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Special issue paper

The cognitive structure of goal emulation during the preschool years

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Humans excel at mirroring both others' actions (imitation) as well as others' goals and intentions (emulation). As most research has focused on imitation, here we focus on how social and asocial learning predict the development of goal emulation. We tested 215 preschool children on two social conditions (imitation, emulation) and two asocial conditions (trial-and-error and recall) using two touch screen tasks. The tasks involved responding to either three *different* pictures in a specific *picture* order (Cognitive: apple→boy→cat) or three *identical* pictures in a specific *spatial* order (Motor-Spatial: up→down→right). Generalized linear models demonstrated that during the preschool years, Motor-Spatial emulation is associated with social and asocial learning, while cognitive emulation is associated only with social learning, including motor-spatial emulation and multiple forms of imitation. This result contrasts with those from a previous study using this same data set showing that motor-spatial and cognitive *imitation* were *neither* associated with one another nor, generally, predicted by other forms of social or asocial learning. Together, these results suggests that while developmental changes in imitation are associated with multiple – specialized – mechanisms, developmental changes in emulation are associated with age-related changes and a more unitary, domain-general mechanism that receives input from several different cognitive and learning processes, including some that may not necessarily be specialized for social learning.

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Compared to most animals, humans are super imitators, mirroring others' actions across diverse domains with incredible fidelity (Subiaul, Patterson, Renner, Schilder, & Barr, 2015; Whiten, 2011).[1] These imitative abilities have been linked to humanity's prowess in the artefact domain, and our ability to develop and sustain language and culture (Boyd, Richerson, & Henrich, 2011; Lewis & Laland, 2012). Equally important is our remarkable ability to mirror others' goals and intentions, a behavioural response referred to as emulation. Like imitation, emulation has been linked to the development of critical cognitive skills including theory of mind (Bellagamba, Camaioni, & Colonnesi, 2006; Meltzoff, 1988, 1995) and causal reasoning (Want & Harris, 2001). Yet, social neuroscientists have, generally, failed to make a distinction between these different mirroring phenomena or social learning behaviours such as emulation and imitation that involve copying others' responses. The conflation of imitation and emulation may be due to the assumption that all mirroring (being actions and/or intentions) is the product of the same neural machinery, mirror neurons, a population of neurons in the inferior frontal and parietal lobe of monkeys and humans. For instance, according the Direct-Matching (DM) hypothesis, to mirror actions is to mirror intentions (Iacoboni *et al.*, 2005; Rizzolatti & Fabbri-Destro, 2008).

This approach stands in contrast to that in the comparative and, more recently, the developmental sciences, which have differentiated between action (imitation) and intention (emulation) mirroring. Researchers have focused on *when* (developmentally) and *why* (contextually/motivationally) children emulate rather than imitate and the contexts or effects of different mirroring processes resulting in emulation or imitation (for reviews, see Lyons, 2009; Over & Carpenter, 2012). However, research has not addressed whether during development performance on mirroring behaviours (imitation and emulation) is related to one another, as well as other types of learning. One difficulty in addressing this relationship is definitional (Nielsen, Subiaul, Galef, Zentall, & Whiten, 2012; Want & Harris, 2002; Whiten, McGuigan, Marshall-Pescini, & Hopper, 2009). Until recently, emulation has been poorly characterized. For instance, Whiten *et al.* (2009) have distinguished between multiple varieties of emulation all of which are characterized by selectively copying some aspect of a demonstrated behaviour while ignoring others (Table 1). This broad conceptualization of emulation as selective and/or idiosyncratic copying aspects of demonstrated events is consistent with terms such as 'rational imitation' (Gergely, Bekkering, & Kiraly, 2002), 'behavioural re-enactment' (Meltzoff, 1995), 'under-imitation' (Heyes, 2012a), and 'generalized' or 'selective' imitation (Gewirtz & Stingle, 1968).

One form of emulation, goal emulation, in which an individual mirrors a model's intended goal but not the model's actions (Whiten & Ham, 1992), has been studied extensively by developmental scientists. Across these studies, participants are provided with an unintended or incomplete response sometimes marked by a language cue, like 'Whoops' (Carpenter, Akhtar, & Tomasello, 1998). The individual then copies some of the model's responses but not others. Various researchers have argued that in such conditions, children are more likely to generate the 'intended' (but unobserved) response than the 'unintended' (and observed) response (Bellagamba *et al.*, 2006; Meltzoff, 1995; Subiaul, Anderson, Brandt, & Elkins, 2012). While some have questioned whether children emulate in these conditions by attributing intentions and goals to the model or

[1] *Unless stated otherwise, action mirroring is used synonymously with imitation and goal/intention mirroring is used synonymously with emulation.*

Table 1. Varieties of Emulation. Different categories of emulation proposed by a number of authors including their definitions and experimental examples. While many other distinctions are possible, we identify two types of goal emulation: Goal emulation as rational imitation or selective imitation (where the goal is observed) and goal emulation as behavioural re-enactment (where the goal is unobserved and must be inferred)

Varieties of emulation	Definition	Example
Emulation *sensu* affordance learning	'. . .[observer] learns from its observation various functional relations in the task. . .' (Nagell *et al*., 1993, p. 175)	Learning that a tool can be used to achieve a result while failing to learn the necessary actions (e.g., Tomasello *et al*., 1987; Nagell *et al*., 1993)
Object movement re-enactment	'Copying what the object does. . . [or] what a model does with an object' (Whiten *et al*., 2004, p. 39)	Observer reproduces the functional movements of objects (e.g., removing ends of dumb-bells) without a live model (e.g., Huang *et al*., 2002)
End-state emulation	'Copying only the end or outcome of an action sequence' (Whiten *et al*., 2004, p. 39)	Upon seeing an opened box, the observer learns that the door must be opened to reveal what is inside (e.g., Carpenter, Call, & Tomasello, 2002)
Goal emulation *sensu* behavioural re-enactment	'. . .go beyond duplicating what was actually done and. . .instead enact what the adult intended to do' (Meltzoff, 1995)	After observing a model attempting but failing to open a container, the child opens the container (e.g., Meltzoff, 1995)
Goal emulation *sensu* rational imitation	'. . .the emulator copies not all results just those that are the goals of the model' (Whiten, 2000, p. 482)	Turning on a lamp with one's hand after observing someone turning on a similar lamp with one's head (e.g., Gergely *et al*., 2002)

whether they are solving such problems using causal (Huang & Charman, 2005; Huang, Heyes, & Charman, 2002), contextual, or rational reasoning (Gergely *et al.*, 2002), there is no doubt that children can learn from incomplete and incorrect information (Hopper, 2010).

Although these studies demonstrate that children are versatile and robust learners, they raise important conceptual questions regarding the relationship between potentially different mirroring responses and their underlying mechanisms. If children are emulating and imitating using the same cognitive (e.g., attributing goals and causal reasoning) or neural mechanisms (e.g., mirror neurons), then distinctions between different mirroring responses such as imitation and emulation may be invalid. For instance, both Heyes' (2012a,b) Associative Sequence Learning hypothesis and Paulus' (Paulus, 2014; Paulus, Hunnius, Vissers, & Bekkering, 2011) Idedomotor Imitation Learning (IMAIL) hypothesis propose that the 'core' mechanism for all forms of social learning including imitation and emulation is associative learning, the same mechanism mediating asocial (individual) learning. According to these associative accounts, children imitate or emulate as a function of matching the effects of their own motor output to that of others' actions. These representations expand with the child's motor development (Paulus, 2014). Importantly, in these associative accounts what underlies these different mirroring responses is not a specialized mechanism *for* social learning, but domain-general 'input mechanisms' including perceptual, attentional, and motivational processes that differentially 'ingest' information for learning (Heyes, 2012a).

Similarly, Rizzolatti and colleagues' (Iacoboni *et al.*, 2005; Rizzolatti, Fadiga, Fogassi, & Gallese, 1999) DM hypothesis proposes that mirror neurons mediate action understanding by directly associating action and perception. Accordingly, observing a model's actions automatically causes corresponding parts of our own motor system to become active and 'resonate' (Rizzolatti, Fogassi, & Gallese, 2001). Any outcome (i.e., 'goal') associated with the activated actions is automatically projected onto the model's actions. Not only do the actions resonate but the goals associated with those actions resonate as well, allowing observers to understand others' behaviour.

While some have challenged the link between mirror neurons and mentalistic 'goals' among other higher order mental-state attributions like intentions or empathy (Heyes, 2010), others have explicitly made this link (Falck-Ytter, Gredeback, & von Hofsten, 2006; Sommerville & Woodward, 2005). For example, Meltzoff's (2007) Like Me Hypothesis proposes that mirroring others' actions results in the personal simulation of others' motor responses and mental states serving as the foundation for a mature theory of mind.

Other prominent social learning theorists such as Whiten & Ham (1992; Whiten, Horner, Litchfield, & Marshall-Pescini, 2004) reject that social learning is mediated by associative processes and is devoid of mental-state reasoning but, nonetheless, 'interpret some of the varieties of what has been called emulation as overlapping with imitation in important ways, rather than as offering a neat dichotomy' (Whiten *et al.*, 2004, p. 38). For instance, according to goal-mediated (Bekkering, Wohlschlager, & Gattis, 2000; Carpenter *et al.*, 1998) or rational theories (Gergely *et al.*, 2002; Kiraly, Csibra, & Gergely, 2013) of social learning, different forms of mirroring (imitation and emulation) are mediated by a common social cognitive process rather than common associative learning mechanisms or mirror neurons alone. Specifically, social learning is the product of reasoning about others' intentions (e.g., Carpenter *et al.*, 1998; Meltzoff, 1995) and/or the physical constraints of a task (Gergely *et al.*, 2002; Kiraly *et al.*, 2013). According to these goal-mediated or rational models of imitation, individuals copy first and foremost others' goals. Context dictates whether the goal is to reproduce the model's effects (end-state emulation) or intentions (goal emulation) using idiosyncratic responses or using the model's *same* actions (imitation). In effect, goal-mediated theories turn the DM Hypothesis on its head: We mirror goals and intentions first and then mirror actions.

Finally, other researchers argue that imitation and emulation are mediated by distinct – specialized – cognitive processes (Bellagamba *et al.*, 2006; Subiaul *et al.*, 2012, 2015, in press). Subiaul's (2010a,b) Multiple Imitation Mechanisms (MIM) hypothesis is a framework that proposes that the cognitive architecture of imitation does not consist of a single domain-general (e.g., associative) or domain-specific (e.g., goal, rational inference) mechanism. Rather, MIM proposes that a variety of mechanisms (including, but not limited to, associative, goal, and rational inference) underlie different forms of imitation depending on the task or domain. However, this original framework did not, specifically, address the cognitive architecture of emulation. Extending the reasoning of MIM to emulation, we hypothesize here that like imitation, there are multiple emulation mechanisms (MEM), and predict that the cognitive architecture of emulation, like that of imitation (i.e., Subiaul *et al.*, 2015), consists of domain-specific mechanisms that are independent of other social and asocial learning processes.

Here, we use the same data set and procedures used by Subiaul *et al.* (2015) to study the cognitive structure of imitation to now study the cognitive structure of goal emulation (c.f., Table 1). We define cognitive structure as the association, organization, or grouping of different learning or cognitive processes. Here, we focus on how different learning processes differentially predict the development of goal emulation. Subiaul *et al.* (2015)

showed that cognitive and motor-spatial imitation development was predicted by few to no other types of learning (see Figure 2). In this study, we examined whether there are developmental changes in goal emulation across the preschool years and whether other forms of learning predict these changes. We tested preschoolers as there are significant developmental changes in social learning during this time (e.g., Dickerson *et al.*, 2013; Subiaul *et al.*, 2015). To test goal emulation, children observed an incomplete and incorrect response and had to infer from the model's errors the correct (unobserved) responses necessary to achieve a goal.

Predictions

Although previous work demonstrated that imitation development was not associated with asocial (individual) learning (Subiaul *et al.*, 2015), the development of goal emulation might, nonetheless, be broadly associated with both social and asocial learning. Such a result would be consistent with associative accounts (Heyes, 2012b; Paulus, 2014). Alternatively, if emulation is goal- or context-mediated, then there should only be associations between cognitive and motor-spatial emulation as well as between emulation and cognitive and motor-spatial imitation (Bekkering *et al.*, 2000; Gergely *et al.*, 2002; Wohlschlager, Gattis, & Bekkering, 2003). Finally, according to the MEM framework, an extension of the MIM framework (Subiaul, 2010b) cognitive and motor-spatial emulation should be independent of one another as well as other social (imitation) and asocial (recall) learning processes.

Methods

Participants

A total of 215 children ranging in age from 26 to 59 months (M = 42.13 months, SD = 7.73, females = 105, males = 110) of racially and ethnically diverse backgrounds completed training and testing in a museum using IRB-approved protocols from The George Washington University and the Smithsonian Institution.

Materials and apparatus

A 54.61-cm Apple Macintosh computer with a detachable Keytech® MagicTouch (Keytec, Garland, TX, USA) touch screen was used to assess social and asocial learning. During the delay between Trial-and-error and recall test, children were provided with an assortment of stickers that varied in size, shape, and colour and were encouraged to place them on a 12.7 cm × 17.78 cm inches white printing paper. This was done to both distract and maintain children's motivation.

Design

There were two tasks: Cognitive and Motor-Spatial. Because the sequences and images presented differed from trial to trial, researchers were able to assess different forms of learning (imitation, emulation, and recall) within subjects, without carryover effects (e.g., Subiaul *et al.*, 2012, 2015, in press). There were four learning conditions: Baseline (Trial-and-Error), Recall, Emulation, and Imitation. However, Baseline and Recall conditions are yoked as Recall tests an individual's ability to recall a sequence learned

Table 2. Sample session for a child participating in the study. The order of conditions presented here represents an example of possible order, which were counterbalanced so that in the final data set, all orders of conditions were equally represented

Block	Training	Experimental conditions		
Block 1: Cognitive Task	Training	Imitation	Baseline/Recall	Emulation
Block 2: Motor-Spatial Task	Training	Baseline/Recall	Emulation	Imitation

during Baseline, making the final design 2 (Tasks: Cognitive, Motor-Spatial) × 3 (Conditions: Recall, Emulation, Imitation). To avoid confusion or interference, tasks were blocked with half of the children being tested first on the Motor-Spatial Task. For each task, all children completed training followed by the four learning conditions. To avoid carryover effects, conditions were presented to children using six unique sequences (three for each task, one sequence was used for Trial-and-Error and Recall). Each of the six sequences consisted of three unique pictures (3.18 cm × 3.18 cm). These pictures varied randomly in content and consisted of different animals, faces, artefacts, and landscapes. The order in which the children were tested on each condition was counterbalanced such that all possible orders were given an equal number of times, with one exception: The Trial-and-Error condition always preceded the Recall condition as participants needed to learn the object- (Cognitive Task) or spatial-based rule (Motor-Spatial Task) before individually recalling that specific rule. Such counterbalancing ensured that our results were not affected by the order in which children experienced the different conditions as all possible orders are equally represented in the final data set.[2] Table 2 shows an example session for a child in the study.

Procedures

Training and testing occurred during a single session lasting 10–15 min per child.

Experimental tasks

Children were presented with two tasks using the same computer (c.f., Figure 1). In the Cognitive Task, children were required to press three different pictures in the correct order regardless of the spatial location.[3] The identity of the pictures differed, and their spatial arrangement varied randomly from trial to trial (Figure 1a). This assessed children's ability to learn an object-based rule. In the Motor-Spatial Task, children were required to press three identical pictures in a target spatial configuration. From trial to trial, the identity of the pictures changed (i.e., three identical pictures, different from the three in the previous trial), but their position remained the same (Figure 1b).[4] This assessed children's ability to learn a spatial-based rule.

[2] *To confirm that order effects were not in play, we ran multiple permutation tests (Hothorn, Hornik, van de Wiel, & Zeileis, 2006, 2008; R Core Team, 2015) examining the effect of order on task performance and found no significant effect of order (10,000 permutations, all* p*-values > .05).*

[3] *For video of Cognitive Task, see: https://www.youtube.com/watch?v=XzwOMF8W5Wc.*

[4] *For video of Motor-Spatial Task, see: https://www.youtube.com/watch?v=W8pjTME_ugY.*

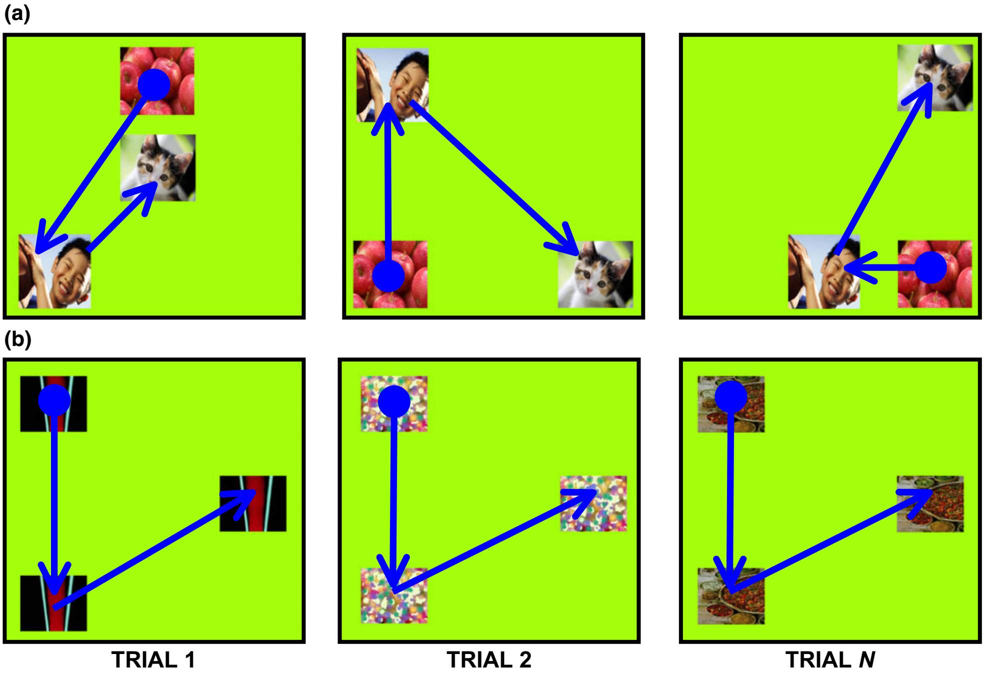

Figure 1. Experimental tasks. (a) Cognitive Task: Three *different* pictures appear on a touch screen. From trial to trial, these same three pictures re-appear in a *different* spatial configuration (apple, boy, cat). (b) Motor-Spatial Task: Three *identical* pictures appear on a touch screen. From trial to trial, a different set of identical pictures appears in the *same* spatial configuration (top, bottom, right). In both tasks, children have to touch each picture in a specific sequence.

Training and testing

Following the protocol developed by Subiaul *et al.* (2012, 2015, in press), children were trained on each task (Cognitive, Motor-Spatial) prior to the introduction of the experimental conditions (Table 2). 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 experimental setup. During training, children were exposed to each task and were 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. Incorrect responses, which terminated a trial, 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!' This procedure made the goal of the task clear and consistent across experimental conditions. Regardless of whether the condition was social or asocial, the goal was familiar and always the same, find 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.

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

Trial-and-error: Children were encouraged to discover the correct sequence entirely by trial-and-error learning. The model and computer provided feedback following each response. Following an error, all items disappeared, the screen turned black, and the model provided the child with verbal (e.g., 'Whoops! That's not right!') and non-verbal feedback (smiles or frowns and eye contact) following correct and incorrect responses. Upon touching all pictures correctly, the video of Jumping Man played, the computer was turned away from the child for 30 s, and the child's attention was diverted to stickers. Performance on Trial-and-Error was used to establish the spontaneous rate of sequence learning and to compare to Recall, Emulation, and Imitation conditions.
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 a previously, individually learned rule.[5]

There were two social learning conditions: Imitation and Emulation:

Imitation: The experimenter faced the child and said, 'Watch me!' and then proceeded to touch pictures in the target 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'.
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 frown said, 'Whoops, that's not right. Let me try again. Watch me'. This same error was repeated three times to make it clear that the model had failed to fulfil 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 *et al.* (1998).

Children were given a total of 20 trials to discover the target rule in each condition. Testing in each condition ended before 20 trials if either a child completed the task (97% of all cases) or when a child was no longer willing to participate (3% of all cases). Because both tasks used the same conditions, we refer to each by identifying the task first (Cognitive or Motor-Spatial) followed by the condition (Baseline, Recall, Emulation, or Imitation); for example, Cognitive Imitation and Motor-Spatial Recall.

Measure of learning

The computer program recorded all responses including specific items touched, number of responses, and errors for each trial. From these data, a learning ratio was calculated as

[5] *While some might take issue with us calling the Recall condition a learning condition given that 'learning' (i.e., serial order) occurred during Baseline, we argue that recall represents a different type of learning, namely the ability to represent and execute individually acquired information following a brief delay. As such, Recall is a measure of operant learning and short-term memory.*

the total number of correct responses (i.e., pictures touched in the target order) to the total number of trials in a condition. This measure captured both improvement across trials and the number of trials needed to complete the task.[6]

Results

How does emulation differ from other learning conditions?

A summary of children's performance across tasks and conditions is presented in Table 3. Previous permutation tests using this same data set revealed that performance in all conditions improved with age (Subiaul *et al.*, 2015; Figure 2), but also that recall, imitation, and emulation performance were greater than trial-and-error on both tasks (Table 4, Subiaul *et al.*, 2015), establishing that learning in the three conditions exceeded Baseline performance (i.e., spontaneous production). Additionally, emulation performance in the Motor-Spatial Task exceeded imitation performance, but in the Cognitive Task, emulation and imitation performance did not differ (c.f., Table 4, Subiaul *et al.*, 2015). Because trial-and-error was included as a necessary precursor to recall, and to establish that the three learning conditions exceeded Baseline performance, we did not consider trial-and-error performance in subsequent analyses.

What social and asocial learning processes are associated with emulation learning?

For initial inspection of the associations between age and the various task–condition combinations, we constructed a Spearman correlation matrix (Table 5).

Subsequently, two generalized linear models (GLMs) were constructed, one for cognitive emulation and another for motor-spatial emulation. GLMs are an extension of traditional linear models that can handle non-normally distributed data through the use of

Table 3. Descriptive statistics for different conditions. (a) Cognitive Task, (b) Motor-Spatial Task

	N	Mean	*SE*
(a) Cognitive Task			
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
(b) Motor-Spatial Task			
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

Note. N = sample size; Mean = average learning ratio (total correct responses/first correct trial); *SE* = standard error of the mean.

[6] *For example, imagine a child makes the following responses across three trials, Trial 1: C (0 correct responses), Trial 2: A→C (one correct response), and Trial 3: A→B→C (three correct responses, condition complete), the learning ratio would be 4/3 (or four correct responses divided by three 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, as pictures did not disappear after a correct response, it was possible for children to make the following response: A→B→A (two correct responses). The maximum ratio was 3 (3/1) and the minimum was 0 (failing to touch any picture in the target order).*

Table 4. Contrasts Between conditions. (a) Cognitive Task, (b) Motor-Spatial Task. *Z* and *p* values based on permutation tests (Hothorn *et al.*, 2006, 2008; R Core Team, 2015)

	Z	Bonferroni-Corrected *p*
(a) Cognitive Task		
Emulation > Trial-and-Error	7.028	<.01
Imitation > Trial-and-Error	5.342	<.01
Recall > Trial-and-Error	7.728	<.01
Emulation = Imitation	1.47	>.8
Recall = Emulation	1.403	>.8
Recall = Imitation	2.741	>.8
(b) Motor-Spatial Task		
Emulation > Trial-and-Error	9.88	<.01
Imitation > Trial-and-Error	6.011	<.01
Recall > Trial-and-Error	8.777	<.01
Emulation > Imitation	5.586	<.01
Emulation = Recall	2.758	>.8
Recall = Imitation	2.914	>.8

Table 5. Spearman's correlation matrix. Includes age and all task–condition combinations

	Age (months)	Motor-Spatial Baseline	Motor-Spatial Recall	Motor-Spatial Imitation	Motor-Spatial Emulation	Cognitive Baseline	Cognitive Recall	Cognitive Imitation
Motor-Spatial Baseline	.32**	–						
Motor-Spatial Recall	.29**	.19	–					
Motor-Spatial Imitation	.30**	–.01	.13	–				
Motor-Spatial Emulation	.52**	.30**	.27**	.33**	–			
Cognitive Baseline	.18	–.08	.18	.21	.09	–		
Cognitive Recall	.24*	.09	.20	.13	.27**	.07	–	
Cognitive Imitation	.37**	.13	.16	.18	.28**	.03	.20	–
Cognitive Emulation	.36**	.13	.22*	.13	.37**	.17	.19	.32**

Note. Bonferroni-corrected $*p < .05$, $**p < .01$.

a link function (Venables & Ripley, 2002). For our data, a binomial error distribution and the logit link function were used since the dependent variable was the binomial learning ratio (no. correct responses, no. trials). Because our data were under-dispersed, as indicated by the ratio of the residual deviance to the residual degrees of freedom (cognitive emulation = 0.62; motor-spatial emulation = 0.62), 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).

Model 1 tested whether age and other learning conditions predicted cognitive emulation. In the final model (QAICc = 513.3), age, motor-spatial emulation, motor-spatial imitation, and cognitive imitation were significant predictors of cognitive emulation (Table 6a). Model 2 tested whether age and other learning conditions predicted motor-spatial emulation. In the final model (QAICc = 494.9), age, motor-spatial imitation, and cognitive recall were significant predictors of motor-spatial emulation (Table 6b).

Discussion

In contrast to imitation, goal emulation has been relatively under-studied and its underlying cognitive features poorly characterized. We previously showed age-related changes in goal emulation across the preschool years (Subiaul *et al.*, 2015). Here, we show that during these years, goal emulation is predicted by social and asocial learning depending on the task. The present findings are in contrast to imitation, whose development was predicted by very few other types of learning (Subiaul *et al.*, 2015). In this respect, the cognitive and neural processes mediating goal emulation appear to be less specialized and more domain-general (i.e., applicable across task domains) than those mediating imitation. Perhaps, goal emulation engages many different cognitive processes because intention mirroring (emulation) requires more cognitive processing than action mirroring (imitation). Below, we explore these possibilities further.

Although comparative and developmental psychologists have distinguished between action mirroring (imitation) and goal or intention mirroring (emulation) (Carpenter & Call, 2002; Heyes, 2011; Hopper, 2010; Huang *et al.*, 2002; Want & Harris, 2002; Whiten & Ham, 1992; Whiten *et al.*, 2009), no study has explicitly tested whether different types of intention mirroring (or emulation) are dissociable within subjects as proposed by the

Table 6. Generalized linear models for emulation. (a) Cognitive and (b) Motor-Spatial Task

	Unstandardized coefficients		Standardized coefficients		
	B	Std. Error	β	*t*	Sig.
(a) Cognitive Emulation					
Age (months)	0.017	0.008	.092	2.136	.034
Motor-Spatial Emulation	1.141	0.059	.098	2.404	.017
Motor-Spatial Imitation	−0.113	0.057	−1.074	−1.994	.048
Cognitive Imitation	0.119	0.049	.090	2.435	.016
(b) Motor-Spatial Emulation					
Age (months)	0.045	0.006	.213	6.988	<.001
Motor-Spatial Imitation	0.161	0.051	.110	3.134	.002
Cognitive Recall	0.136	0.050	.080	2.735	.007

MEM framework or whether they are associated with one another, consistent with hypotheses proposing that all social learning processes are mediated by a single associative learning mechanism (Heyes, 2012a,b; Paulus, 2014) or goal/rational reasoning processes (Kiraly *et al.*, 2013; Wohlschlager *et al.*, 2003). The results of the present study do not support the predictions of the MEM framework, which hypothesized that there would be MEMs. Instead, results suggest that, in contrast to imitation (Subiaul *et al.*, 2015), emulation appears to be supported by a more unitary, domain-general mechanism that receives input from multiple cognitive processes, both social and asocial (c.f., Figure 2). This conclusion is based on the fact that both cognitive and motor-spatial emulation were associated with one another, and while their cognitive structures were not identical, both were associated with other social, asocial, or both learning processes (c.f., Table 4). However, exactly which mechanism(s) underlie emulation is still unclear. Consistent with the GOADI theory (Wohlschlager *et al.*, 2003), cognitive emulation was predicted by motor-spatial emulation as well as by cognitive imitation. In addition, motor-spatial imitation predicted motor-spatial emulation. However, inconsistent with GOADI, motor-spatial imitation was negatively predictive of cognitive emulation, and cognitive imitation did not predict motor-spatial emulation, highlighting the importance of task specificity when thinking about the cognitive structure of social learning and the cognitive processes that underlie them. Furthermore, cognitive recall also predicted motor-spatial emulation, which perhaps suggests that domain-general learning processes play a significant role in emulation learning, consistent with associative models (Heyes, 2012b; Paulus, 2014).

Nonetheless, we cannot overlook the fact that while a more unitary mechanism appears to mediate emulation, this does not seem to be the case for imitation (c.f., Figure 2). As such, we can reject the hypothesis that a single, unitary mechanism explains *all* forms of social learning, emulation and imitation alike. Rather, results from this and other studies (Subiaul *et al.*, 2015, in press) suggest that the cognitive architecture of social learning includes a domain-general (and more unitary) social learning mechanism supporting emulation across tasks as well as various domain-specific mechanisms supporting different forms of imitation on different tasks. This result is striking given that they were generated from the same data set (Figure 2). Thus, the development of imitation and emulation appears to rely on different underlying processes, that is on multiple underlying cognitive and neural mechanisms (Figure 2).

Our overall conclusion that emulation and imitation rely on different cognitive processes is consistent with a number of studies (Horner & Whiten, 2007; Subiaul *et al.*, 2012, 2015; Want & Harris, 2001) showing that children generally excel in emulation before they succeed in imitation. However, the specific cognitive processes underlying either emulation or imitation appear to be somewhat specific to the task at hand. For example, Subiaul *et al.* (2015) showed that Motor-Spatial Imitation was associated with Motor-Spatial Emulation, but the same was not true for Cognitive Imitation, which was not associated with either social (Emulation) or asocial (Recall) learning processes. Likewise, here we found that Motor-Spatial Emulation was associated with both social (Motor-Spatial Imitation) and asocial learning (Cognitive Recall), while Cognitive Emulation was associated with only social learning (Motor-Spatial Emulation, Cognitive and Motor-Spatial Imitation). Together, these results suggest that while the development of goal emulation is associated with the development of a variety of social and asocial learning processes depending on the task, the development of imitation is likely more task and domain specific and, generally, not associated with concomitant developmental changes in other social or asocial learning processes.

This overall pattern of results is most consistent with a framework that predicts a mosaic organization of social learning, henceforth, the Mosaic Social Learning (MSL) Hypothesis. This framework proposes that the cognitive structure of social learning is mosaic, including multiple specialized, domain-specific mechanisms that support imitation learning across different tasks and domains as well as a unitary and domain-general mechanism that supports emulation learning. Thus, the main prediction of the MSL hypothesis is that no single mechanism can fully capture social learning across tasks and domains and instead, different mechanisms apply to different forms of social learning.

Some might interpret the domain generality of emulation as *prima facie* evidence that all mirroring processes including imitation and emulation share the same underlying 'general' cognitive and neural mechanisms be it associative learning (Heyes, 2012b; Paulus, 2014; Ray & Heyes, 2011) or general (executive) cognitive functions (Heyes, 2012a,b). Yet these models are challenged by the fact that the Cognitive and Motor-Spatial Tasks are uniquely matched on 'general' cognitive processes, including visual attention, inhibition, serial knowledge, and working memory (Subiaul *et al.*, 2012). Furthermore, conditions were matched in the type of feedback (social and asocial) children received, the model used across conditions was the same, and the responses used to achieve the goal (to find Jumping Man) were familiar to the child and did not vary throughout the study.

Given that both tasks share so many of the same parameters, if there was a common system underlying all mirroring behaviours, be it goals (Bekkering *et al.*, 2000; Wohlschlager *et al.*, 2003), associative learning, or general executive and perceptual processes (Heyes, 2004, 2012b; Paulus, 2014), one would expect similar structures (with varying strength in the associations) between different types of learning rather than completely different patterns of associations reported here and elsewhere (Subiaul *et al.*, 2012, 2015). As summarized in Figure 2, analyses of the present data set produced models for imitation and emulation indicating different cognitive structures, consistent with the MSL framework.

While we have interpreted the different models for emulation and imitation (c.f., Figure 2) to mean that the cognitive processes underlying emulation rely on imitation but the processes mediating imitation performance do not rely on emulation during development, the nature of this unidirectional association is currently unknown and merits further study. Previous research suggests that imitation is more domain specific and specialized for learning by imitation within specific domains (Subiaul *et al.*, 2015, in press). In contrast, the unidirectional association found here suggests that emulation learning is more domain general and, perhaps, less specialized for social learning *per se*. This pattern of results is consistent with the hypothesis that goal emulation is mediated by cognitive and neural mechanisms that are likely to receive input from other mechanisms supporting behaviours that are domain specific (e.g., imitation) and others that are domain general (e.g., recall).

An important limitation of this study is that it tested only one type of intention mirroring (goal emulation) and only one possible type of goal emulation, *sensu* behavioural re-enactment (Meltzoff, 1995). Future studies should explore the relationship between different types of emulation (c.f., Table 1). One might hypothesize that certain forms of emulation such as end-state and affordance learning might be closely associated with one another, but differ from other types of emulation such as goal emulation. This type of patterning might suggest that the former is mediated by causal reasoning, and the latter, by mental-state reasoning. Alternatively, because all forms of emulation involve idiosyncratic responses and inhibiting the execution of observed responses, one might

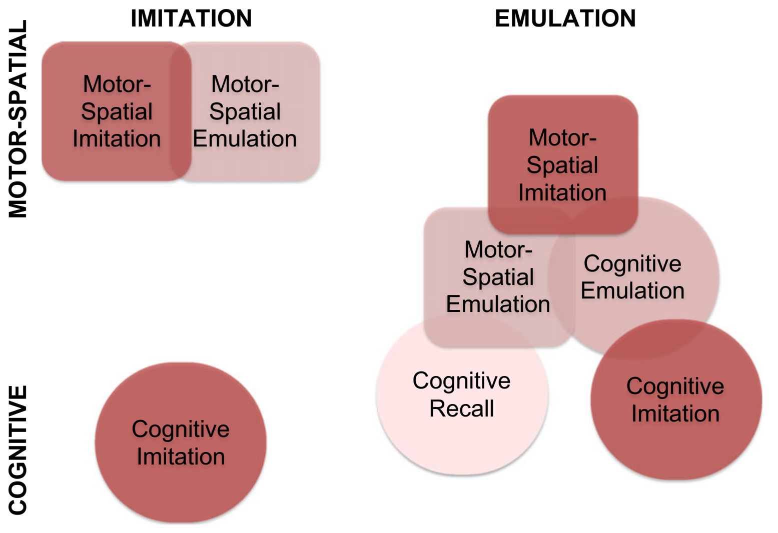

Figure 2. Cognitive structure of mirroring (social learning) mechanisms. The figure depicts a summary of the cognitive structure of mirroring mechanisms as indicated by the results from Subiaul *et al.* (2015) on the left, and the present study (c.f., Table 6) on the right. Shapes correspond with tasks (circles = Cognitive, squares = Motor-Spatial). Colours correspond with learning conditions (red = Imitation, dark pink = Emulation, light pink = Recall). Overlapping shapes show significant associations. Age was significantly associated with all learning conditions (not shown).

expect that all covary with executive and causal reasoning processes (Buchsbaum, Seiver, Bridgers, & Gopnik, 2012; Gopnik, 2012). As a result, all forms of emulation might be strongly associated with one another.

The present study represents a first step in understanding the developmental relationship between social and asocial learning during the preschool years. From a practical standpoint, these findings are relevant to early educators who may be able to exploit emulation learning as a way to dramatically and rapidly increase information acquisition at the point of school entry. The use of emulation as an alternative learning tool is particularly relevant given that certain forms of emulation develop before imitation (e.g., motor-spatial).

In short, there is nothing simple about imitation and emulation, and so we should be sceptical of any framework that suggests a single system mediates all mirroring processes regardless of task or domain. The parsimony of such hypotheses is appealing, but it cannot account for the growing number of studies across the neuropsychological (Goldenberg, 2006; Goldenberg & Karnath, 2006; Rumiati *et al.*, 2005), developmental (Cutting, Apperly, & Beck, 2011; Subiaul *et al.*, 2012; Vanvuchelen, Roeyers, De Weerdt, 2011; Want & Harris, 2001), and comparative (Hopper, 2010; Myowa-Yamakoshi & Matsuzawa, 1999; Renner & Subiaul, 2015) sciences showing dissociations between tasks, age groups, and types of social and asocial learning. While comparative psychologists have long distinguished between different types of social learning (Thorndike, 1898, 1911), in the past thirty years researchers have not only proposed that imitation and emulation represent different types of social learning, but that there are also different types of emulation (Whiten & Ham, 1992; Whiten *et al.*, 2009) and imitation (Subiaul, 2010a). Here, we advance a novel framework, the MSL hypothesis, which proposes that mirroring includes both domain-general mechanisms mediated by general processes, such as emulation and domain-specific mechanisms whose development and functioning is largely independent of domain-general systems, such as imitation. Defining the contours of the different social learning mechanisms that form this mosaic psychological faculty will not be easy. However, rejecting the notion of a single mirroring system, while recognizing that there are unique challenges associated with imitating and emulating across domains and tasks, is a necessary first step.

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