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SHORT REPORT

Becoming a high-fidelity – *super* – imitator: what are the contributions of social and individual learning?

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Abstract

In contrast to other primates, human children's imitation performance goes from low to high fidelity soon after infancy. Are such changes associated with the development of other forms of learning? We addressed this question by testing 215 children (26–59 months) on two social conditions (imitation, emulation) – involving a demonstration – and two asocial conditions (trial-and-error, recall) – involving individual learning – using two touchscreen tasks. The tasks required responding to either three different *pictures in a specific* picture *order (Cognitive: Airplane→Ball→Cow) or three* identical *pictures in a specific* spatial *order (Motor-Spatial: Up→Down→Right). There were age-related improvements across all conditions and imitation, emulation and recall performance were significantly better than trial-and-error learning. Generalized linear models demonstrated that motor-spatial imitation fidelity was associated with age and motor-spatial emulation performance, but cognitive imitation fidelity was only associated with age. While this study provides evidence for multiple imitation mechanisms, the development of one of those mechanisms – motor-spatial imitation – may be bootstrapped by the development of another social learning skill – motor-spatial emulation. Together, these findings provide important clues about the development of imitation, which is arguably a distinctive feature of the human species.*

Research highlights

- Do children become better imitators because they become better learners?
- Performance on four learning conditions using two tasks improved with age.
- Imitation learning was not associated with individual learning across tasks.
- Imitation learning in a motor-spatial task was associated with emulation.

Introduction

Imitation, defined here as the ability to vicariously learn and replicate others' responses and knowledge, is a pillar of human cognitive and social-cultural development. In contrast to other animals, human children's imitative responses are both remarkable in their versatility and high fidelity (Dean, Kendal, Schapiro, Thierry & Laland, 2012; Herrmann, Call, Hernandez-Lloreda, Hare & Tomasello, 2007; Subiaul, 2007; Whiten, 2011). Although some imitative responses are present early in infancy (Barr, Vieira & Rovee-Collier, 2001; Bauer, Hertsgaard, Dropik & Daly, 1998; Meltzoff & Moore, 1977), during the preschool years imitation undergoes significant changes, going from low to high fidelity (Dickerson, Gerhardstein, Zack & Barr, 2013; Horner & Whiten, 2005; Lyons, Young & Keil, 2007; McGuigan, Makinson & Whiten, 2010; Subiaul & Schilder, 2014). Various authors have argued that high-fidelity imitation

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is what supports and makes cumulative cultural evolution possible in humans (Boyd & Richerson, 1994; Lewis & Laland, 2012; Tomasello, 2014).[1] It is an open question, however, whether changes in domain-general – universal – learning processes (Heyes, 2012) or domain-specific – specialized – social learning mechanisms (Subiaul, 2007, 2010) are associated with the increasing fidelity of human children's imitation performance across development.

Despite a burgeoning number of developmental and comparative studies on imitation (Nielsen, Subiaul, Galef, Zentall & Whiten, 2012), many questions still remain regarding the nature of imitation and its development since Piaget (1945/1962) first proposed what is arguably the most comprehensive model nearly half a century ago. According to Piagetian constructivism, changes in imitation performance directly correspond to changes in sensorimotor and cognitive development, one developmental milestone serving as a necessary building block to the next (Piaget, 1962). While there have been several important challenges to this view of imitation development (Carver & Bauer, 1999; Mandler, 2004; Meltzoff, Kuhl, Movellan & Sejnowski, 2009), Piaget's larger theoretical framework remains highly influential (Jones, 2009; Sirois, Spratling, Thomas, Westermann, Mareschal *et al*., 2008). For instance, the Piagetian concept of embodied cognition or 'embodiment' (Meltzoff *et al*., 2009; Sirois *et al*., 2008) has been revived by contemporary research in cognitive development and neuroscience. Consistent with Piagetian constructivism, a number of studies have demonstrated that understanding and predicting the actions of others is facilitated by directly experiencing and executing those same actions (Cannon, Yoo, Vanderwert, Ferrari, Woodward *et al*., 2014; Falck-Ytter, Gredeback & von Hofsten, 2006; Sommerville, Woodward & Needham, 2005). Some of these authors have proposed that phylogenetically conserved mirror neurons, a neural population that was originally identified in the inferior frontal lobe of rhesus monkeys (Fadiga, Fogassi, Pavesi & Rizzolatti, 1995; Iacoboni, Woods, Brass, Bekkering, Mazziotta *et al*., 1999; Marshall & Meltzoff, 2011; Rizzolatti, Fadiga, Gallese & Fogassi, 1996), respond to both the observation and execution of goal-directed actions in human adults and infants alike (Cannon *et al*., 2014; Falck-Ytter *et al*., 2006; Iacoboni *et al*., 1999).

Alternatively, Heyes (2012) has proposed that associative learning underlies imitation learning as does all multi-modal learning. In this view, the domain-generality of associative learning processes precludes the need for any specialized imitation mechanism, as associative learning and imitation are both theorized to depend on the same cognitive and neural processes.

Others argue that while associative learning is important, it is insufficient to explain imitation (Bekkering, Wohlschlager & Gattis, 2000; Meltzoff, 1995; Tomasello & Carpenter, 2005; Wohlschlager, Gattis & Bekkering, 2003). According to the Goal-Directed Imitation (GOADI) model, there is an intermediate step between the perception of a stimulus and the execution of a matching response: namely, reasoning about a model's goals or intentions. According to this goal-mediated model for imitation, regardless of the task or domain, individuals form representations of the goals of others' actions in addition to the actions themselves.

Although Piagetian constructivist, associationist, and GOADI theories differ on whether imitation development is mediated by direct experience or by representing others' goals/intentions, they all treat imitation as a unitary concept where one cognitive mechanism is sufficient to explain *all* types of imitative performance. But there are reasons to be skeptical of this unitary view. For instance, monkeys perform poorly on 'motor imitation' tasks that involve copying specific actions with tools (Fragaszy & Visalberghi, 2004), but perform well on 'cognitive imitation' tasks which involve copying abstract rules and conventions (Subiaul, Cantlon, Holloway & Terrace, 2004; van de Waal, Borgeaud & Whiten, 2013). Special human populations such as individuals with Autism Spectrum Disorders or ASD have also been characterized in part by imitation-specific impairments (Williams, Whiten & Singh, 2004); Specifically, individuals with ASD fail on motor imitation tasks but succeed on cognitive imitation tasks (Subiaul, Lurie, Romansky, Klein, Holmes *et al*., 2007). Given that the monkeys tested were not immersed in a human social-cultural environment during development, and individuals with ASD have significant social impairments including difficulties inferring others' goals and intentions (Baron-Cohen, 1991), their general failure in motor imitation but success in cognitive imitation challenges a unitary – domain-general – view of imitation. Instead, these results are more consistent with the Multiple Imitation Mechanisms (MIM) model which hypothesizes that there are different imitation mechanisms (MIM), responsible for copying different types of information with high fidelity (Nadel, 2006; Subiaul, 2010).

In a direct comparison of preschoolers' ability to imitate novel motor-spatial and cognitive rules (see Figure 1), Subiaul, Anderson, Brandt and Elkins (2012) showed that 3-year-olds successfully imitated novel cognitive rules (e.g. Airplane → Ball → Cow),

[1] For another perspective see Taylor and colleagues (Taylor, Cheke, Waismeyer, Meltzoff, Miller *et al*., 2014)

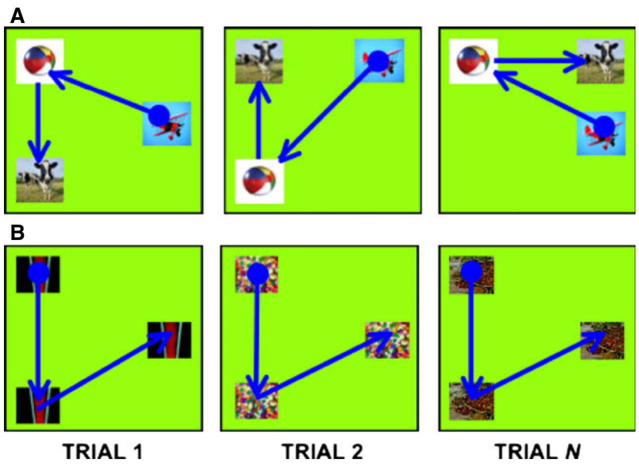

Figure 1 *Computer-based tasks. (A) Cognitive Task: three different pictures appear on a touch-screen. From trial to trial, these three pictures re-appear in a different spatial configuration. (B) Motor-Spatial Task: three identical pictures appear on a touch-screen. From trial to trial, a different set of identical pictures appears in the same spatial configuration. In both tasks, children must touch each picture in a target sequence.*

yet failed to imitate novel motor-spatial rules (Up → Right → Down). Four-year-olds excelled at imitating both types of rules (Experiment 1). These results indicate that motor-spatial and cognitive imitation are developmentally dissociable. Further, although 3-year-olds had difficulty imitating novel motor-spatial rules, they could recall motor-spatial rules that they had learned via trial-and-error in an asocial 'recall' condition (Experiment 2) and reproduced the model's goal – after observing the model repeat the same error – using idiosyncratic means in a goal emulation condition (Experiment 3). Thus, 3-year-olds' motor-spatial imitation difficulties also appear to be dissociable from their ability to individually learn, recall and emulate new motor-spatial rules. However, Subiaul *et al*. (2012) did not test children in all learning conditions using both the Cognitive and the Motor-Spatial Task. As such, it left unanswered whether children become high-fidelity – super – imitators because they become better learners in general or because they become better social learners in particular.

To address that question, in the present study 215 preschool-age children ranging from 26 to 59 months of age were tested. This is a period characterized by rapid improvements in imitation fidelity that ranges from the ability to imitate subtle actions and gestures (Dickerson *et al*., 2013), including causally irrelevant actions on objects (Lyons *et al*., 2007; McGuigan *et al*., 2010; McGuigan, Whiten, Flynn & Horner, 2007) as well as copying novel, abstract rules and categories (Loucks & Meltzoff, 2013; Subiaul *et al*., 2007; Subiaul, Vonk & Rutherford, 2011; Williamson, Jaswal & Meltzoff, 2010). In the present study, all children were tested in four different learning conditions using the Cognitive and Motor-Spatial Tasks (Figure 1). Two conditions involved individual (asocial) learning (Trial-and-Error, Recall following trial-and-error learning) and two others involved social learning (Imitation, Emulation), where a model demonstrated a target sequence prior to testing. We first determined whether our manipulations were successful by testing whether learning in the imitation, emulation, and recall conditions exceeded learning in the trial-and-error condition (see Barr & Hayne, 2000). Then our models tested how imitation, emulation and recall were interrelated as a function of age and task type or domain (Cognitive or Motor-Spatial).[2] Specifically, we tested whether improvements in children's imitation fidelity is best characterized by (a) associations with individual learning mechanisms as measured by recall following trial-and-error learning – consistent with domain-general associationist theories or Piagetian constructivism, (b) associations with other social learning process measured by emulation learning – consistent with a domain-general, goal-mediated (GOADI) view or (c) no significant association between learning mechanisms across tasks or age groups – consistent with a more domain-specific (MIM) model.

Methods

Participants

Two hundred and fifteen children[3] ranging in age from 26 to 59 months (M = 42.13 months, SD = 7.73, females = 105) completed training and testing in the Smithsonian Institute's National Museum of Natural History in Washington, DC using IRB approved protocols from both the Smithsonian and the George Washington University.

Experimental tasks

Children were presented with two different tasks using the same computer (see Figure 1). In the Cognitive Task, children were required to press three different pictures in

[2] For the purposes of this study, the domains in question, cognitive and motor-spatial, were operationalized using the Cognitive and the Motor-Spatial Task; as such, domain and task will be used interchangeably throughout.

[3] In all, 28.4% of parents reported that their children belonged to a racial or ethnic minority.

the correct order regardless of the spatial location. The identity of the three pictures on the screen differed and their spatial arrangement varied randomly from trial to trial (Figure 1A). This task assessed children's ability to learn a serial object-based rule. In the Motor-Spatial Task, children were required to press three pictures in a target spatial configuration regardless of the picture identity. The identity of the three pictures on the screen was the same and their position on the screen remained constant from trial to trial. However, from trial to trial the picture changed (Figure 1B). This task assessed children's ability to learn a serial spatial-based rule.

Training and testing

Following the protocol developed by Subiaul and colleagues (2012), children were trained on each task (Cognitive, Motor-Spatial) prior to the introduction of the experimental conditions. Training was similar to the Trial-and-Error condition (described below) and ensured that performance on the experimental conditions did not reflect any lack of familiarity with the touchscreen, experimenter, or protocol. During training, children were exposed to each task and encouraged to 'Find "Jumping Man"' by touching the pictures on the screen in a target order. Children received social feedback from the model and asocial (audio, visual) feedback from the computer following each response, correct or incorrect. An incorrect response terminated the trial. Incorrect trials generated a brief (~500 ms) 'boom' sound, all pictures disappeared, the screen turned black for 2 s, and the experimenter said, 'Whoops! That's not right!' Following a correct response, the computer generated a brief (~500 ms) 'bing' sound, all pictures remained on the screen and the experimenter said, 'That's right!' When all three pictures were touched in the correct order, a 5 s video clip of a man doing a backward somersault – 'jumping man' – played in the middle of the screen accompanied by music or clapping and the model smiled and said, 'Yay! You found jumping man!' To advance to testing, children had to independently respond to all three pictures on the screen in the target order without making any errors.

Training and testing occurred during a single session lasting 10 to 15 minutes per child. All children completed training for each task followed by the four learning conditions for each task. To avoid carryover effects, six unique sequences were used throughout the study (three for each task, one sequence was used for Trial-and-Error and Recall). Sequences remained the same within conditions and differed between conditions. In each condition, children were allowed up to 20 trials to touch all three pictures in the target order. However, once the child responded correctly to all three pictures (i.e. first correct trial), they moved on to the next condition. To avoid confusion or interference, tasks were blocked with half of the children being tested first on the Motor-Spatial Task. The order in which the children were tested on each condition was counterbalanced such that all possible orders of conditions were given an equal number of times,[4] with the restriction that the Trial-and-Error condition was always followed by the Recall condition.[5]

The two asocial learning conditions were Trial-and-Error and Recall:

Trial-and-Error learning (henceforth, Trial-and-Error)

Children were encouraged to discover the correct sequence entirely by trial-and-error learning.[6] Upon touching all pictures correctly and the completion of the Jumping Man video, the computer was turned away from the child for 30 seconds, and the child's attention was diverted to stickers and stamps. Performance on this condition was used to establish the spontaneous rate of sequence learning and directly compared to recall, emulation and imitation performance.

Individual Recall (henceforth, Recall)

Thirty seconds after the completion of the Trial-and-Error condition, the computer was turned back around and the child was told, 'Okay, it's your turn again. Can you find jumping man again? Remember, start with picture number 1.' The same sequence from the Trial-and-Error condition was used in the Recall condition to assess the child's ability to encode and recall an individually learned rule.

The two social learning conditions were Imitation and Emulation:

Imitation

The experimenter faced the child and said, 'Watch me!' and then proceeded to touch pictures in the target

[4] Such counterbalancing ensures that any statistical significance in our results is not a product of the order in which children experienced the different conditions since all possible orders are equally represented in the final dataset.

[5] The Trial-and-Error condition was always followed by the Recall condition because participants needed to learn the object- or spatial-based rule before individually recalling that specific rule.

[6] Both the model and the computer provided feedback following each response to equate other factors that might influence performance across tasks and conditions. Specifically, social feedback consisted of eye-contact, smiles, etc. and verbal reinforcement (e.g. 'That's right!' Or, 'Whoops! That's not right!').

sequence (e.g. A→B→C) three consecutive times. Immediately after the third and final demonstration, the experimenter faced the child and exclaimed, ‘Yay! I found Jumping Man! OK, now it’s your turn. Can you find Jumping Man? Remember, start with picture number 1.’

Goal Emulation (henceforth, Emulation)

Procedures were identical to those described above except that the experimenter touched the first picture correctly and then incorrectly touched the last picture in the sequence, skipping the second (middle) item. Following this error, the experimenter faced the child and with a sad face said, ‘Whoops, that’s not right. Let me try again. Watch me.’ This same error was repeated three times and made it clear that the model had failed to fulfill their goal (i.e. to find Jumping Man). Following the last demonstration, the experimenter turned to the child and said, ‘Whoops, that’s not right. I can’t find Jumping Man. Now it’s your turn. Can you find Jumping Man? Remember, start with picture number 1.’ This procedure was equivalent to the non-verbal re-enactment procedure used by Meltzoff (1995) and the ‘Whoops’ paradigm used by Carpenter, Akthar and Tomasello (1998).

Because both tasks used these same conditions, we will refer to each by first identifying the task and then the condition (e.g. Cognitive Imitation, Motor-Spatial Recall).

Measure of learning

A learning ratio measure was calculated for each condition and task. The ratio is calculated as the total number of correct responses (i.e. pictures touched in the target order) to the total number of trials in a condition. Trials were stopped either when a child completed the tasks (97% of all cases), or when a child was no longer willing to participate (3% of all cases). For example, imagine a child makes the following responses across 3 trials, Trial 1: *C* (0 correct responses), Trial 2: A→*C* (1 correct response), Trial 3: A→B→C (3 correct responses, condition complete), the learning ratio would be 4/3 (or 4 correct responses divided by 3 trials) = 1.33. Children could not make the following response: A→*C*→*B* because an incorrect response (e.g. touching C after A) terminated the trial. However, since pictures did not disappear after a correct response, it was possible for children to make the following response: A→B→*A* (2 correct responses). The maximum ratio was 3 (3/1) and the minimum was 0 (failing to touch any picture in the target order).

Results

Does learning differ between conditions?

In order to answer any question about imitation fidelity and its relation to learning in other conditions, we first have to establish that Imitation, Emulation and Recall performance exceeds Trial-and-Error learning. To that end, children’s performance (Figure 2) across conditions (Trial-and-Error, Recall, Imitation, Emulation) was included in two repeated measures non-parametric *permutation tests* (Hothorn, Hornik, van de Wiel & Zeileis, 2006, 2008),[7] one for the Cognitive Task and another for the Motor-Spatial Task.

For the Cognitive Task, there was a main effect of Condition, $maxT = 8.63$, $p < .001$. Post-hoc contrasts with a Bonferroni correction for multiple comparisons across conditions showed that performance across conditions significantly exceeded Trial-and-Error performance, but beyond this, no two conditions were significantly different from one another (Tables 1A and B).

For the Motor-Spatial Task, there was a main effect of condition, $maxT = 10.55$, $p < .001$. Post-hoc contrasts with a Bonferonni correction for multiple comparisons across conditions revealed that Trial-and-Error was significantly lower than all other conditions. In addition, Emulation performance was higher than Imitation (Tables 2A and B). The results replicate those reported previously by Subiaul *et al.* (2012) showing differences between conditions within the Motor-Spatial Task.

Which factors are associated with changes in imitation fidelity?

Two generalized linear models (GLMs) were constructed, one for Cognitive Imitation and another for Motor-Spatial Imitation. GLMs are an extension of traditional linear models that can handle non-normally distributed data through the use of a link function (Venables & Ripley, 2002). For our data, a binomial error distribution and the logit link function were

[7] Permutation tests are a robust non-parametric alternative often used when data are not normal, as was the case here (Shapiro-Wilk test, Cognitive Task: W = 0.84, $p < .001$, Motor-Spatial Task: W = 0.87, $p < .001$). Rather than assuming some underlying distribution, in a permutation test the data are randomly permutated, in this case 10,000 times, and each time a test statistic is calculated. The observed test statistic is then compared to the 10,000 permutated statistics to determine the significance level of the observed data. More detail can be found in Hothorn *et al.* (2008).

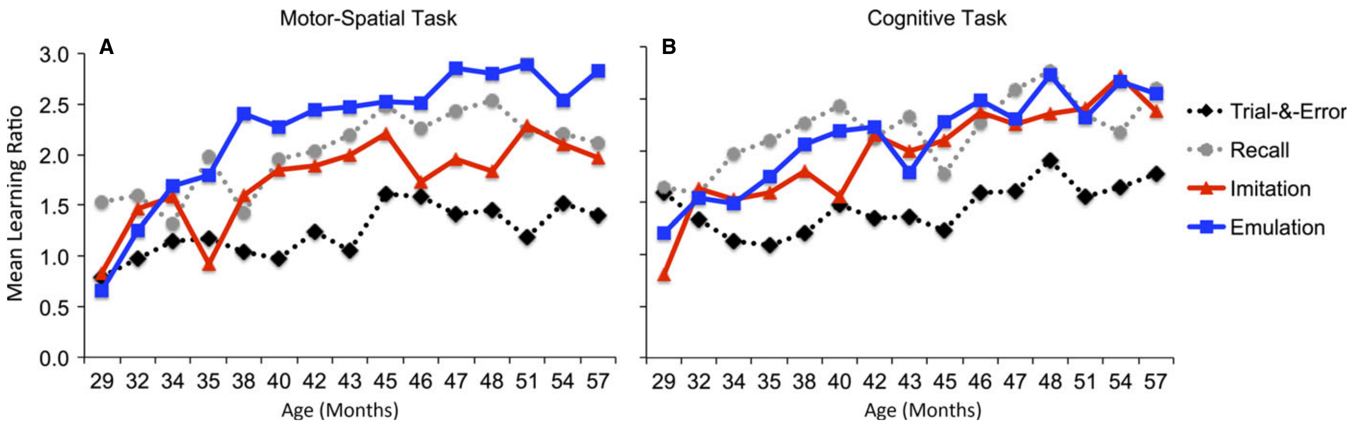

Figure 2 *Age-related changes in social (solid lines) and asocial (dotted lines) learning in (A) the Motor-Spatial and (B) the Cognitive Task.*

Table 1 *Results for the Cognitive Task*

A. Cognitive Task Condition Contrasts

Contrasts for Cognitive Task	Z	Bonferroni Corrected *p*
Trial-and-Error vs. Emulation	−7.028	<.01
Trial-and-Error vs. Imitation	−5.342	<.01
Trial-and-Error vs. Recall	−7.728	<.01
Emulation vs. Imitation	−1.470	>.8
Emulation vs. Recall	1.403	>.8
Imitation vs. Recall	2.741	>.8

B. Learning Ratios for the Cognitive Task Conditions

Cognitive Task condition	*N*	Mean	Standard Error
Trial-and-Error	203	1.394	0.058
Recall	203	2.194	0.067
Imitation	203	1.939	0.077
Emulation	203	2.069	0.071

Table 2 *Results for the Motor-Spatial Task*

A. Motor-Spatial Task Condition Contrasts

Contrasts for Motor-Spatial Task	Z	Bonferroni Corrected *p*
Trial-and-Error vs. Emulation	−9.880	<.01
Trial-and-Error vs. Imitation	−6.011	<.01
Trial-and-Error vs. Recall	−8.777	<.01
Emulation vs. Imitation	−5.586	<.01
Emulation vs. Recall	−2.758	>.8
Imitation vs. Recall	2.914	>.8

B. Learning ratios for the Motor-Spatial Task Conditions

Motor-Spatial Task condition	*N*	Mean	Standard Error
Trial-and-Error	192	1.206	0.042
Recall	192	1.994	0.064
Imitation	192	1.737	0.067
Emulation	192	2.227	0.072

appropriate since the dependent variable was the binomial response total number of correct responses and total number of trials (Venables & Ripley, 2002). This response variable is essentially the learning ratio described above, but the actual division of scores is not carried out and the two numbers are modeled together as a binomial response. Because our data were under-dispersed, as indicated by the ratio of the residual deviance to the residual degrees of freedom (Cognitive imitation = 0.55; Motor-Spatial imitation = 0.84), we used a quasibinomial error distribution (Venables & Ripley, 2002). We explored all possible models that included the predictor variables age (months), the learning ratios on the five other learning conditions, and all age by condition interaction terms. The final model for each task was determined using quasi Akaike's information criterion with correction for finite sample size (QAICc).[8]

Model 1 tested whether age, learning conditions, and age by learning condition interactions were associated with Cognitive Imitation fidelity. Only age was a significant predictor of Cognitive Imitation fidelity in the final model (Table 3A). Model 2 tested whether age, learning conditions, and age by learning condition interactions were associated with Motor-Spatial Imitation fidelity. Age and Motor-Spatial Emulation were significant predictors of Motor-Spatial Imitation fidelity in the final model (Table 3B). In neither final model were any interaction terms significant, which indicates that age and any significant learning condition acted

[8] The advantage of this approach is that it is much better than backwards/forwards selection since all possible models are explored and the best is selected based on how much variance is explained, with penalty for more complicated models.

Table 3 *Final GLM models*

A. Cognitive Imitation (QAICc = 559.8)

	Unstandardized coefficients		Standardized coefficients		
	B	Std. Error	Beta	*t*	*p*
Age (months)	0.025	0.008	0.125	3.147	.002
Motor Spatial Recall	0.112	0.067	0.064	1.681	.092
Cognitive Emulation	0.105	0.060	0.068	1.754	.081

B. Motor-Spatial Imitation (QAICc = 528.9)

	Unstandardized coefficients		Standardized coefficients		
	B	Std. Error	Beta	*T*	*p*
Age (months)	0.017	0.006	0.088	2.762	.006
Motor-Spatial Emulation	0.181	0.047	0.118	3.826	<.001

additively (not interactively) with the dependent measure.

In a final set of analyses we tested whether there were age-related changes on Emulation and Recall in both the Cognitive and the Motor-Spatial Tasks. Two age groups were created using a median split: younger ($\leq$ 42 months) and older (> 42 months). Permutation tests were used to compare each group's performance on these learning conditions across tasks. Results showed that older children significantly out-performed younger children on all four learning conditions (mean $\pm$ standard error, Cognitive Recall: younger = 2.05 $\pm$ 0.09, older = 2.39 $\pm$ 0.09, Z = 2.53, $p = .04$; Cognitive Emulation: younger = 1.82 $\pm$ 0.10, older = 2.37 $\pm$ 0.09, Z = 3.96, $p < .01$; Motor-Spatial Recall: younger = 1.75 $\pm$ 0.09, older = 2.30 $\pm$ 0.08, Z = 4.37, $p < .01$; Motor-Spatial Emulation: younger = 1.86 $\pm$ 0.11, older = 2.68 $\pm$ 0.07, Z = 5.84, $p < .01$, Bonferroni correction used for multiple tests). These results show that there were significant age-related improvements across all learning conditions. Yet, as the GLM models above show, such improvements in performance failed to significantly predict age-related improvements in imitation.

Discussion

In contrast to other primates, humans are super imitators, quickly going from being low- to high-fidelity imitators after infancy (Barr, Dowden & Hayne, 1996; McGuigan *et al*., 2007; Young, Rogers, Hutman, Rozga, Sigman *et al*., 2011). Exactly what is associated with these developmental changes in this potentially unique feature of human social learning is the subject of significant debate (Nielsen *et al*., 2012), but relatively limited empirical research. Surprisingly few studies have systematically examined age-related changes in preschoolers' imitation fidelity (Bauer, Wiebe, Carver, Waters & Nelson, 2003; Dickerson *et al*., 2013; Flynn & Whiten, 2013; Williams, Casey, Braadbaart, Culmer & Mon-Williams, 2014; Young *et al*., 2011). Existing studies, however, have not examined whether increases in fidelity are related to other learning mechanisms and whether there are domain-general or domain-specific effects. To fill this gap, the present study sought to test whether improvements in preschool children's imitation fidelity is best characterized by (a) associations with other asocial – individual – learning processes such as recall – consistent with a domain-general associationist or Piagetian constructivist view, (b) associations with other social learning process such as emulation – consistent with a domain-general goal-mediated (GOADI) view or (c) dissociations between different kinds of imitation mechanisms and between imitation mechanisms and other social and asocial learning processes – consistent with a multiple imitation mechanisms (MIM) view.

Results showed that, first, during the preschool years: Recall, Imitation and Emulation performance all exceeded Trial-and-Error learning (see Tables 1 and 2). Second, there were robust age-related improvements in accuracy across all learning conditions (see Figure 2). Third, despite age-related improvements in learning across non-Trial-and-Error conditions and equivalent levels of learning between all conditions in the Cognitive Task and most conditions in the Motor-Spatial Task, imitation learning was not uniformly associated with social (Emulation) or asocial/individual (Recall) learning mechanisms (see Table 3). Instead, changes in imitation fidelity were age-specific and domain-specific. That is, increases in Cognitive Imitation were only significantly associated with age.

Increases in Motor-Spatial Imitation were significantly associated with both age and Motor-Spatial Emulation. Neither Cognitive nor Motor-Spatial Imitation was significantly associated with one another.

The lack of significant associations between imitation and the other learning conditions is surprising given that task parameters were nearly identical and that learning conditions were measured within tasks. While the Motor-Spatial and Cognitive Tasks involved learning different types of rules, they both involved responding to three pictures in a specific order on the same computer. The lack of significant associations between Recall following Trial-and-Error learning and Imitation for either task (Table 3) among preschoolers does not provide support for a strong associationist (Heyes, 2012) or Piagetian constructivist (Piaget, 1962) view of imitation. However, such accounts may explain social learning in other tasks and domains (Barr, 2013; Bird, Brindley, Leighton & Heyes, 2007; Bird, Osman, Saggerson & Heyes, 2005; Cannon *et al*., 2014; Cook, Bird, Lunser, Huck & Heyes, 2012; Sommerville *et al*., 2005; Williamson & Meltzoff, 2011). Specifically, tasks that involve copying simple, familiar responses should correlate more strongly with asocial learning measures than tasks that involve imitating more complex, novel responses that do not already exist in the observers' behavioral repertoire or that have been extensively trained (e.g. Bird *et al*., 2005). The fact that Motor-Spatial and Cognitive Imitation were not significantly associated is consistent with the theory that there are at least two imitation learning mechanisms with potentially independent developmental trajectories (Subiaul, 2010; Subiaul *et al*., 2012).

The significant association between imitation and emulation in the Motor-Spatial Task may be taken as preliminary support for the goal-mediated view of imitation development. Specifically, GOADI theorists would argue that emulation (or goal-directed) learning mediates imitation performance (Bekkering *et al*., 2000). But while children's ability to reason about goals may facilitate the development of motor-spatial imitation learning, there was not a significant association between Cognitive Emulation and Imitation as would be predicted by the GOADI theory (see Subiaul *et al*., 2012, for a dissociation in performance between Motor-Spatial Imitation and Emulation). These findings suggest that there is increasing specialization in imitation systems in this age range that is independent of the development of other reasoning and social learning processes.

While not addressed by the present study, it may be that during infancy (< 1.5 years) a more domain-general social learning mechanism scaffolds or mediates imitation performance followed by divergence between domain-general and domain-specific learning as predicted by Piagetian constructivism (Piaget, 1962). A domain-general (or unspecialized) social learning mechanism may explain significant associations between social and asocial learning tasks early in development (Cannon, Woodward, Gredeback, von Hofsten & Turek, 2012; Young *et al*., 2011) and is consistent with the association between emulation and imitation in the Motor-Spatial Task. Future studies using the Cognitive and Motor-Spatial Tasks could be conducted longitudinally and across a wider age range (both younger and older children) to provide a clear understanding of developmental divergence across different learning conditions in the Cognitive and Motor-Spatial Tasks.

The lack of any significant association between cognitive and motor-spatial imitation and other learning conditions during the preschool years suggests that imitation may be like 'executive functions', which consist of interconnected but dissociable subsystems such as the visuo-spatial sketchpad, phonological loop and central executive (Baddeley, 1996, 2012; Bauer & Zelazo, 2013; Best & Miller, 2010). Based on these and previous studies (Dickerson *et al*., 2013; Subiaul *et al*., 2012; Young *et al*., 2011), we hypothesize that during the preschool years these mechanisms mature and differentiate themselves from other learning systems, resulting in at least two non-verbal 'elemental' imitation mechanisms (Renner, Zimmerman, Schilder, Mendelson, Golojuch *et al*., 2013). One of these mechanisms is predicted to mediate the imitation of object-based rules (i.e. cognitive imitation). The other is predicted to mediate the imitation of spatial-based rules (i.e. motor-spatial imitation). During the preschool years, these elemental imitation mechanisms may become increasingly specialized and dissociate from other learning processes (e.g. emulation and recall). While cognitive imitation may allow children to copy object-based rules with high fidelity, it does not support the imitation of spatial-based rules (Renner *et al*., 2013). In contrast, the earlier emergence of motor-spatial emulation prior to motor-spatial imitation may support children's ability to learn new motor responses via goal-mediated mechanisms as well as motor-spatial relationships necessary to operate complex and functionally opaque objects and tools (Subiaul, 2007).

Conclusion

Many researchers have conceptualized imitation as a unitary learning mechanism (Piaget, 1962; Uzgiris, 1973, 1981). According to that view, any developmental change in imitation performance is due to general developmental changes in other learning processes, including emulation and recall. The present study casts doubt on important aspects of that assumption. Here, we demonstrate that imitation performance becomes increasingly more accurate and specialized within specific domains during the preschool years. We hypothesize that underlying these changes are domain-specific imitation mechanisms (i.e. cognitive and motor-spatial). However, goal-directed social learning or emulation – a low-fidelity social learning mechanism – was significantly associated with increasing fidelity in imitation performance in the Motor-Spatial Task. This result is consistent with the hypothesis that emulation develops early (e.g. Subiaul *et al.*, 2012; Want & Harris, 2002) and may scaffold the development of more specialized imitation learning mechanisms, responsible for high-fidelity motor imitation, which some (Boyd, Richerson & Henrich, 2011; Lewis & Laland, 2012; Tomasello, 2014) have linked to a distinctively human form of social learning: cumulative cultural evolution.

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Graphical Abstract

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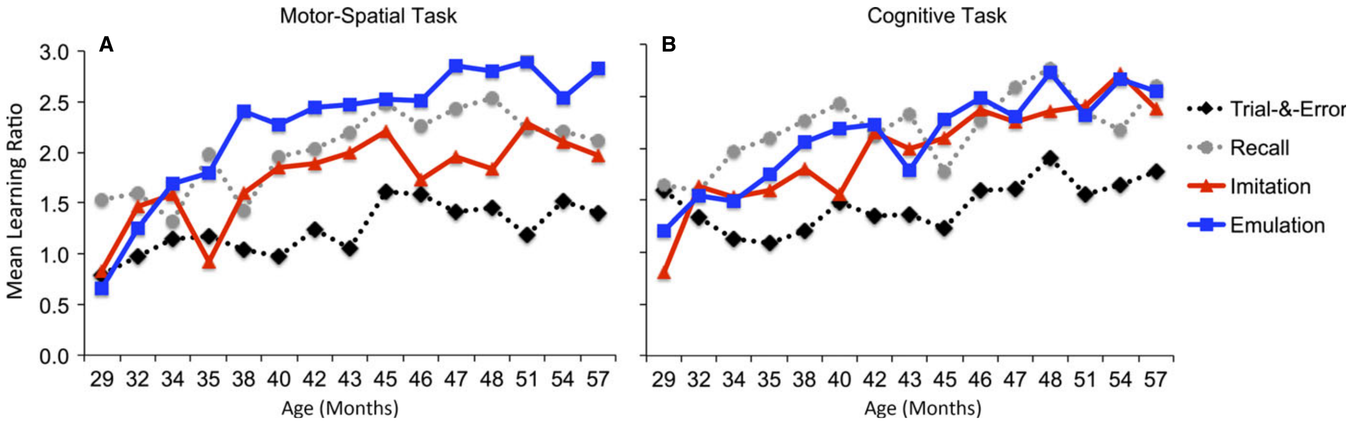

Preschool children's ability to learn two different tasks by imitation, emulation and individual learning significantly improved with age. However, these broad age-related changes were generally not associated with improvements in imitation fidelity. These results indicate that children's imitation performance is not mediated by domain-general learning processes but by domain-specific imitation mechanisms, specialized for copying either object- or motor/spatial-based rules.