x 34 cm) with a temporal resolution of 60 Hz and spatial resolution of 1024 x 768 pixels. The monitor was fixed onto a stand that was adjusted to each participant’s hip height and presented in the horizontal axis so as to face upwards with respect to the participant’s view. Each trial featured the presentation of four targets with the home position affixed next to the monitor (Fig. 1) with each marking the end of a movement segment. The movement segments subtended amplitudes of 25.0 cm for segment 1, 38.5 cm for segment 2, 13.5 cm for segment 3, and 24.5 cm for segment 4. Participants performed the movements while holding a micro-switch that depressed upon contact with each target. This switch indicated the initiation and completion of each movement segment. A custom program developed in E-prime 2.0 (Psychology Software Distribution Ltd, Sherrif Hutton, York) was used to control the experimental stimuli and record data.

Participants began each trial with their right hand located over the home position. The four targets appeared on the screen and participants had to move to each of the targets in a sequential order. The sequence was assigned specific absolute and relative time goals. The absolute time goal was 3000ms. The relative time goal was a 10% (300 ms), 40% (1200 ms), 10% (300 ms) and 40% (1200 ms) of the absolute time for segments 1 to 4, respectively.

[Insert Figure 1 about here]

Experimental Design and Procedures

Participants engaged in pre-test and acquisition phases before an immediate post-test. They then returned a day (~24hrs) later to complete retention and transfer tests. Prior to the pre-test, participants received instructions about the task including the absolute and relative time goals. The pre-test, post-test, and retention test phases involved attempts to complete the movement sequence for the pre-instructed absolute and relative times without any augmented feedback. The transfer phase featured two counterbalanced tests that introduced a novel relative time with the same absolute time (relative timing transfer), and a novel absolute time with the same relative time (absolute time transfer). The relative time transfer (RT-TRANS) involved a relative time goal of 30% (900 ms), 10% (300 ms), 20% (600 ms) and 40% (1200 ms) and an absolute time of 3000 ms. The absolute time transfer (AT-TRANS) involved an absolute time goal of 4500 ms with a relative time of 10%, 40%, 10% and 40%. There were 10 trials for each test phase (pre-test, post-test, retention test, relative timing transfer, and absolute timing transfer). The order of relative and absolute transfer tests was counterbalanced across participants.

For the acquisition phase, participants were randomly assigned to one of four experimental observational learning groups, which were differentiated by the nature of demonstrations observed. In each case, the participants observed 60 video recordings of a model executing attempts of the movement sequence. All recordings were displayed on the same monitor as the target stimuli such that the resulting view was aligned with the border of the presentation monitor and only the moving limb of the model in that space was visible to the observers. Augmented feedback regarding the absolute time and relative time of the observed performance in milliseconds was presented following each recording. The participants were instructed to process the feedback and advance to the next trial in their own time.

The absolute and relative times that were observed by each of the groups are shown in Table 1. The criterion group (CRIT) observed a model executing the absolute time goal and relative time goal precisely, and with no variability. The model demonstration was a perfect performance taken from one of over 300 trials previously executed by a confederate volunteer. The absolute timing variability group (ATV) observed a set of six demonstrations in which the executed absolute time varied, but the relative time goal was upheld. The relative timing variability group

(RTV) observed a set of six demonstrations in which the absolute time did not vary, but the relative time was varied from trial-to-trial. In manipulating observed variability, we ensured the same differences in the degree of variability were presented. That is, the observed models were equally either too fast or too slow with respect to the target time (e.g., 2500 ms model = -500 ms difference, 3500 ms model = +500 ms difference). The fourth group observed the full complement of variability (FULL) via demonstrations that featured a combination of variable absolute and relative times. The models for the variability groups – ATV, RTV, and FULL – were created through modification of the original CRIT model. This was done by lengthening or shortening each of the four movements segments to the desired timing parameters using i-Movie (Apple Inc., Cupertino, CA). All participants indicated at the conclusion of their participation that they were unaware that the observed videos had been modified and stated that they believed the performances to be ecological movement representations. The demonstrations were presented in a pseudorandom order with the caveat that the same model could not be presented over two consecutive trials and each model was presented only once for every set of six trials.

[Insert Table 1 about here]

Dependent Measures and Data Analysis

There were two dependent measures: total error and relative timing error. Total error was calculated using the following equation:

$$\text{Total Error} = \surd CE^2 + VE^2$$

where CE (constant error) is the mean signed error difference between the actual movement time and criterion movement time, and VE (variable error) is the standard deviation of these signed error differences. Relative timing error was calculated using the following equation:

$$\text{Relative Timing Error} = |R_1 - .1| + |R_2 - .4| + |R_3 - .1| + |R_4 - .4|$$

where R_i is the proportion of the absolute time taken up by an individual segment (e.g., Badets, Blandin & Shea, 2006; Hayes, Roberts, Elliott, & Bennett, 2014). Values for any dependent variable that fell more than 2.5 standard deviation units from the mean were considered outliers and were removed from the datasets before analysis. The entire trial containing an outlier was removed from analysis. Less than 8% of the total number of trials were removed.

The participants' learning of the absolute time and relative time goals was assessed via a 4 Group (CRIT, ATV, RTV, FULL) by 3 Test (Pre, Post, Retention) mixed-measures analyses of variance (ANOVA),while the transfer of learning to each of the new relative and absolute timing goals was examined using a 4 Group (CRIT, ATV, RTV, FULL) by 2 Test (Retention, RT-TRANS/AT-TRANS) mixed-measures ANOVAs for each of the dependent measures. Significant effects ($p < .05$) featuring more than two means were decomposed using Tukey's Honest Significant Difference *post hoc* procedure.

Results

Learning

For the Absolute Timing Error analysis, there was no significant main effect of Group, *F*(3, 36) < 1, although there was a significant main effect of Test, *F*(2, 72) = 9.04, $p < .05$, $\eta^2_p = .20$, indicating a decrease in absolute timing error from pre-test (Mean (±SE) = 879.8 ± 77.5) to post-test (529.0 ± 60.6) that was maintained at retention (582.0 ± 93.6) (Fig. 2). Moreover, there was no significant Group x Test interaction, *F*(6, 72) < 1.

[Insert Figure 2 about here]

The analysis of Relative Timing Error revealed a significant Group x Test interaction, *F*(6, 72) = 2.57, *p* = .026, η^2_p = .18 (Fig. 3). Post hoc analyses (p < .05) revealed that all groups reduced their relative timing error from Pre-test (CRIT = 0.29 ± .04; ATV = 0.36 ± .04; RTV = 0.35 ± .04; FULL = 0.30 ± .04) to Post-test (CRIT = 0.13 ± .02; ATV = 0.27 ± .02; RTV = 0.14 ± .02; FULL = 0.21 ± .04), and that this reduction was maintained after a period of retention (CRIT = 0.14 ± .02; ATV = 0.27 ± .02; RTV = 0.16 ± .02; FULL = 0.19 ± .03). Furthermore, post hoc analyses revealed no significant differences between groups at Pre-test. However, the CRIT and RTV groups performed with less relative timing error than the ATV group at Post-test and Retention test. The analyses also revealed that the FULL group performances were intermediate to those of the CRIT and RTV groups and the ATV group at Post-test and retention test without being statistically different.

[Insert Figure 3 about here]

Relative Timing Transfer

The analysis of Absolute Timing Error in Relative Timing Transfer Test performances revealed a significant main effect of Test, *F*(1, 36) = 15.58, p = .0004, η^2_p = .30, which indicated that the Total Error generated by all participants was higher in transfer (1024.8 ± 132.6) than in retention testing (582.0 ± 93.6). There were no significant differences between Groups, $F(3, 36) < 1$.

The analysis of Relative Timing Error in the Relative Timing Transfer Test also revealed a significant effect of Test, $F(1, 36) = 22.91$, $p < .0001$, $\eta^2_p = .39$, which described an increase in error from retention (0.19 ± .01) to transfer (0.24 ± .01). However, this analysis did reveal a main effect of Group, $F(3, 36) = 6.76$, $p < .001$, $\eta^2_p = .36$. Post hoc analysis ($p < .05$) of this effect revealed that the ATV (0.28 ± .01) group performed with significantly more relative timing error than the CRIT (0.17 ± .01) group. There were no other between-group differences (RTV = 0.19 ± .02; FULL = 0.22 ± .02) (Fig. 4).

[Insert Figure 4 about here]

Absolute Timing Transfer

The analysis of Absolute Timing Error in Absolute-Timing Transfer Test performances revealed a significant main effect of Test, $F(1, 36) = 13.69$, $p < .001$, $\eta^2_p = .28$. Again, this effect revealed a decrease in accuracy from retention (582.0 ± 93.6) to transfer (976.5 ± 151.2).

The analysis of Relative Timing Error in Absolute-Timing Transfer Test performances also revealed a significant Group by Test interaction, $F(3, 36) = 4.14$, $p = .01$, $\eta^2_p = .26$ (Fig. 5). Post-hoc ($p < .05$) analysis of this effect revealed that the interaction was driven by a significant decrease in CRIT performance from Retention (0.14 ± 0.02) to the AT-TRANS test (0.21 ± .02) such that there were no group differences in performance at transfer (ATV = 0.25 ± .02; RTV = 0.20 ± .02; FULL = 0.23 ± .02). Although the RTV group (0.16 ± .02) performance was significantly better than that of the ATV group (0.27 ± .02) at retention, there was no longer a statistical difference between the two groups at transfer.

[Insert Figure 5 about here]

Discussion

In this study, we set out to determine the degree to which error in the relative and absolute timing outcomes of model demonstrations influence the learning that results from observation. We had participants learn a novel relative and absolute timing pattern by observing constant accuracy in relative and absolute timing (CRIT), constant accuracy in relative timing and variable error in absolute timing (ATV), constant accuracy in absolute timing and variable error in relative timing (RTV) or variable error in relative and absolute timing (FULL). The results revealed that all observation groups were able to execute the criterion absolute timing, and thus, acquire the absolute features of the skill (*cf.* Skully & Newell, 1985). However, the same groups' absolute timing began to deteriorate at relative and absolute transfer tests. Meanwhile, the CRIT and RTV groups successfully executed the criterion relative timing, and thus, acquired the relative features of the skill with an intermediate performance from the FULL group. The CRIT group were able to retain this superior relative timing at the relative timing transfer test, although began to deteriorate at the absolute timing transfer test.

The combination of learning absolute timing regardless of model variability and the superior learning of relative timing for the CRIT and RTV groups, highlight the differential effect that one type of error can have on the learning of alternative features of a skill. That is, only for the acquisition of relative timing did there appear to be an effect of model variability. While these findings support and extend previous evidence of model variability or error serving general benefits to motor learning (Andrieux & Proteau, 2013; Brown et al., 2010; Buckingham et al., 2014; Rohbanfard & Proteau, 2011), they may also reflect how observed errors in absolute timing mitigate the acquisition of relative features. In other words, it would appear that the learning of relative timing was most enhanced by the constant and accurate performance of absolute timing (CRIT, RTV), as opposed to variable and erred absolute timing (ATV, FULL). This suggests that in order to promote the acquisition of relative timing through observed model variability, there needs to be at least some consistency in the absolute domain so as to accommodate the reallocation of internal resources. Indeed, previous evidence suggests that the acquisition and reproduction of relative features is subject to the allocation of cognitive resources and visual attention, which are essential to the pick-up of visual information prior to mapping observed into executed actions (Hayes et al., 2014; Wohlschläger, Gattis & Bekkering, 2003; see also Bach, Peatfield & Tipper, 2007). In this regard, the benefit of observed model variability, namely variability in relative timing, may be best served by more closely attending to the relative features without concern for variable changes in the scaling or absolute features.

The transfer tests conducted following the retention phase were intended to determine the degree to which each group could perform accurately under new timing constraints and whether transfer of learning was influenced by exposure to particular types of error in observed demonstrations. In this regard, our data highlights that the group effects found for relative timing error in both the relative and absolute transfer tests were generally consistent with the retention phase, although the performance of the CRIT group deteriorated at the absolute transfer test. One consideration is that the CRIT group’s lack of exposure to errors leaves them without the referent information that accommodates the detection and avoidance of errors (Andrieux & Proteau, 2013; Rohbanfard & Proteau, 2011).

Interestingly, the CRIT group relative timing is superior at post-test and retention, but becomes attenuated at absolute transfer compared to the other groups. It is possible that because this group observed constant and accurate timing information, they could have initially acquired the relative features through the neural mechanisms that are responsible for the straight one-to-one mapping of observed demonstrations into executed actions. Indeed, this conjecture is adapted from previous evidence that learning through observation involves the direct mapping of an observed novel action onto neural regions that are also responsible for the execution of the same action (e.g., Cross et al., 2009). These suggestions are linked to evidence of a human Action Observation Network (AON) (i.e., superior temporal sulcus (STS), inferior parietal lobule (IPL), inferior frontal gyrus including ventral premotor cortex (IFG/vPM)) and the discovery of mirror neurons in the macaque monkey brain (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). At the same time, it is problematic to posit that this detailed neuronal architecture, and its associated firing pattern, can explain learning by observing variable or erred performances. Although the aforementioned neural network no doubt contributes to learning by observing variable models, it is noteworthy that the corticospinal excitability typically associated with the straight one-to-one mapping of observed actions is also modulated by the errors that are reflected within the observed model (Buckingham et al., 2014). Thus, as well as being sensitive to the explicit kinematic details of human movement, the neural mechanisms that underpin learning through observation may also be sensitive to trial-to-trial variability and error. However, further research is required in order to examine these suggestions.

With respect to the transfer of absolute timing, it appears the benefit of observation was lost when learners had to transfer to an alternative relative or absolute timing pattern. In part, these findings support the notion that the learning of relative features – coordination of movement skills – may be achieved through the observation of relative or biological motion, whilst the learning and transfer of absolute features may be limited until after physical practice is introduced. (Newell, 1985; Scully & Newell, 1985; see also, Generalized Motor Program and the representation of invariant features (Schmidt, 1975)). This suggestion is consistent with evidence of observation accommodating the learning of invariant spatio-temporal parameters, while limiting the transfer of lower-level parameters (Hayes, Andrew, Elliott, Roberts, & Bennett, 2012; see also, Wolpert & Ghahramani, 2000 and Wolpert & Flanagan, 2010). Indeed, the benefits of observation are suggested to be limited to the features reflected within external visual afference (i.e., spatio-temporal dynamics), whereas physical practice (or an interleaved practice schedule) includes additional efferent and reafferent signals that are instrumental to the absolute features. As a result, the ability to transfer the absolute features following observation-alone may become compromised.

At the same, it is important to recognize that there was at least some initial learning of the absolute features (i.e., pre-test to post-test/retention improvement), which has also been reflected in other empirical accounts (e.g., Andrieux & Proteau, 2013; Hayes et al., 2007; Rohbanfard & Proteau, 2011). While we cannot categorically attribute this to observation per se due to the absence of a control/placebo group, it is possible that the absolute features were detected during observation (see Hamilton, Joyce, Flanagan, Frith, & Wolpert, 2007; Shim, Carlton, & Kim, 2004), which then accommodated its immediate replication within movement. This replication is akin to the straight one-to-one mapping mechanism proposed earlier (see above). Upon presentation of the novel task constraints that no longer comprise the same timing parameters as the observed models (relative or absolute timing transfer), the observer can no longer simply replicate what was observed previously, but instead, she must adapt or transfer her learning. In this instance, it is understandable that absolute timing performance may begin to decline.

In making our interpretations, it is important to recognize that the sequential-timing task of the present study allowed us to control many potential sources of error and/or variability in our modeled performances. For instance, it constrained the performer's direction of action and choice of effector, such that there could be no variability in the strategy chosen to execute the skill (Buchanan & Dean, 2010; 2014). Furthermore, it allowed us to vary the absolute error by artificially manipulating the velocity of the action and the resulting timing outcome. Thus, the trial-by-trial spatial variability that typically emerges in iterative attempts of a manual movement was held constant throughout. This is a key point: all precision movements are associated with a degree of inherent neuromuscular variability (Meyer, Abrams, Kornblum, Wright & Smith, 1988; Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979) as movements of the same speed and distance will naturally show a trial-by-trial spatial variability that is ultimately reduced as the movement progresses into its latter stages (Elliott et al., 2010). In this way, spatial information regarding the limb's position may provide critical information to the observer about the underlying movement dynamics. In light of this suggestion, we acknowledge that further categorization and testing of the observational impact of error and variability within the spatial distribution is also warranted for future study.

In summary, the observation of model demonstrations promoted the learning of absolute timing, although it failed to transfer this skill feature to novel relative and absolute timing patterns. These findings highlight the advantages served by observing model demonstrations for the direct reproduction of absolute features, while also reflecting its limitations upon transferring this source of information (Scully & Newell, 1985). Meanwhile, the observation of the criterion and relative timing variability enhanced the learning of relative timing, which would suggest an advantage of presenting constant absolute timing. This learning advantage may result from the constant absolute timing accommodating internal resources to become more centered around relative timing information (Hayes et al., 2014). Finally, it is only during the absolute timing transfer test that the full advantage of model variability can be realized as relative timing performance begins to deteriorate following the observation of the criterion model. We suggest the initial learning following the observation of the criterion model is attributed to the direct one-to-one mapping of observed into executed actions via the neural architecture that is synonymous with mirror processes; the Action Observation Network. However, this one-to-one mapping procedure is limited to the reproduction of the criterion, and fails in its transfer to alternative settings. Alternatively, learning following the observation of a variable model, namely relative timing variability, can be attributed to the same neural mechanisms, but with the added benefit of coding errors that require some form of correction or intervention (Buckingham et al., 2014). As a result, the performer is able to both reproduce and transfer this source of information when needed.

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Figure Captions

Figure 1: Illustration of the four segment timing task. Targets are indicated by the *black filled circles*, home position is indicated by the *white square* and movement segment directions are indicated by the *grey arrows*.

Figure 2: Mean total error (±SE) as a function of the test (PRE, POST, RET).

Figure 3: Mean relative timing error (±SE) as a function of Test (PRE, POST, RET) and experimental Group (CRIT, ATV, RTV, FULL).

Figure 4: Mean relative timing error (±SE) of Relative Timing Transfer Test performances plotted as function of Group (CRIT, ATV, RTV, FULL).

Figure 5: Mean relative timing error (±SE) of Absolute-Timing Transfer Test performances plotted as function of Group (CRIT, ATV, RTV, FULL) and Test (RET, AT-TRANS).

Table Captions

Table 1: The absolute timing and relative timing characteristics of the modeled demonstrations viewed by each of the groups.