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Kinematic Measures of Imitation Fidelity in Primary School Children

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Abstract

We sought to develop a method for measuring imitation accuracy objectively in primary school children. Children imitated a model drawing shapes on the same computer-tablet interface they saw used in video clips, allowing kinematics of model and observers' actions to be directly compared. Imitation accuracy was reported as a correlation reflecting the statistical dependency between values of the model's and participant's set of actions, or as a mean absolute difference between them. Children showed consistent improvement in imitation accuracy across middle childhood. They appeared to rationalize the demands of the task by remembering duration and size of action, which enabled them to re-enact speed through motor-planning mechanisms. Kinematic measures may provide a window into the cognitive mechanisms involved in imitation.

Imitation is an important means by which one individual learns from another and by which learning spreads between individuals within a culture (Whiten & Ham, 1992; Whiten et al., 1999). Imitation is necessary to learn language, gesture and any other skills that require an individual to learn from someone else by watching them. Hence, it is suggested that it may be essential for social cognitive development (Meltzoff & Gopnik, 1993; Rogers & Pennington, 1991).

Imitation was introduced as a feature of universal development by Baldwin, (1994) whose ideas were later developed by Piaget (1952), who described the capacity for deferred imitation as a crucial milestone at the final stage of sensorimotor development, relying on cognitive representation. Research in children has since continued to study imitation as an essential aspect of cognitive development that develops in the first years of life, in neonates (Meltzoff & Moore, 1977) and with the development of deferred imitation that occurs in the first year (Meltzoff, 1988). More recently, researchers have begun to explore the utility of cognitive mechanisms in imitation such as causal understanding, hierarchical thinking and secondary representation (Flynn & Whiten, 2008; Horner & Whiten, 2005; Nielson., Dissanayake, 2004; Want & Harris, 2001; Want & Harris, 2002; Whiten, Flynn, Brown, & Lee, 2006). Selectivity of imitation has also become a topic of interest as some children imitate actions that are unnecessary to achieve a goal. Some imitation research has been the subject of heated debate as to whether reports of imitation could be open to alternative explanations (Jones, 2009) but imitation remains to be seen as a universal aspect of human cognitive development.

Because imitation research has typically concerned itself with the cognitive processes behind imitation, it has usually examined what or how children imitate rather than how accurately they do so. Some researchers utilise a coding for partial imitation, or a task may have several components, only some of which may be imitated (McGuigan, Makinson, & Whiten, 2010), but the research is still usually driven by the question of whether an individual demonstrates imitation, whether for some or all components of a modelled action.

An alternative question to ask about imitation is to ask how well a person imitates. It is not clear whether asking this alternative question can tell us anything about the cognitive processes that underpin imitation or just the level of development of the motor skills necessary to enact it. Traditionally the cognitive ‘representational’ aspects of imitation have been separated from the purely sensorimotor functions that precede imitation in development. For example, if a young boy was asked to imitate his father kicking a football at a goal, success at the task would be dependent on his motor skills, and one would expect that his capacity to match his father’s behaviour would depend upon how well he is practiced at football, rather than whether he can represent the relationship of the kicking action to the goal. Therefore, on the face of it, it does not make obvious sense to measure accuracy of movement on the assumption that it will tell us about the development of the cognitive mechanisms that imitation.

However, there are 2 reasons for questioning the dichotomy between cognitive and motoric function. One is the increasing appreciation of grounded cognition theories. These offer the perspective that cognitive functions cannot be partitioned off into amodal computational or mnemonic functions that are separate from the sensory and motor systems which relate directly to the environment. Rather, grounded cognition theories consider that experience and knowledge is maintained by the modalities in which it is captured, experienced and rehearsed. Grounded cognition theories (Barsalou, 2008) focus on the role of sensorimotor systems in memory, the simulation and understanding of others’ actions, and the important role of environment in shaping behaviour. Grounded cognition theories are particularly pertinent to the study of imitation suggesting that it is dependent upon the development of the ability to perform a specific visuomotor matching function by which sensory information about perceived actions, primarily encoded by visual systems, can be mapped onto information coding for the execution of the same actions in motor cortex. This sensorimotor integration function has been at the centre of Active Intermodal Mapping or Perception-Action Matching theory (Meltzoff & Moore, 1997; Sommerville & Decety, 2006), Mirror Neuron theory (Arbib, 2005; Gallese, Keysers, & Rizzolatti, 2004; Rizzolatti & Craighero, 2004) and Associative Learning theories (Brass & Heyes, 2005; Heyes, 2001; Keysers & Perrett, 2004).

On this basis, it needs to be asked whether the representational aspects of imitation can really be separated from the capacity to perceive and execute the actions involved. If one returns to the example of kicking a ball as mentioned above, increasing practice involves an increasingly fine and detailed representation of the kicking action, such as how hard and with which part of the foot the ball is kicked. Such detail is commensurate with development of the skill (or its imagery in the case of keen spectators).

The second reason is that there may be relationships between certain aspects of motoric skills and cognitive functions if they are jointly involved in imitation. If it is possible to distil an imitation task into several components and we find that they are variably associated with each other or individual differences, then we may better help understand how cognitive processes that constitute imitation are organised. For example, as will be further discussed, spatial and temporal aspects of actions may be dissociable. Subiaul, (2010) advocates multiple imitation mechanisms and suggests that different stimuli types are imitated by different mechanisms. Similarly, since we know that different areas of intra-parietal sulcus respond specifically to different visuomotor processes (Culham & Kanwisher, 2001), it is possible that separable features of the same action are each served by separable imitation mechanisms (Williams, 2008). This could be particularly important as different profiles of strengths and weaknesses across a range of different imitation mechanisms will affect propensity to imitate different features of behaviours, and hence potentially promote the development of different aspects of cognition. Conversely, given that the form and timing of actions will interact in determining their outcomes, the transmission of these two characteristics may be associated. For example, if large and fast actions are both associated with common outcome and tend to be executed together, then one may predict that they will be associated with each other during imitation.

Attempts to quantify imitation abilities have been most explored with children who have autism, among whom the capacity for imitation has long been questioned (Ritvo & Provence, 1953). It is evident that children with autism will imitate in both qualitatively and quantitatively different ways. Children with autism will make more errors and less accurate copies when asked to imitate a set of actions, compared to other children of similar age and IQ. It seems to be that better imitation fidelity is associated with stronger social and cognitive development (Williams, Whiten, & Singh, 2004; Rogers & Williams, 2006). For example, among children with autism, stronger imitation skills predict better language skills as measured by verbal IQ (Charman et al., 2003; Charman, 2006). But group differences are relative and the ability to imitate improves with age and verbal IQ (Smith & Bryson, 1994; Smith & Bryson, 1998). In autism, there is some evidence of a dissociation of impairment between different skills (Williams et al., 2004). For example, imitation of means-end reasoning seems to be relatively intact in autism as does imitation of goal-directed gesture. Imitation of meaningless actions, and the way in which actions are performed, referred to as ‘style’ (Hobson & Lee, 1999) or ‘adverbial aspects’ (Perra et al., 2008), appears to be more affected (see also Wild, Poliakoff, Jerrison, & Gowen, 2012). However, the evidence base remains poor. Whilst differences in performance on different types of imitation may well be seen in autism, they could result from different experimental designs. Therefore, we are still unsure the extent to which imitation abilities within a population of children map differentially onto cognitive or behavioural differences. In order to address these questions, finer methods of measuring imitation ability are required.

In autism research, the most commonly used approach to measurement of imitation ability has been the ‘do-as-I-do’ method (Hayes & Hayes, 1952), in which models show participants a series of actions and participants are asked to repeat them. The ‘do-as-I-do’ indexes the degree of similarity between observed and enacted actions. If done properly, two raters establish inter-rater reliability and observe an imitated action blind to the participant’s group status. Nevertheless, scoring remains necessarily crude, as the coding remains subjective, and rates an act of imitation on a limited scale (e.g. 0,1,2 or 3). It also provides a single summary rating that combines accuracy across all the elements including the speed and coordination. The method imposes no presumptions on the ways in which the copied action may differ from the modelled action and doesn’t credit the imitator’s ability to take into account the relative importance of different aspects. In this way, the do-as-I-do method supports 'blind-copying', as the preferred method of imitation, rather than action-understanding.

An arguably more robust test of action-imitation that has been developed is the two-way model (Dawson & Foss, 1965). In this approach, participants are divided into 2 groups and both view different ways of performing an action, such as 2 ways to open a box to obtain a reward. They are then presented with the same problem and the means to perform the task in either way. If imitators are more likely to use the method they observed to open the box, than the method that they didn’t, this is robust evidence for imitation in the group. Essentially, this method tests the capacity to discriminate between shown actions, in the way they are re-enacted. Whilst this method has been employed powerfully to demonstrate imitation in children and non-human primates, its dichotomous nature does not tell us how good children are at imitating. An expansion of this approach to involve multiple actions would ask if the rank order of a set of modelled actions, when measured according to a specified parameter, could be reliably reproduced by an imitator. Put another way, the 2-way method asks to what extent the variability of the imitator's behavioural output is statistically dependent upon the variability of the input by the model. With multiple stimuli and responses, this statistical dependency is captured by the correlation coefficient.

Recent studies have begun to explore the use of kinematics to explore imitation (Wild, Poliakoff, Jerrison, & Gowen, 2010; Wild et al., 2012). Furthermore, software has been recently developed for making objective kinematic measurements of actions outside of the laboratory environment using a portable computer fitted with a touch-sensitive screen (Culmer, Levesley, Mon-Williams, & Williams, 2009). This makes it possible to compare the kinematics of an action executed by one person (the model), with the kinematics of an action executed by another (the actor) who has seen the action and is being asked to copy it, permitting measurement of imitation fidelity on several levels. Firstly, we can look at imitation for different parameters of measurement. In this article, we present data from parameters of movement path length, duration and speed. Movement path length reflects the size of object drawn by the model, duration is the time taken to complete it and speed is derived from these two variables.

Each of these measures generates a type of accuracy measure. Like the do-as-I-do method, a simple measure of similarity can be carried out by looking at the average amount of difference between the modelled and imitated actions. Alternatively, by looking at a series of actions for a single individual we can look at how well the actor discriminates the actions from each other in the strength of correlation between the modelled and enacted actions, which may perhaps provides a better measure of how accurately the imitator changes according to the model's changes.

The first purpose of this study was to develop a method for measuring imitation accuracy objectively, by developing a paradigm for comparing kinematics between model and observer and then by comparing potential analytic approaches. To this end, we wished to know whether the action-parameters themselves influenced the magnitude of error. We were also interested in whether the parameters of accuracy would be closely predictive of each other which would be consistent with a single mechanism managing imitation. Finally, we hypothesised that participants' imitation fidelity for speed and size of the shape would be affected by age, intelligence and motor skills. Motor skills could be measured by tasks that we administered in the same sessions using the same computerised technology. Also, in view of the well-documented association between autism and poor imitation, we predicted that traits of autism, even in a typical population would predict imitation abilities. The Social Responsiveness Scale (SRS) is an instrument that is based on the premise that the autism phenotype is continuously distributed in the typical population (Constantino & Todd, 2003; Constantino et al., 2003). Therefore, we predicted that there would be a negative relationship between the participant's SRS scores and their ability to imitate accurately.

METHOD

Participants

The study received ethical approval from the local ethics committee and was also approved by the school management boards from where the children were recruited. All children from two mainstream Irish primary schools were invited to participate and children (n=58, age range 7-13, mean = 10.32) were recruited from those whose parents consented. The number and gender breakdown of participants in each class is shown in Table 1.

Procedures

Children’s imitation abilities and other motor skills were assessed using a portable computer with a touch-sensitive screen (Toshiba Model Tectra M7). The participants interact with the images on the screen by using a tablet stylus. The recorded position of the stylus tip on the laptop screen over time provides a detailed record of participants’ movements. This facilitated a precise analysis of the children’s performance while enabling them to complete the tasks in the style of pen and paper tasks. Custom-built software stores and analyses this record to provide detailed kinematics measures (Culmer et al., 2009).

Children completed the imitation tasks and 4 other control motor tasks. In general the order of the tasks was as follows: Imitation, Tracking and Tracing (see below). However, class-time restraints meant that this order sometimes had to be altered if there was not an adequate time slot for the longer tasks to be completed. The Wechsler Abbreviated Scale of Intelligence (WASI-IV- Wechsler, 1999) was conducted in a separate session after the computer tasks had been completed.

Imitation Task Stimuli

Stimuli consisted of 45 video-clips of the same model drawing a shape on the same touch-screen tablet laptop that the children had in front of them. She faced the camera and performed the actions with a neutral expression on her face, keeping her gaze on the surface of the touch-screen. Importantly, the camera angle (that was maintained constant throughout the trials), was adjusted so that light reflecting from the screen of the computer prevented participants from seeing what the model was drawing, thereby requiring them to imitate her action to complete the task. She was instructed before each clip to draw one of 5 specific shapes and to draw them at slow, medium or fast speeds, and small, medium or large size. This resulted in 45 trials, consisting of five different shapes (circle, square, triangle, oval and pentagon), drawn in three different sizes (small, medium and large) at three different speeds each (slow, normal and fast).

However, whilst stimuli could be classified according to the model's intended speed or size, actual measured speeds or sizes followed a more continuously variable distribution.

Imitation Task Procedure

The participants were asked to watch the video-clips played on the screen of another portable computer. The task took approximately 30 to 45 minutes to complete and was completed in a single sitting. The instructions at the start of the task were as follows: "You are about to see some movie clips. Each clip shows a woman drawing on a tablet like the one in front of you. Watch carefully what she draws and how fast or slow she draws it. Wait until you are told and then try to copy her drawing actions as closely as you can. Remember to try and copy the size and speed of her actions as well as their shape". The task was delivered in a Microsoft 'PowerPoint' presentation, such that after each video-clip the instruction, "now you do it" was given. Prior to viewing the first video the participants were reminded to try to draw the shape at the same size and speed as they saw it drawn.

Control Motor Tasks

Control motor tasks were administered to test the hypothesis that variability in imitation ability would be attributable to differences in level of motor control.

Tracking Task

Participants were asked to keep their stylus on a moving green dot as it moved in a figure-of-eight pattern about the screen. There were 9 trials, at slow, normal and fast speeds and it required approximately ten minutes to complete. Our outcome measure was the average (root-mean-squared-error - RMSE) distance between the pen and dot over the course of the trial.

Tracing Task

The screen shows ‘tramlines’ outlining the shapes of a house, a tree and a random path. Participants were asked to trace the lines, keeping their pen between them. A moving bar at the top of the screen illustrated how much time participants had left to complete the task as they progressed. Shapes were traced at 3 levels of increasing speed. The outcome measure is tracing accuracy at the fastest speed.

Other Measures

Each participant completed the four subtests of the WASI-IV: Vocabulary, Similarities, Matrix Reasoning and Block Design). Class teachers also completed a Social Responsiveness Scale (Constantino & Todd, 2003) for each child. The SRS is designed to assess the degree to which individuals express the autism phenotype, on the assumption that the autism phenotype is normally distributed within the typical population.

RESULTS

Individual Differences

Firstly, we examined individual differences. We wished to know whether our method could discriminate between children and obtain a spread of performance measures that were predictive of other differences, and also to get a general idea as to how well children were able to imitate. To obtain individual performance measures we derived 2 types of accuracy measures in the form of correlations and mean errors. We examined these for the movement parameters of trial duration and path length, from which the parameter of speed was derived.

Correlation Measures Of Imitation Accuracy

As discussed above, the ‘two-way method’ tests the capacity of the imitator to discriminate between alternative methods of demonstration and so a corollary of this approach is to test whether an imitator ranks a group of actions in the same order as they have been demonstrated, according to a pre-specified variable. We therefore used a rank-correlation coefficient (Spearman’s) as a measure of ranking consistency. We considered a statistically significant correlation between demonstrated and repeated actions, to be evidence of imitation.

For the measure of object size (path length), most participants showed significant imitation and some remarkably high correlations (n = 58, mean R = 0.616, SD = 0.303; max r =0.92). Of the 9 participants who failed to show evidence of size imitation as inferred by the rank correlation coefficient for path length, 5 were in year 1, 1 was in year 2 and 3 were in year 3. For the measure of duration, all but 3 of the participants showed significant ($P<0.05$) rank correlation coefficients between the duration of their actions and those of the demonstrator. All of these 3 had also not shown significant effects size either. We also found strong evidence for imitation of trial duration ($n = 58$, mean $R=0.731$, max $r = 0.96$) even though we had asked participants to copy size and speed. Only 3 did not show evidence for imitation (none of these had imitated path length either and all were from year 3). On comparing correlation measures of accuracy for speed and duration, we found accuracy to be better for duration than path length (paired t-test with non-imitators excluded: mean r for duration = 0.807 SD=0.135; mean r for path length = 0.728, SD=0.154; $t=3.82$, $df=48$, $p<0.001$). For the measure of drawing speed, derived from these 2 measures, all but the 3 who had not shown imitation for trial duration, showed significant imitation ($n = 58$, mean $R= 0.700$, $SD = 0.240$; max = 0.96). However, again, with non-imitators excluded, trial duration was imitated significantly more accurately than speed (mean r for duration = 0.778 ,SD=0.160; mean r for path length = 0.728, SD=0.167; $t=2.90$, $df=54$,$p=0.005$), though there was no difference for accuracy of speed imitation vs size imitation (path length r mean = 0.728 SD=0.154 ; speed 0.741 SD=0.156; paired t-test: $t=1.52$, $df = 48$, $p> 0.1$)

Correlation between the 3 accuracy measures was high considering all subjects ($n=58$, size vs duration $r = 0.695$; size vs speed $r = 0.647$; duration vs speed $r = 0.928$; all $p<0.001$) but more moderate when only considering those who showed evidence of imitation (size vs duration r = 0.501, n=49, p<0.001; size vs speed r = 0.454, n=49, p=0.001; duration vs speed r = 0.840, n=55, p<0.001) .

Mean Error Measures Of Imitation Accuracy

An alternative approach to determining the extent to which the imitator copies the demonstrator, is simply to measure the difference between the demonstrated and copied actions. To this end, we calculated the Mean Absolute Error (MAE – the distance a number is from zero), as well as the variability (SD) of these errors. We also calculated the Root Mean Squared Error (RMSE) which is a closely related but which is derived from residuals rather than errors. All had a parametric distribution according to the Kolmogarov-Smirnov test (P>0.05). As expected, within measures of speed, length or trial duration, the values correlated closely with each other, given that all reflect the amount of variability of the imitated parameter around the demonstrated parameter. Strongest correlations were between the RMSE measures and mean absolute error, and between RMSE and variability of error (see Table 2). Correlations were weaker between mean error and variability of error. We therefore selected RMSE as the measure of error for the next stage of our analysis. The RMSE measures showed only moderate correlations with Spearman measures of imitation fidelity, showing them to be quite different measures (Table 3).

Linear Regression Of Error Measures

We then went on to investigate whether any of our measures of individual differences would prove to be correlates of imitation skill. For each of our accuracy measures, we ran a linear regression analysis with the variables of the participant's age, sex, verbal IQ, performance IQ, motor control as measured by the tracing task, motor control as measured by the tracking task, and SRS score. Results are shown in Table 4. We found that Age was a very strong predictor performance for size on both accuracy measures, a little less so for duration and least on speed where the correlation with the Spearman measure of accuracy did not reach significance. The only other measure which predicted accuracy was tracing ability which was a highly significant correlate of accuracy for both speed and duration measured by the Spearman but not the RMSE. Of interest, the RMSE measure of accuracy for path length showed an almost significant trend towards significance with SRS score.

Group Effects

Group Correlations

To investigate the performance of the group as a whole the mean of each parameter for the group was plotted against that of the model. Results are shown in Figure 2. For object size, R^2=0.886 and the equation for the line was y=0.633x + 311.6. For Trial duration, R^2=0.886 y=0.644x +4.435 and for speed, R^2=0.904, y=0.404x +45. Mean disagreement for each parameter was then calculated. This was the mean of the absolute difference between group and model for the 45 conditions as a percentage of the overall mean for the model and the group. Hence we found that for path length, the mean level of disagreement between demonstrator and imitator was 15.07% of the average path length for both demonstrator and imitator across all conditions. For duration, this figure was 25.3 % and for speed it was 37.3%.

Effects Of Conditions

The effects of age and stimulus size and speed on error patterns were investigated with repeat measures ANOVA. Initially, difference between demonstrated and copied parameter was calculated for each trial and then recalculated as a percentage of the demonstrated parameter to adjust for magnitude. The 45 conditions (5 shapes x 3 sizes x 3 speeds) were then collapsed to 9 conditions (3x sizes and 3 x speeds) by taking the mean value of the 5 shapes for each shape-size combination. This ensured that assumptions of parametricity were unviolated. The repeat measures ANOVA was then run as a 3 size (small, medium and large) x3 speed (slow, medium and fast) design with covariates of age and tracing ability. Because of non-sphericity of data, Greenhouse-Geisser correction was applied.

Object Size

This revealed main effects of stimulus size ($F(2,55)=8.144$; $p=0.001$, $\eta^2=0.131$) and a stronger interaction between age and size ($F(2,55)=12.582$; $p<0.001$, $\eta^2=0.189$). There was a significant 3 way interaction between size, speed and age of small effect ($F(2,55)=3.35$; $p=0.015$, $\eta^2=0.058$) but all other effects including main effects of age and tracing error were insignificant (all $p>0.1$).

Trial Duration

This revealed main effects of age and tracing error (Age: $F(1,54)=4.664$, $p=0.035$ $\eta^2=0.08$; tracing error: $F(1,54)=6.964$, $p=0.011$, $\eta^2=0.114$) as well as a main effect of speed (F(2,53)=8.27,p=0.002, η^2=0.133), interactions between tracing error with speed (size: F(1,54)=6.427, p=0.006 η^2=0.106) and interactions between age and size (F2,53)=4.946, p=0.012, η^2=0.084), and between size, speed and age ((F2,53)=3.105,p=0.029, η^2=0.054).

Speed Error

When the Repeat Measures ANOVA was run with tracing ability as a covariate, there were no significant effects (p>0.1 with the exception of the effect of stimulus speed which was almost significant: F(2,53)=3.441, p=0.052, η^2=0.06). The main effects of tracing as a covariate were only evident as a trend (F(1,54)=3.43; p = 0.069; η^2=0.06 and interactions between tracing ability and effects of size, or speed were not significant (all p>0.1).

In an effort to understand why stimulus magnitude should affect imitation accuracy for size and duration but not speed, the repeat measures ANOVA was then re-run without the covariate of tracing error. Then there were highly significant effects of both the size and speed of the shape being demonstrated on the percentage error made by the participant (demonstrated speed: F(2,55)=21.12, p<0.001, η^2=0.274; demonstrated size: F(2,55)=11.28, p<0.001, η^2=0.168 . Effects are shown in Figure 3. Slowest speeds were overestimated, whilst fastest speeds were underestimated. Furthermore, the error for speed was affected by the size as well as the speed of the demonstrated action, in that smaller objects increased the overestimation of speed compared to larger objects, whilst larger objects increased the underestimation. There was no main effect of age

($F(2,56)=0.346$, $p=0.558$, $\eta^2=0.006$) but age interacted significantly with size ($F(2,55)=3.871$, $p=0.041$, $\eta^2=0.065$) and marginally so with speed ($F(2,55)=3.357$, $p=0.055$, $\eta^2=0.057$) .

DISCUSSION

In this study, we developed a method for generating objective measures of imitation accuracy for the speeds and sizes of movements. We hypothesised that our measures would show developmental improvement across primary school years, whilst also correlating with fine motor control, IQ and behavioural traits indicative of social behaviour. We also hypothesised that length, time and speed would be imitated in a closely dependent manner consistent with dependency on a single imitation mechanism.

For the purpose of initial analysis, we defined imitation operationally, as occurring where a significant statistical dependency could be demonstrated between the variability of the demonstrator's behaviour and that of the observer. By defining imitation statistically was not to make any assumptions about the cognitive mechanisms underpinning the relationship between demonstrated and re-enacted behaviour. Rather, it was following a similar principle to the 2-way method which also determines the presence of imitation by a statistical dependency between the demonstrators' behaviour and that of the observing group (Whiten, Custance, Gomez, Teixidor, & Bard, 1996). In our case however, the much larger number of behaviours being examined meant that a separate value could be assigned to each individual observer, quantifying the degree of statistical dependency. We found that most participants showed evidence of imitation, with some showing very high levels of fidelity, with r-values up to 0.92 for speed or 0.96 for path length or trial duration. Notably, we used the Spearman rank correlation coefficient as opposed to the Pearson correlation coefficient. Whilst the choice of this approach was largely forced on us because of the non-parametric distribution of the sample for a significant number of individuals, it is also more consistent with the 2-way model, which tests whether observers evidence discrimination between 2 demonstrated variables in their imitation behaviour, rather than how quantitatively close their copy is to the model. A disadvantage of a non-parametric correlation is that we are not able to obtain measures of slope and constant and fidelity is also subject to bias as was evident from the group correlation analyses. Therefore, in theory, an individual may be able to show a perfect correlation, in so far as performing the imitated actions in exactly the same rank order as they were displayed, but their actions could still be quantitatively quite different because they show bias, by changing at a different rate or starting from a different baseline. This was most evident in our group analyses that showed very strong correlations between the model parameters and those of the group mean, but regression equations with slopes of 0.44-0.64 and high constants. Interestingly, these two forms of bias compensated for one another to reduce the average disagreement but this still amounted to 15-37.3%.

We then explored an alternative approach to measuring imitation by measuring the quantitative difference between two actions as a mean error for each trial. We also calculated variability of errors and the root mean square error for all the trials combined for each individual. All these latter measures represent the spread of the values of the imitated actions around the value of the expected action and therefore showed high levels of intercorrelation. One disadvantage of this approach was that it did not easily provide a means of defining whether imitation occurred or not, thereby requiring that all participants were included in the analysis irrespective of whether they had imitated or not.

It is unclear if, or in what way, individual differences in the mean-error and correlational measures of fidelity might capture different aspects of imitation ability. In a recent study, (Braadbaart, Waiter, & Williams, 2012) examined correlates of these 2 measures of imitation accuracy with the brain activity measured using fMRI whilst subjects performed a simple imitation task. The correlation measure for speed predicted activity in ventromedial frontal cortex and inferior somatosensory cortex, whilst RMSE corresponded to activity in primary sensorimotor cortex. These findings suggest that RMSE may be more predictive of motor control, whilst correlation may correspond to more cognitive or representational aspects of imitation.

We examined this issue further by looking at relationships of fidelity measures with age, IQ, motor ability and social behaviour using linear regression. We found strong effects of age on all variables, showing that imitation fidelity continues to improve throughout middle childhood. The association of age was also a strong indicator that our test is likely to discriminate between good and poor imitators and that imitation fidelity continues to improve throughout middle childhood. No other factors influenced variability for any accuracy measures apart from a relationship between tracing error and the Spearman measures for speed and trial duration. Whilst the Spearman measure showed a strong relationship with tracing ability, the RMSE measures only showed a relationship with age. On the face of it, these findings seem at odds with the suggestion that the RMSE measure should correspond better with level of motor control. However, closer examination of the tracing task reveals an important commonality with the imitation of speed/time task. To optimise accuracy on the tracing task, the participant must move as slowly as is allowed. This means planning the speed of his or her movement to be in keeping with the moving bar which provides constraint on the minimum permitted speed of movement. This suggests that the capacity to plan movement speed in order to complete a movement within a required period is an important determinant of imitation accuracy, and is in keeping with the possibility that in imitating speed; participants formed representations of path length and duration and then planned their movements to replicate these.

The group-wise analysis threw further light on this relationship. The group demonstrated some consistent patterns of error in tending to overestimate slower and smaller actions whilst underestimating larger and faster actions. This is an example of a ‘contraction bias’, typical of situations where participants are asked to make quantitative estimations (Poulton, 1979), and tend to have a bias towards the mean as they show reluctance to select more extreme values. We found that younger children showed greater contraction bias than older children and so evidently this was an important means by which age affected accuracy.

When tracing ability was included in the model as a covariate, effects of stimulus size or speed on the error were no longer significant. Although tracing ability in itself was not a predictor of error, the results are consistent with the hypothesis that motor planning, underpinning both speed imitation and tracing ability, is important for speed imitation.

The finding of strong evidence for imitation of action duration surprised us because participants had only been asked to copy speed and size of object. Indeed, the fidelity of imitation as measured by the strength of correlation was greater for action duration than speed or size. The most likely reason for this we suggest, is that duration, which only requires a time-estimate, is easier to remember than speed, and if duration and size are remembered, then speed would be reliably copied also.

In considering the relevance of these findings to the broader study of imitation, it is necessary to first review the nature of the task here. Although the actions were goal-directed, the outcome of the actions was not observed by the imitator, the children only saw the drawing action and did not see an action outcome. Hence, the actions copied in this study may be better considered as meaningful or transitive gestures rather than object-directed actions. Wild et al., (2010) found that imitation of speed was less likely in the presence of a goal but they examined meaningless actions. Secondly, our measurements focussed on the speed and size of the actions rather than their form. This was previously termed ‘adverbial’ imitation by Perra et al.(2008) which they found best distinguished their autism group from controls.

Consequently, it is necessary to be interpret these findings in a context of the goal-directed imitation literature with some caution. In detecting a contraction bias, we find that children are imitating conservatively, which appears at some odds with literature suggesting that children are more likely to over-imitate (Horner & Whiten, 2005; McGuigan et al., 2010) and that they may do so to comply with prescriptive norms or cultural expectations (Kenward, Karlsson, & Persson, 2011; Nielsen & Blank, 2011). In our study however, the degree of error was not the result of intentional action selection but rather a mismatch between magnitudes of perceived and executed actions, presumably as a result of the functioning of the visuomotor system. Nevertheless, the children did appear to employ a form of selective imitation in apparently choosing to imitate the duration and size of actions. This behaviour would be consistent with the view that they understand the causal role of duration in determining speed and so make the rational choice to copy this aspect of the action, in order to optimise performance (Lyons, Damrosch, Lin, Macris, & Keil, 2011). It is also arguable that speed may constitute a form of secondary representation of action, being derived from primary forms of representation in the form of duration and size. This would be consistent with the area of ventral medial frontal cortex activation shown in association with this parameter by (Braadbaart et al., 2012).

Apart from this study, those of Wild et al. and that of Hobson and Lee, ‘adverbial’ imitation or its equivalent appears to have been little studied. This is perhaps surprising given its importance in everyday life. When we learn skills, it often the way that they are done as much as what is done that is the key to their success. Furthermore, we learn novel skills through iteration, by the intentional modulation and modification of previously learned actions (Wolpert, Doya, & Kawato, 2003). Given the potential role of feed-forward processes in imitative development, this approach may correspond more closely to the motoric skills required for imitation in middle childhood than previous measures. Perhaps one reason for a lack of work in this area has been that studies of action dynamics have traditionally required sophisticated and expensive kinematic measurement systems, whereas the Kinematic Assessment Tool utilised in this study enabled rapid data collection in the setting of a primary school. Hence, recent technological developments are making this area of research a much more straightforward process.

Nevertheless, the approach as it stands so far is limited to quantitatively variable measures, which limits its scope for the study of imitation. In our study, we did not explore whether participants imitated the shape correctly, as we did not have a reliable measure of how close the form of the drawn shape was to the form of the modelled shape. In future iterations of this method, it will be possible to have forms which vary in continuous ways (e.g. ellipses that vary in relative lengths of axes or triangles with variable angles). However, the method is likely to remain limited to aspects of imitation that depend upon the capacity to vary action as opposed to those that depend upon action-selection or decision-making.

CONCLUSION

In this paper, we argue that there is a need for more accurate, objective and comparable measures of imitation and report a novel experimental method used to measure imitation fidelity in children. This initial study focussed on the problem of imitating speed and size of a gestural action and demonstrates the potential of varying the parameters of an action along a continuum and measuring the degree of correspondence between them. Some promising findings emerged which will be useful in further developing and applying objective measures of imitation fidelity. We demonstrated that we could obtain meaningful measures of imitation fidelity that could separately reflect accuracy and reliability (or consistency) of performance, and which could distinguish between children according to differences in age, and one case motor control. Secondly, we found that participants are prone to systematic error and by distilling a task into performance on its measurable components potentially provided information about the cognitive models participants employed to complete the task. In summary, this study demonstrates that careful, objective measurement of kinematic parameters may offer novel insights into the cognitive mechanisms that underpin imitation.

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Table 1. Description of Participants.

Class	Male/ Female	Age	SRS score	Verbal scale IQ	Performance scale IQ	Tracking score	Tracing score	
1	5/5	7.77	18.89	108.80	105.40	1.41	1.89	Mean
		10	9	10	10	10	10	n
		0.3	12.43	7.33	11.38	0.11	0.38	SD
2	5/5	8.79	27.80	114.20	109.78	1.28	1.83	Mean
		10	10	10	9	10	9	n
		0.52	14.93	11.04	13.45	0.14	0.53	SD
3	5/5	9.84	19.00	101.20	102.11	1.28	1.76	Mean
		10	9	10	9	10	10	n
		0.34	18.77	7.42	6.37	0.09	0.22	SD
4	3/6	10.97	22.67	101.11	107.44	1.24	1.60	Mean
		9	9	9	9	9	9	n
		0.39	21.21	9.29	7.81	0.12	0.26	SD
5	5/5	11.95	20.50	101.00	105.60	1.29	1.64	Mean
		10	10	10	10	10	10	n
		0.29	18.43	7.59	11.01	0.13	0.33	SD
6	5/4	12.89	12.44	99.86	102.56	1.25	1.54	Mean
		9	9	7	9	9	9	n
		0.27	10.24	6.87	14.69	0.19	0.15	SD
Total	28/30		20.36	104.66	105.48	1.29	1.71	Mean

			56	56	56	58	57	n
			16.38	9.70	10.97	0.14	0.34	SD

Table 2. Correlations between RMSE measures of accuracy and variability of error across trials

	Mean error duration	Mean error size	Mean error speed	RMSE duration	RMSE size	RMSE speed	SD duration error	SD size error	SD speed error
Mean error duration	1	.288	.597	**.968**	.472	.556	**.850**	.449	.463
Mean error size		1	0.216	.342	**.896**	0.149	.388	**.820**	0.045
Mean error speed			1	.500	.314	**.955**	.344	.271	**.842**
RMSE duration				1	.498	.463	**.955**	.471	.378
RMSE size					1	0.219	.500	**.973**	0.091
RMSE speed						1	.314	0.154	**.960**
SD duration							1	.468	0.244

error									
SD size error								1	0.02
SD speed error									1

Table 3. Correlations between Spearman and RMSE measures of imitation accuracy.

	Spearman duration	Spearman speed	RMSE size	RMSE duration	RMSE speed
Spearman size	.501	.454	−.758	−.535	−0.263
Spearman duration	1	.840	−.557	−.365	−.493
Spearman speed		1	−.454	−.279	−.566
RMSE size			1	.498	0.219
RMSE duration				1	.463
RMSE speed					1

Table 4. Results of linear regression analysis

Measure of Imitation accuracy		Size			Duration			Speed		
		Std. Beta	t	*p*	Std. Beta	t	*p*	Std. Beta	t	*p*
Spearman	Age	0.696	5.357	**<0.001**	0.368	2.566	**0.014**	0.299	2.012	0.051
	Sex	−0.072	−0.644	0.5240	−0.01	−0.08	0.937	−0.038	−0.295	0.769
	Verbal IQ	0.148	1.138	0.2630	0.071	0.505	0.617	0.078	0.535	0.596
	Performance IQ	0.096	0.849	0.4020	0.033	0.276	0.784	0.094	0.754	0.455
	Tracking error	−0.202	−1.731	0.0920	−0.131	−1.062	0.294	−0.253	−1.982	0.054
	Tracing Error	−0.186	−1.666	0.1050	−0.451	−3.6	**0.001**	−0.429	−3.305	**0.002**
	SRS score	0.085	0.772	0.4450	−0.091	−0.761	0.451	−0.007	−0.058	0.954
RMSE	Age	−0.607	−4.319	**<0.001**	−0.525	−3.135	**0.003**	−0.476	−3.011	**0.004**
	Sex	0.151	1.294	0.203	−0.056	−0.403	0.689	0.007	0.051	0.96
	Verbal	−0.146	-	0.292	0.02	0.1	0.9	0.00	0.0	0.98

	IQ		1.067			2	05	2	16	7
	Performance IQ	0.031	0.264	0.793	−0.088	−0.62	0.539	−0.241	−1.794	0.08
	Tracking error	−0.129	−1.075	0.288	−0.032	−0.225	0.823	0.145	1.072	0.29
	Tracing error	0.23	1.854	0.071	−0.111	−0.75	0.457	−0.006	−0.045	0.965
	SRS score	0.226	1.979	0.054	0.066	0.481	0.633	0.067	0.522	0.605

Figure 1.

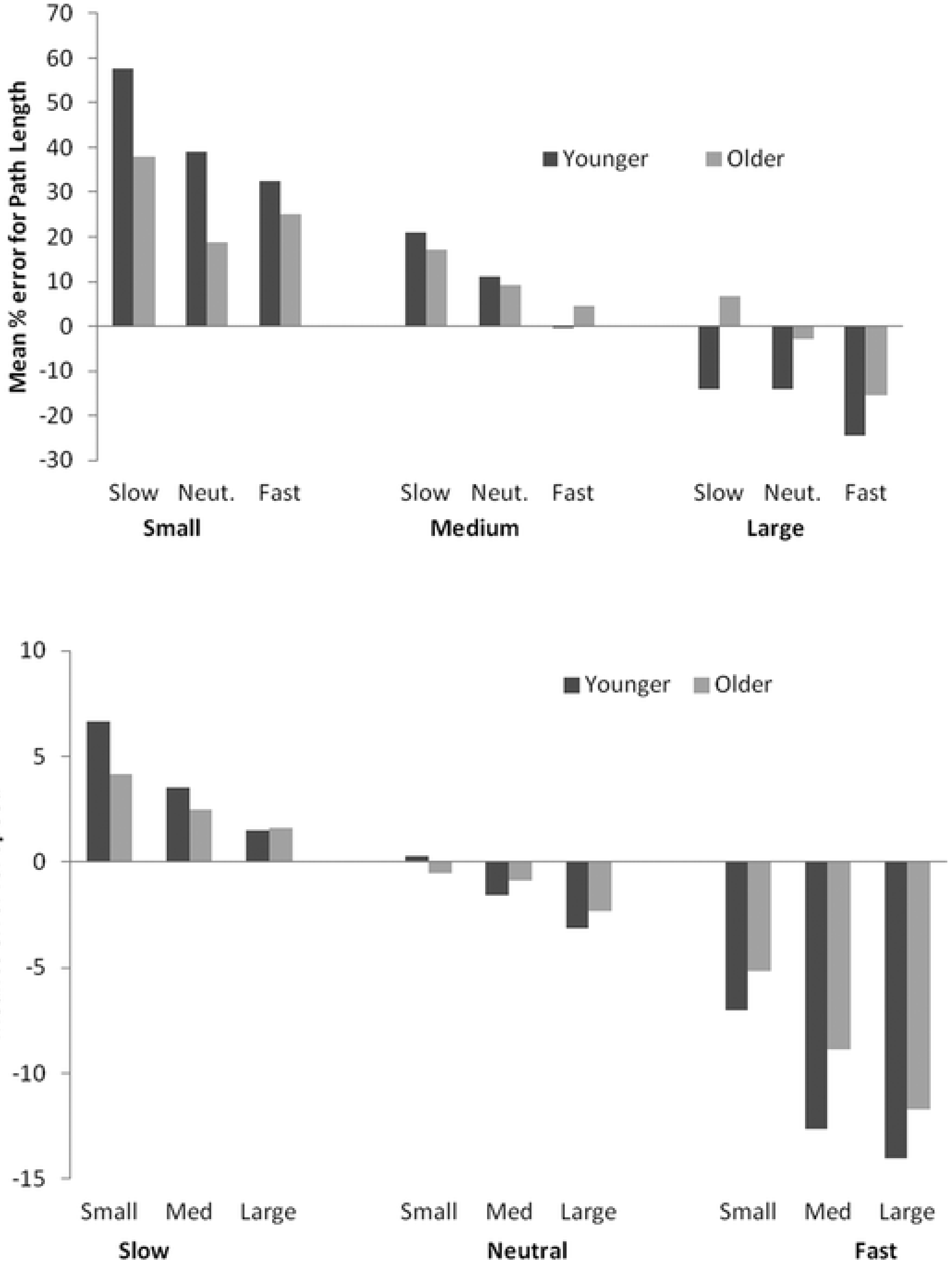

Mean % error for Path Length
70
60
50
40
30
20
10
0
-10
-20
-30
■ Younger
■ Older
Slow
Neut.
Fast
Small
Slow
Neut.
Fast
Medium
Slow
Neut.
Fast
Large
Mean % error for Speed
10
5
0
-5
-10
-15
■ Younger
■ Older
Small
Med
Large
Slow
Small
Med
Large
Neutral
Small
Med
Large
Fast

Figure 2.

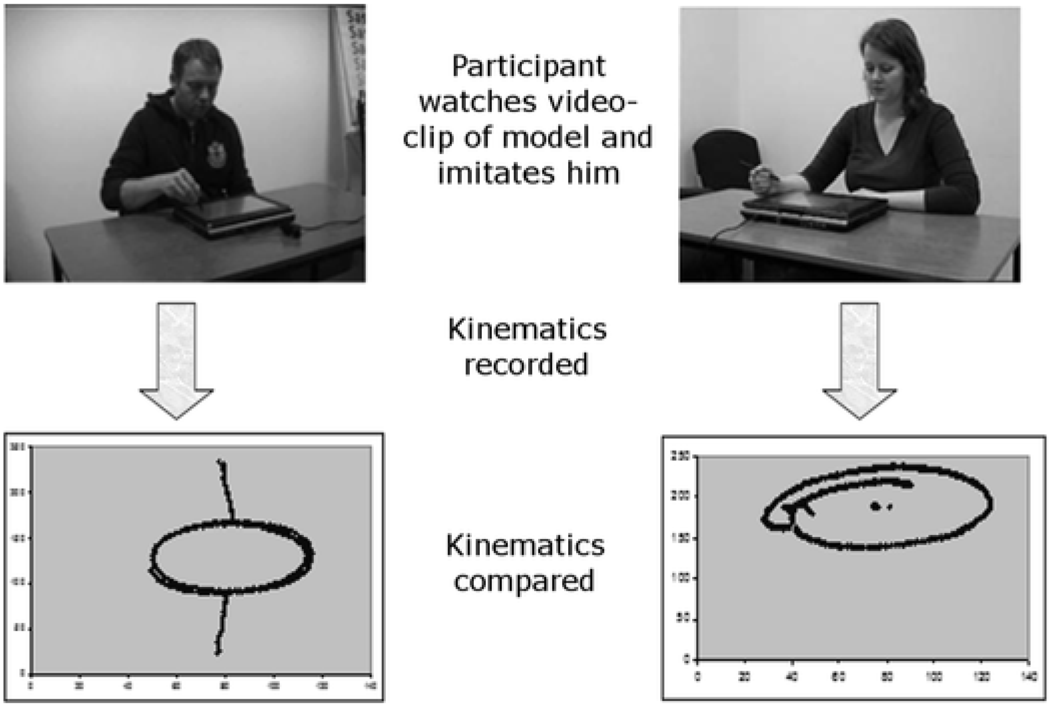
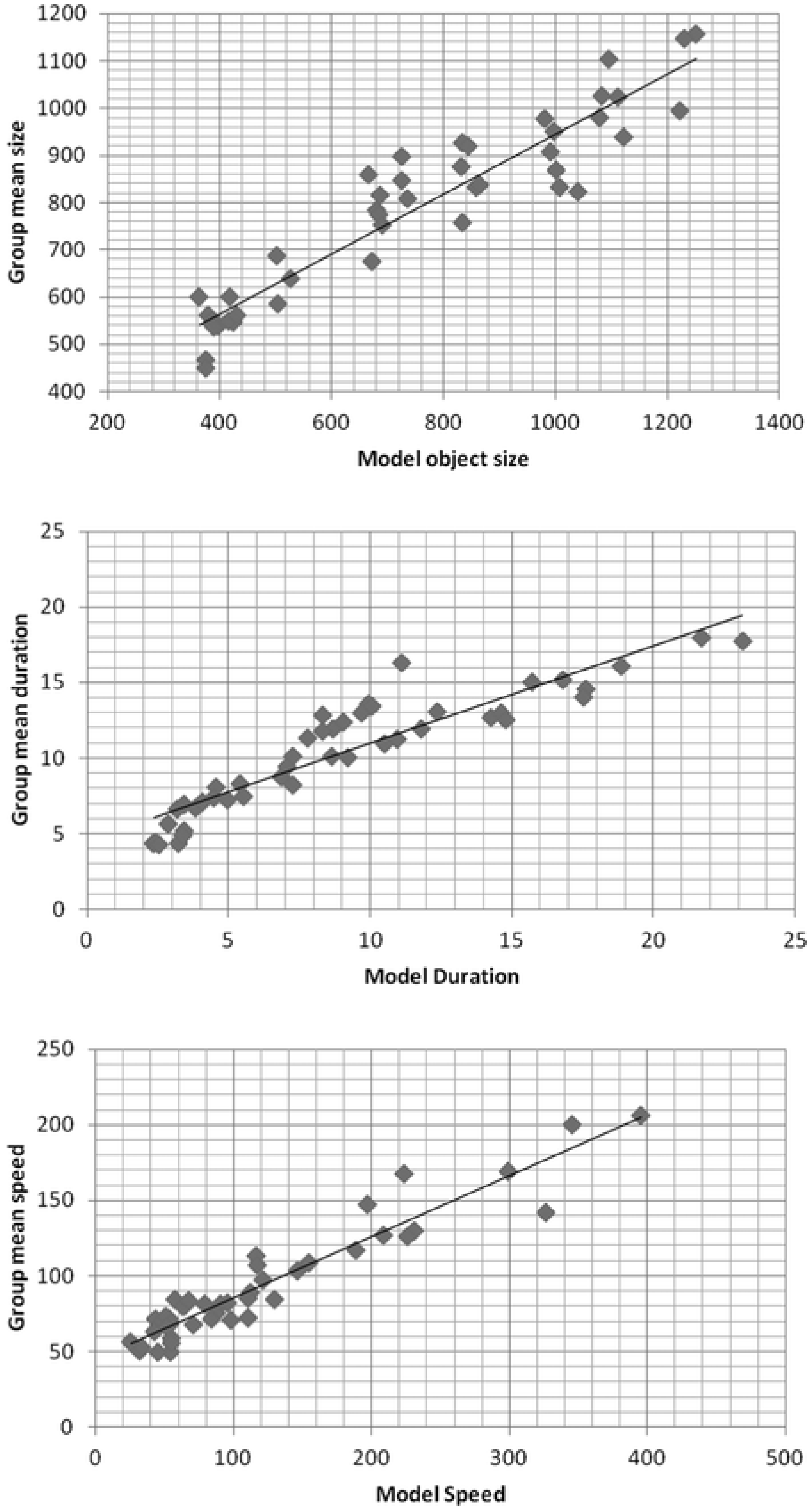

Participant watches video-clip of model and imitates him
Kinematics recorded
Kinematics compared
250
200
150
100
50
0
0
20
40
60
80
100
120
140

Figure 3.


Group mean size
1200
1100
1000
900
800
700
600
500
400
200
400
600
800
1000
1200
1400
Model object size
Group mean duration
25
20
15
10
5
0
0
5
10
15
20
25
Model Duration
Group mean speed
250
200
150
100
50
0
0
100
200
300
400
500
Model Speed