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Only domain-specific imitation practice makes imitation perfect

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ABSTRACT

Does imitation involve specialized mechanisms or general—unspecialized—learning processes? To address this question, preschoolers (3- and 4-year-olds) were assigned to one of four "practice" groups. Before and after the practice phases, each group was tested on a novel Spatial Imitation sequence. During the practice phase, children in the Spatial Imitation group practiced jointly attending, vicariously encoding, and copying the novel spatial sequences. In the Item Imitation group, children practiced jointly attending, vicariously encoding, and copying novel item sequences. In the Trial-and-Error group, children practiced encoding and recalling a series of novel spatial sequences entirely through individual (operant) learning. In the Free Play (no practice) control group, children played a touchscreen drawing game that controlled for practice time on the touchscreen and mirrored some of the same actions and responses used in the experimental conditions. Results of the difference between pre- and post-practice effects on novel spatial imitation sequences showed that only the Spatial Imitation practice group significantly improved relative to the Free Play group. Individual Spatial Trial-and-Error practice did not significantly improve spatial imitation. The effect of Item Imitation practice was intermediate. These results are inconsistent with the hypothesis that general processes alone--or primarily--support imitation learning and is more consistent with a mosaic model that posits

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an additive—interaction—effect on imitation performance where a more general social cognitive mechanism (i.e., natural pedagogy) gathers the relevant information from the demonstration and another more specialized mechanism (i.e., imitation specific) transforms that information into a matching response.

Introduction

All specialized cognitive skills (e.g., face processing) involve general, nonspecialized (e.g., visual attention) cognitive processes (Fodor, 2000; Kanwisher, 2010; Posner, Petersen, Fox, & Raichle, 1988). General learning mechanisms have long been associated with the development of complex, human-specific cognitive skills such as language and literacy development (Elman, 1996; Lee Swanson, Orosco, & Lussier, 2015; Lonigan, Lerner, Goodrich, Farrington, & Allan, 2016). An ongoing debate in the cognitive sciences is whether social cognition represents a special kind of cognition that is mediated by specialized mechanisms dedicated to processing information vicariously learned from conspecifics or whether nonsocial—general—cognitive processes mediate social and asocial cognition alike (Happe, Cook, & Bird, 2017; Heyes & Pearce, 2015; Heyes, 2012a).

Imitation, the ability to faithfully replicate demonstrated responses, is a foundational learning and social-cognitive construct whose underlying component cognitive features remain opaque. Researchers examining the development of imitation have addressed the problem in different ways. Some have focused on the role of more domain-general memory (Barr & Hayne, 2000) or learning processes (e.g., Heyes, 2016a). Others have focused on domain- and task-specific social learning processes (e.g., Subiaul, 2010; Subiaul, Patterson, & Barr, 2016; Zentall, 2012), the role of communicative/pedagogical cues (e.g., Csibra & Gergely, 2009), social learning strategies and information use (Morgan, Laland, & Harris, 2015; Rendell et al., 2011; Wood et al., 2016), and mental-state reasoning (e.g., Carpenter, Call, & Tomasello, 2002; Tomasello & Carpenter, 2007) or end-state reasoning (e.g., Bekkering, Wohlschlager, & Gattis, 2000). But rarely have imitation researchers considered the interaction of these different processes and how they shape imitation development (Barr, 2002; Heyes, 2016b; Subiaul, Patterson, Schilder, Renner, & Barr, 2015; Uzgiris, 1981).

Part of the problem may be historical. Imitation has been studied for more than a century; each successive generation has conceptualized and operationalized imitation differently (Galef, 1988; Subiaul, 2010; Zentall, 1996). Consequently, there is neither a "consensus" definition of imitation nor a consensus "method" or tool to measure it. In the developmental sciences, we have learned much about *what* children imitate and remember as well as *when* in development such skills emerge (Barr & Hayne, 2000; Barr, Dowden, & Hayne, 1996; Meltzoff, 1988; Over & Carpenter, 2012; Vanvuchelen, Roeyers, & De Weerdt, 2011a, 2011b; Young et al., 2011). But it is an under-appreciated fact among developmental scientists that we know relatively little about *how* children imitate. Specifically, the component cognitive processes underlying imitation performance across task domains and how such cognitive processes change during the course of development[1] are largely unknown. We know even less about the source(s) of individual differences in imitation performance and, consequently, why imitation performance varies—sometimes significantly—on what are otherwise superficially similar tasks.

Most of what we know about individual differences and the component cognitive processes supporting imitation performance comes from research on autism spectrum disorder (ASD). Individuals diagnosed with ASD are characterized by pervasive communication and social learning deficits (American Psychiatric Association, 2013). Researchers studying ASD have linked imitation deficits to a variety of skills and component cognitive processes, including forming multimodal representations,

[1] For an exception, see the work by Heyes and colleagues (Bird, Brindley, Leighton, & Heyes, 2007; Bird & Heyes, 2005; Bird, Osman, Saggerson, & Heyes, 2005; Catmur & Heyes, 2013; Cooper, Cook, Dickinson, & Heyes, 2013).

motor-planning, or praxis (Smith & Bryson, 1998), self–other correspondences, identification and empathy (Hobson & Lee, 1999; Rogers & Pennington, 1991), executive functions such as inhibitory control and shifting (Williams, Whiten, & Singh, 2004), and pretend play and joint attention (Carpenter, Pennington, & Rogers, 2002; Charman et al., 1997). Other studies have pointed to specific task and information domains that pose particular challenges for individuals with ASD (Subiaul et al., 2007; Williams et al., 2004). For instance, some researchers have pointed to specific deficits and/or delays in object imitation (Hobson & Hobson, 2008), gestural/body imitation (Stone, Ousley, & Littleford, 1997), and serial action imitation (Dawson & Adams, 1984).

Together, these studies suggest that imitation includes domain-general component cognitive processes (e.g., executive functions: inhibition, shifting, working memory) in addition to specialized component cognitive processes such as social attention processes (e.g., joint and shared attention) that apply to many different social skills. However, it is still unknown whether there are any specialized cognitive "copying mechanisms" per se. It is possible that imitation is an emergent skill that arises from domain-general associative learning and memory processes combined with social attention/orientation processes. In that case, imitation might not require any additional specialized cognitive processes and should covary with asocial learning (Heyes, 2012a, 2012b). Alternatively, imitation learning may be like other specialized social cognitive skills that rely on both general and specialized cognitive processes. In that case, imitation would be mediated by both domain-general and specialized process (es) for generating mirror representations of vicariously learned, rather than individually acquired, responses. According to one hypothesis there are multiple imitation mechanisms, each dedicated to copying (or forming matching representations of) observed responses in particular cognitive domains (Subiaul, 2010; Subiaul, Anderson, Brandt, & Elkins, 2012; Subiaul, Patterson, et al., 2016). This hypothesis makes two assumptions. First, it assumes that the imitation of sounds, gestures, or object-based actions (e.g., tool use) poses unique correspondence problems (Nehaniv & Dautenhahn, 2002) involving distinct self–other representations among other content-specific representational challenges. Second, it assumes that imitation learning in a given task domain requires processes over and above those used for individual learning within that same task domain; that is, there are dedicated cognitive mechanisms *for* imitation learning.

In an effort to examine these predictions, Subiaul, Patterson, et al., 2016 tested preschool-age children on two social conditions (imitation and emulation) and two asocial conditions (trial-and-error and recall) using two different touchscreen tasks. The social conditions—imitation and emulation—involved three demonstrations prior to testing. In the imitation condition, children observed the model execute the target sequence (A → B → C) prior to responding to the same sequence. In the emulation condition, before children were allowed to respond, they observed the model generate a correct response followed by an incorrect response (A → [skip B] → C),[2] marking the error as unintentional by saying, "Whoops! That's not right." What makes imitation and emulation social learning conditions is that the target sequence can be gleaned from the model's actions. The main difference is that in the imitation condition children can faithfully replicate the model's responses, whereas in the emulation condition they cannot. Instead, children in the emulation condition must inhibit imitation and infer the target sequence from the model's correct (A) and incorrect (A → C) responses.

In the asocial learning conditions (recall and trial-and-error), there was no demonstration prior to testing, and learning was entirely mediated by individual learning. The procedures used in the recall condition mirrored those used in the social conditions except that children copied their *own* responses rather than a model's responses. Tasks and procedures were matched so that they were nearly identical and varied only in the types of input children received. In each task, children responded to either three *identical* pictures in a specific *spatial* sequence (Spatial Task: top → bottom → right; cf. Fig. 1A) or three *different* pictures in a specific *item* sequence (Item Task: apple → boy → cat; cf. Fig. 1B). The goal for children in all conditions was the same—to respond to all items on the screen in the correct order to find "Jumping Man," a 5-s video clip that is very appealing and motivating to young children.

[2] This procedure parallels the "reenactment" paradigm developed by Meltzoff (1995)—a measure of goal emulation (Subiaul et al., 2016).

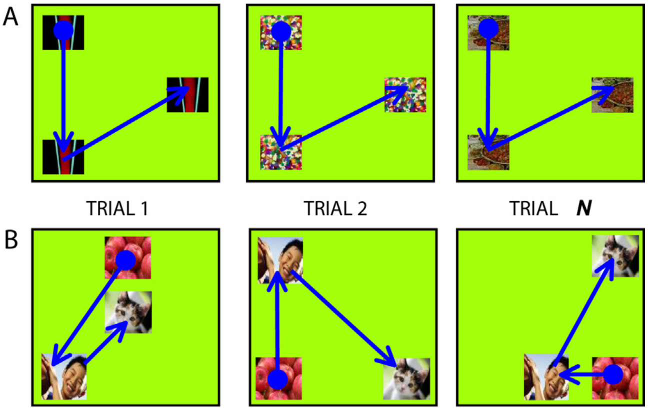

Fig. 1. Computer-based tasks. (A) Spatial Task. Identical items appeared simultaneously in different spatial positions on a touch-sensitive screen. Item position remained fixed from trial to trial, but items' identity changed as shown. The objective was to respond to each item (irrespective of *identity*) in a specific spatial sequence (top, bottom, right). (B) Item Task. Different items appeared simultaneously in different spatial positions on a touch-sensitive screen. Item position changed from trial to trial, but the sequence in which they must be touched (ordinal position) remained constant as shown. The objective was to touch each item (irrespective of location) in a specific item sequence (apple, boy, cat) as shown.

If social learning and asocial (individual) learning covary as Heyes (2012b) suggested, there should be significant associations between tasks and conditions. That is, because social learning and asocial learning within tasks involved encoding and recalling the *same* content type (e.g., spatial), they should engage the *same* cognitive processes. Alternatively, if social learning requires proprietary systems above and beyond those used for individual learning, dissociations are expected. Using generalized linear models, Subiaul, Patterson, et al. (2016) demonstrated that both spatial imitation fidelity and item imitation fidelity were significantly associated with age. However, there were no significant associations between spatial imitation and item imitation. Moreover, neither form of imitation (item or spatial) was significantly associated with individual learning despite the fact that the content was identical in the imitation and individual learning conditions.[3] Success in encoding and recalling spatial- or item-based sequences learned by trial-and-error learning did not predict children's ability to imitate the same types of sequences. There was a unique association, however, between spatial imitation and spatial emulation (Subiaul, Patterson, et al., 2016; but see Subiaul et al., 2012). The association between emulation and imitation suggests that goal emulation—reasoning about others' action goals—might bootstrap the development of certain forms of imitation, as some have suggested (Meltzoff, 2007).

The current study built on this work and explored how component social and asocial learning processes affect imitation performance using a "practice" paradigm. One domain-general mechanism for imitation learning is likely to be working memory (WM) (Rumiati & Tessari, 2002), the ability to temporarily store and manipulate information online (Baddeley, 1986, 1996, 1998, 2012). Various studies have shown that WM constrains novel imitation in both children (Bauer & Mandler, 1992; Bauer, 1992; Harnick, 1978; Subiaul et al., 2015) and adults (Rumiati & Tessari, 2002; Rumiati et al., 2005). One possible hypothesis is that spatial information is cached in spatial WM. Looping this information in WM through repeated observation–execution experiences is expected to activate multisen-

[3] In the social learning literature, imitation learning is often contrasted with another type of vicarious learning, emulation learning (*sensu* affordance learning or object movement reenactment), using a "ghost" control (Hopper, 2010). Ghost controls present observers with the same cues observed in the social demonstration (i.e., with a live agent) except that cues are generated automatically, as if produced by an invisible agent or ghost. But herein lies the problem; previous work (Biro & Leslie, 2007; Subiaul, Vonk, & Rutherford, 2011) has shown that such ghost conditions activate social percepts of animacy and agency and affect learning in ways similar to those in conditions with live agents. In this particular paradigm, priming social percepts in ghost conditions (e.g., "This computer is alive") positively correlates with imitation learning, whereas priming non-agentive features (e.g., "This computer is a machine") does not (Subiaul et al., 2011). In sum, whereas ghost conditions are a good control for the copying of specific motor actions that are not visible, it is a poor control for goals and intent.

sory (associative) learning processes, resulting in an imitative response. We refer to this hypothesis as the *general learning hypothesis.*

Specialized social cognitive processes, such as joint attention (Cardon & Wilcox, 2011; Ingersoll & Schreibman, 2006), and other natural pedagogical cues, such as eye contact (Csibra & Gergely, 2009), have been hypothesized to be essential component processes of social learning, including imitation. Csibra and Gergely (2009) argued that social learning is mediated by a dedicated communication system that allows humans to transmit generic knowledge via ostensive cues that direct and focus attention on relevant information. This mechanism derives "generalizable" knowledge from observed experience (p. 151). We refer to this hypothesis as the *natural pedagogy hypothesis.*

Alternatively, imitation performance may be mediated by dedicated, domain-specific copying mechanisms. According to Subiaul (2010), imitation is domain specific and includes proprietary copying mechanisms. Each imitation mechanism identifies, manipulates, and produces domain-specific matching representations that result in mirror motor responses. Consistent with this view is research described above showing that superficially similar tasks involving the copying of two different types of sequences (Fig. 1: Item Task and Spatial Task) are dissociable from one another as well as from individual learning in the same task (Subiaul et al., 2012, 2015; Subiaul, Patterson, et al., 2016; Subiaul, Zimmermann, Renner, Schilder, & Barr, 2016). We refer to this hypothesis as the *multiple imitation mechanism (MIM) hypothesis.*

In summary, the general learning hypothesis assumes that social learning and asocial learning share common cognitive elements (e.g., WM, among other domain-general processes), so individual learning in a given task should improve imitation learning in that same task. In contrast, both the natural pedagogy and MIM hypotheses assume dissociations between social learning and asocial learning because they are mediated by distinct cognitive processes (e.g., joint attention, sociocommunicative inferences). So, imitation learning in one task should transfer to imitation learning in a different task. The MIM hypothesis goes further and assumes dissociations between different forms of social learning because different content types pose unique copying demands (e.g., copying communicative gestures poses different cognitive demands than copying tool use). So, imitation learning will transfer *only* to tasks that share the *same* content type.

Here, we aimed to test the core predictions of these three hypotheses in preschoolers using a spatial imitation task (Fig. 1A). We chose to study spatial imitation for three reasons. First, spatial imitation is a relatively late developing skill in preschoolers, arising *after* item imitation (Fig. 1B) and spatial trial-and-error learning and recall (Subiaul et al., 2012, 2015; Subiaul, Zimmermann, et al., 2016). Second, the Spatial Task is analogous to the Corsi Blocks Task and Knox Blocks Task, which have been widely used to assess WM in adults (Corsi, 1972; Kessels, van den Berg, Ruis, & Brands, 2008; Rossi-Arnaud, Pieroni, Spataro, & Baddeley, 2012) and children (Kemps, De Rammelaere, & Desmet, 2000). Third, imitation learning in the Spatial Task predicts performance on more ecologically valid tool-mediated imitation tasks (Subiaul, Zimmermann, et al., 2016).

The current study, therefore, used tasks that are highly standardized and similar to one another to examine the effects of practice type on spatial imitation learning. By holding general cognitive processes constant across practice groups, we can better evaluate how different types of input and content affect imitation learning. Table 1 summarizes the input-specific components (social: +/−) and content-specific components (spatial: +/−) in each practice group. Briefly, in the Spatial Imitation group, children practiced imitating new spatial sequences (Social +, Spatial +). In the Item Imitation practice group, children practiced imitating new sequences on the Item Task (Social +, Spatial −). In the Trial-and-Error group, children were trained to execute spatial sequences on their own

Table 1
Summary of input-specific (social: +/−) and content-specific (spatial: +/−) components in practice groups.

	Practice group			
	Spatial imitation	Item imitation	Spatial trial-and-error	Free play
Social input	+	+	−	−
Spatial content	+	−	+	−

(Social –, Spatial +). Finally, in the no practice control—Free Play—group, children played with a drawing application on a touchscreen (Social –, Spatial –). This active control group controlled for familiarity with the touchscreen, the experimenter, and the duration of the practice phase.

Predictions

We predicted that Spatial Imitation practice should have the most robust effect on spatial imitation in a post-test relative to a Free Play control because the elements in practice and post-test are identical (Thorndike & Woodworth, 1901; Oei & Patterson, 2014). However, Item Imitation and Spatial Trial-and-Error practice should also improve spatial imitation performance at post-test relative to a Free Play control. The reason for this is that each of those practice groups shared a feature with the Spatial Imitation practice group: social—pedagogical—cues (Item Imitation practice) or spatial content (Trial-and-Error practice). Alternatively, the contributions associated with practicing the processing of social input (Item Imitation) and those associated with practicing spatial content (Spatial Trial-and-Error) might not be equal. If imitation learning is mediated by asocial (individual) learning processes, we might expect that Spatial Trial-and-Error practice might be better than Item Imitation practice (e.g., Fig. 2A—general learning hypothesis) relative to a Free Play control. However, if imitation is mediated by domain-specific social learning processes as predicted by the natural pedagogy and MIM hypotheses, we should expect that, relative to a Free Play control, Item Imitation practice should produce more robust improvements in spatial imitation during post-testing than Spatial Trial-and-Error practice (e.g., Fig. 2A—natural pedagogy hypothesis), with Spatial Imitation practice being more robust than Item Imitation practice (e.g., Fig. 2A—MIM hypothesis). Given that social input and content are matched across practice groups, the effects of those two practice groups may be additive. That is, the benefits of Item Imitation and those of Spatial Trial-and-Error may equal the benefits of Spatial Imitation practice.

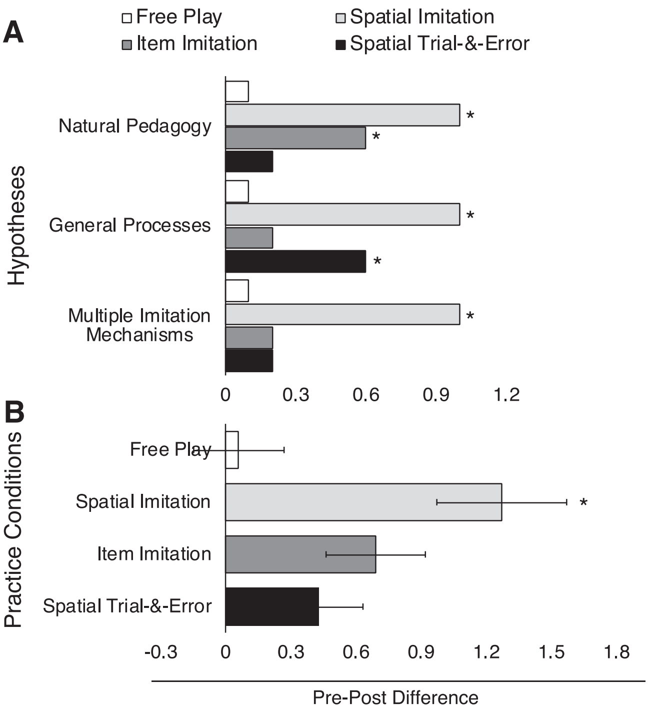

Fig. 2. (A) Hypotheses' predictions. (B) Results for difference between pre- and post-practice tests. *Significantly different from Free Play (no practice), $p < .05$. Error bars represent standard errors.

Method

Participants

This study consisted of 108 typically developing preschool-aged children (3- and 4-year-olds).[4] Children were recruited in the Discovery Room of the Smithsonian Institute's Natural History Museum. Independent groups of children were tested at age 3 ($n = 53$, $M_{age} = 3$ years 5.54 months, $SD = 3.51$ months; 25 girls) and age 4 ($n = 55$, $M_{age} = 4$ years, 6.04 months, $SD = 3.02$ months; 32 girls). Participants were primarily Caucasian (59.26%). Because we were interested in the effects of changes pre- to post-practice performance, additional children ($n = 21$) were excluded from the analysis for imitating the sequence at ceiling on the first trial of the pre-practice test. According to responses from caretakers, 71% of children were in child care, 35% were bilingual, and 96% had some exposure to touchscreens (e.g., tablets, iPads, iPhones).

Apparatus

Computer tasks

Two different computerized tasks were used in the current study: a Spatial Task (Fig. 2A) and an Item Task (Fig. 2B). In each, picture items were displayed simultaneously throughout each trial on a MagicTouch detachable touch-sensitive screen that was placed in front of an Apple iMac monitor. In the Spatial Task,[5] the identities of the items on the screen were identical, and their positions on the screen remained the same. However, from trial to trial, the identities of the pictures changed (cf. Fig. 2). For example, three identical pictures—A, A, A—appeared simultaneously on the touchscreen. Each picture needed to be touched in a specific spatial sequence: $A^{top} \rightarrow A^{bottom} \rightarrow A^{right}$. From trial to trial, a different set of identical pictures—B, B, B—appeared in the same spatial position and needed to be touched in the same spatial sequence as in the previous trial ($B^{top} \rightarrow B^{bottom} \rightarrow B^{right}$).

In the Item Task,[6] the identities of the items on the screen were different from one another, and their positions on the screen varied randomly from trial to trial (cf. Fig. 1B). For example, three *different* pictures comprising a sequence—for example, A, B, C—appeared simultaneously on the touchscreen. Each picture needed to be touched in a specific sequence: A → B → C. From trial to trial, the pictures appeared in different spatial positions.

Both computer tasks used a 4×4 template in which pictures could appear in any of 16 non-overlapping positions on the screen. Two novel sequences were used for the pre- and post-practice tests. Sequences used in the Spatial Task always involved a change in direction (e.g., up, down, right). Sequences in the Item Task always involved nameable items (e.g., panda, chair). None of the sequences was ever repeated between phases. The 5-s video of Jumping Man always played when the correct sequence was completed.

Procedure

All participants were tested in four phases: (a) *orientation,* where children were familiarized with the Spatial Task prior to the pre-practice test; (b) *pre-practice test,* where children received a demonstration on a novel spatial sequence and then were allowed to respond (pre-practice imitation performance); (c) *practice,* where each group participated in a different practice type (see Table 2); and (d) *post-practice test,* same procedures used in pre-practice test where every child was tested with a new spatial sequence. Each phase is described in detail below. Phases are summarized in Table 2.

[4] Five-year-olds were also tested ($n = 48$) but excluded from the final analysis because they performed at ceiling on pre- and post-practice testing.
[5] Video of Spatial Task: https://www.youtube.com/watch?v=W8pjTME_ugY.
[6] Video of Item Task: https://www.youtube.com/watch?v=XzwOMF8W5Wc.

Table 2
Summary of design and procedures.

Practice group	Pre-practice test	Practice type	Post-practice test
Spatial imitation ($n = 22$)	Spatial imitation	Spatial imitation	Spatial imitation
Item imitation ($n = 29$)	Spatial imitation	Item imitation	Spatial imitation
Spatial trial-and-error ($n = 26$)	Spatial imitation	Spatial trial-and-error	Spatial imitation
Free play (no practice) ($n = 26$)	Spatial imitation	Touchscreen play	Spatial imitation

Orientation to the spatial task (Phase 1)

To familiarize children with the contingencies of the touchscreen task, all children were oriented to the Spatial Task prior to the pre-practice test, including learning about the goal/reward video of Jumping Man, a 5-s video clip of a man doing a backward somersault. Descriptions of the orientation and testing procedures have been described in detail elsewhere (Subiaul et al., 2012, 2015; Subiaul, Zimmermann, et al., 2016). Briefly, during orientation, children were encouraged to touch all the items on the screen in the correct sequence to find Jumping Man. No demonstration was provided. Children received social feedback from the experimenter (emotional expressions, verbal feedback) and asocial feedback from the computer (audio, visual) following each response, whether correct or incorrect. An incorrect response terminated the trial and generated a brief (~500-ms) "boom" sound, at which point all pictures disappeared, the screen turned black for 2 s, and the experimenter frowned and 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 smiled and said, "That's right!" When all pictures were touched in the correct sequence, Jumping Man played in the middle of the screen accompanied by music or clapping and the experimenter smiled and said, "Yay! You found Jumping Man!" These same contingencies were present in all phases of the experiment. To advance to the pre-practice test (Phase 2), children needed to independently respond to all pictures on the screen in the target spatial sequence without making any errors. Because all children were provided with this orientation, all children had a common understanding of the goal of the task—to touch all items on the screen in a specific order to find Jumping Man.

Pre-practice spatial imitation test (Phase 2)

Following training on the Spatial Task, all children were tested on an imitation condition with a new spatial sequence. At the start of the demonstration, the experimenter said "Watch me!" and then proceeded to touch all items on the screen in the target sequence. This procedure was repeated two additional times (for a total of three demonstrations) prior to testing. Following the demonstration, the experimenter said to the child, "Now it's your turn. Can you find Jumping Man?" Based on prior work, 3-year-olds were tested on 3-item sequences and 4-year-olds were tested on 4-item sequences (Subiaul et al., 2012, 2015). The pre-practice Spatial Imitation test ended once children correctly responded to all items on the screen, thereby activating Jumping Man.

Practice (Phase 3)

Following the pre-practice test, preschool-aged children were randomly assigned to one of four experimental "practice" conditions: Free Play (no practice), Spatial Imitation, Item Imitation, and Spatial Trial-and-Error. All practice conditions were timed so that each was approximately 10 min (range ~9–11 min), after which the practice phase ended.

Free play: Using the commercially available Apple Macintosh drawing application Paintbrush, children were directed to freely play by selecting different colors and drawing with their finger. Children filled a box by sliding their finger like a paintbrush on the screen inside the window until the box was filled with color. This procedure was repeated for each box until approximately 10 min had elapsed.

Spatial imitation practice: For this practice type, procedures were identical to those of pre-practice test except that children started with a 2-item sequence. Once children responded correctly to two consecutive sequences on the first trial following a demonstration, they were presented with a new sequence that was 1 item longer and so on to a maximum of 5 items executed within approximately 10 min.

Item imitation practice: Imitation practice followed the same procedures described above for Spatial Imitation practice except that children practiced imitating sequences—following a demonstration—on the Item Task (Fig. 2B).

Spatial trial-and-error practice: This practice type used the same procedures described above for the two imitation conditions except that children were not provided with any demonstration prior to executing spatial sequences. Instead, children were encouraged to "Find Jumping Man" on their own and learn novel spatial sequences entirely by trial-and-error learning.

Post-practice test (Phase 4)

Post-practice testing immediately followed the practice phase described above (Phase 3). Procedures were identical to those used during the pre-practice test (Phase 2) except that all children were tested with a novel spatial sequence.

Coding

Measure of learning

The computer automatically recorded all responses (i.e., picture items touched by participants) on the touchscreen for each trial. A trial ended either when children made a sequence error or when they touched all items in the correct sequence. During the pre- and post-practice testing phases, we calculated a learning ratio that consisted of the total number of correct responses while learning a new sequence during a given phase divided by the total number of trials it took children to respond correctly to all items on the screen (i.e., trials to correct). We then generated a difference score by subtracting the pre-practice test ratio from the post-practice test ratio. Consequently, positive numbers represent improved performance from pre- to post-practice, and negative numbers represent a decrement in performance.

Results

Preliminary analyses

First, we examined whether covariates of age, sex, familiarity with touchscreens, multilingual status, and pre-practice test performance were associated with the difference score (i.e., pre- and post-practice differences). There was no significant correlation between age and the difference score ($r = -0.08$, $p = .42$), sex of the child and the difference score ($r = -0.15$, $p = .13$), familiarity with touchscreen devices and the difference score ($r = -0.02$, $p = .84$), or whether the child was multilingual and the differences score ($r = -0.06$, $p = .56$). However, children's difference score was negatively associated with the pre-practice test performance ($r = -0.38$, $p < .01$). This negative correlation suggests that, not surprisingly, the children who performed poorly during the pre-practice test benefitted most from practice. Note that for these analyses, and for all analyses below, our data were visually inspected and appeared to meet the assumptions of normality and homogeneity of variances unless otherwise noted.

Does practice enhance spatial imitation?

To test for improved performance within practice groups, we used paired permutation tests (Hothorn & Gerhard, 2009; Hothorn, Hornik, van de Wiel, & Zeileis, 2008) rather than paired parametric tests because the calculated learning ratio was not normally distributed. This revealed that children improved (i.e., post-practice test scores were significantly higher than pre-practice test scores) for the Spatial Imitation practice group ($Z = 2.33$, $p < .005$) and Item Imitation practice group ($Z = 2.37$, $p = .048$), but not for the Trial-and-Error group ($Z = 1.51$, $p = .41$) or Free Play control group ($Z = 0.31$, $p = .77$) (all p values are Bonferroni corrected). From these analyses, there appeared to be improvement in the two imitation practice groups but not in any other group.

In a follow-up analysis, we directly compared the improved performance across practice groups. Difference scores (post-practice test learning ratio–pre-practice test learning ratio) were normally distributed. Therefore, we conducted a one-way analysis of variance (ANOVA) across practice conditions (Spatial Imitation, Item Imitation, Spatial Trial-and-Error, and Free Play) on difference scores. As can be seen in Fig. 2B, there was a significant effect of practice group condition, $F(3, 107) = 3.55$, $p = .02$. Follow-up, pairwise, post hoc Tukey's t tests ($p < .05$) showed that only Spatial Imitation differed from the Free Play control group ($p = .003$); neither Item Imitation ($p = .20$) nor Spatial Trial-and-Error ($p = .69$) practice significantly differed from the Free Play control group. However, Spatial Imitation was not significantly different from Item Imitation ($p = .31$) and was only marginally different from Spatial Trial-and-Error ($p = .07$). The difference between Item Imitation and Spatial Trial-and-Error was not significant ($p = .84$).

How does performance during practice trials affect spatial imitation?

These results suggest that practice in some contexts increases performance. However, these results do not address which component feature(s) of practice is most important. They are also silent about any individual differences that might contribute to improvement within practice groups. The above ANOVA did not take into account individual differences in learning during the practice condition. This is because even within practice groups, children may have exhibited differences within learning that are not captured by an across-group analysis (e.g., ANOVA). Thus, we simultaneously examined how improvement during the practice phase affected the pre-practice to post-practice difference across practice groups. To do so, we explored the predictive ability of a variety of different measures collected during the practice phase on the pre–post difference score of different practice groups. These practice performance measures included the longest sequence that children practiced (longest sequence length; range = 3–5 items), the total number of trials that children experienced during practice (total number of trials), and a composite practice performance score that weighted children's performance accuracy (correct trials/total trials) based on the sequence length practiced. This composite practice performance score was calculated as follows: composite practice performance scores = 2 * (correct 2-item trials/total 2-item trials) + 6 * (correct 3-item trials/total 3-item trials) + 24 * (correct 4-item trials/total 4-item trials) + 120 * (correct 5-item trials/total 5-item trials). In this formula, a higher weight is given to children's performance on longer sequences based on the inverse of the probability of correctly guessing the sequence of a particular length. The probability of correctly guessing a 2-item sequences is 1/2, the probability of correctly guessing a 3-item sequence is $1/2 \times 1/3 = 1/6$, the probability of correctly guessing a 4-item sequences is $1/4 \times 1/3 \times 1/2 = 1/24$, and the probability of correcting guessing a 5-item sequence is $1/5 \times 1/4 \times 1/3 \times 1/2 = 1/120$.

We ran a general linear model to examine how individual differences during practice predicted pre- to post-practice effects while controlling for differences due to practice condition. In the model, the response variable was the pre- to post-practice difference score. Continuous predictors included the practice performance measures described above (longest sequence length, total number of trials, and composite practice performance score), and because the result of our previous ANOVA indicated practice condition differences, practice condition (Item Imitation, Spatial Imitation, Spatial Trial-and-Error) was included as a categorical predictor, with the reference level being Item Imitation. Because the Free Play condition involved no content- or task-specific practice by design, it was not included in this analysis. Multicollinearity was examined and was within an acceptable range (all variance inflation factors [VIFs] were ≤ 2). Results from the full model can be seen in Table 3. Because an ANOVA previously examined the effects of practice condition on pre- to post-practice difference scores, we focused on how practice performance relates to pre- to post-practice differences.

Examining the results from this model revealed that of the practice performance measures tested, only longest sequence length was a significant predictor of children's difference score (Table 3). This

Table 3
Results of model testing the role of practice performance in explaining pre- to post-practice differences.

	Beta	*SE*	*T*	*p*
Spatial imitation	0.43	0.34	1.28	.20
Spatial trial-and-error	−0.48	0.58	−0.84	.41
Longest sequence length	0.66	0.24	2.81	.01*
Total number of trials	0.01	0.02	0.64	.53
Composite practice performance score	−0.01	0.01	−1.50	.14

* $p < .05$.

result indicates that if children mastered longer sequence lengths during the practice period, they achieved higher spatial imitation scores in the post-test. Surprisingly, the total number of trials given to children during the practice condition did not predict difference scores, nor did the composite practice score (Table 3). Given that our previous ANOVA suggested some differences among practice conditions, in a follow-up analysis we examined whether the effect of longest sequence length differed among conditions. We ran a general linear model with practice condition, longest sequence length, and their interaction as predictor variables and with pre- to post-practice difference score as the response variable. The interaction between practice condition and longest sequence length was not significant ($p = .61$). This result shows that, regardless of practice type, children who reached longer (more complex) sequences during practice were more likely to show an improvement in spatial imitation during the post-test. In addition to the previous result showing that pre-practice spatial imitation was associated with post-practice imitation, these results point to individual differences influencing learning. Inevitably, some of these differences involve general learning mechanisms. However, because children were randomly assigned to groups and all groups appeared to have benefitted equally from practicing long sequences, such individual differences in general cognitive abilities cannot account for the group-specific practice effects reported above (cf. Fig. 2B).

Which hypothesis best predicts imitation performance?

Finally, we combined the knowledge gained from all the above analyses into a single general linear model to test how well each of our three hypotheses predicted the observed difference score. This general linear model included a social input predictor variable, which was scored as *yes* if the practice type involved imitation (Spatial, Item) and *no* if it did not, and a task-specific predictor variable, which was scored as *yes* if the practice involved the Spatial Task and *no* if it involved the Item Task (cf. Table 1). We also included pre-practice test score as a predictor given that it was found to be important in previous analyses. We were unable to include longest sequence length because children in the Free Play practice group did not have this measure to serve as a predictor. Again, VIFs were examined, and all were within an acceptable range (here, <2).

The final model indicated that social input during practice was the strongest predictor of the difference score. The positive estimate indicated that social input (i.e., imitation) led to the greatest performance increase from pre- to post-testing (Table 4). In addition, children's pre-test score also significantly predicted their difference score, as was expected based on our initial correlational analyses. Finally, task specificity appears to have had a marginal effect on the difference scores ($p = .06$). However, the estimate for task specificity was smaller than that for social input, indicating that the effect of task type was noticeably weaker.

Table 4
Results of model testing the role of input- and task-specific variables.

	Beta	*SE*	*T*	*p*
Social input	0.80	0.23	3.43	.001*
Spatial content	0.44	0.23	1.93	.060
Pre-practice test score	−0.35	0.17	−2.02	.046*

* $p < .05$.

Discussion

Here, we sought to characterize the component cognitive processes underlying one particular form of imitation—spatial imitation—that has been associated with the imitation of tools and object use (Subiaul, Zimmermann, et al., 2016). Using a brief "practice" paradigm, we explored the role of domain-general learning mechanisms, such as Spatial WM, as well as domain-specific social-communicative processes, such as pedagogical cues, during spatial imitation. We asked two questions. First, does imitation practice significantly improve imitation performance? And, second, would any type of practice suffice? The answer to the first question is clearly *yes.* Children significantly benefitted from a brief imitation-specific practice intervention lasting just 10 min. Specifically, in the Spatial Trial-and-Error and Spatial Imitation practice groups, children practiced the exact same task but used different procedures, social versus individual learning. The Item Imitation and Spatial Imitation practice groups condition used the same procedure, social learning, but different tasks (cf. Tables 1 and 2). The answer to the second question—would any type of practice suffice?—is *no.* Despite the overlap between procedures and tasks, Spatial Imitation practice produced the most robust practice effect, with Item Imitation practice showing a moderate effect and Spatial Trial-and-Error practice showing poor to no practice effect at all. Below, we discuss the predictions of the three different hypotheses for imitation learning and relate those predictions to the results from the current study.

General learning hypothesis

According to the general learning hypothesis, imitation learning is not mediated by specialized social learning mechanisms. Rather, domain-general learning processes, including WM and associative learning, underlie imitation. These are processes that are believed to be responsible for all types of learning, social and asocial alike (Heyes, 2012a, 2012b, 2016a). This hypothesis assumes that what makes learning "social" is the source of the information rather than any underlying mechanism. In the current study, this general learning hypothesis would predict significant improvements in Spatial Imitation following Spatial Trial-and-Error practice because the core process—spatial learning—was identical in both tasks. Results were inconsistent with this hypothesis. Practicing Spatial learning by trial-and-error did not significantly improve spatial imitation performance relative to a Free Play (no practice) control. It is important to note here that group differences between the Spatial Imitation and Spatial Trial-and-Error groups cannot be accounted for by differences in the total number of trials, duration of practice, or rate of learning (composite score), as indicated by our analysis of performance measures from the practice phase. Nonetheless, one individual difference during practice did predict post-test performance. Specifically, those who learned longer sequences during practice did better at post-test regardless of practice condition. One possible interpretation is that general cognitive processes (e.g., sustained or focused attention, motivation, fatigue) explains this specific result. However, as we have already noted, because children were randomly assigned to learning groups and all groups appeared to show some level of learning, such domain-general abilities or skills cannot explain the specific group differences reported here.

A domain-general mechanism that is unlikely to underlie improved performance from pre- to post-testing is WM, specifically spatial WM. WM was controlled in the Spatial Trial-and-Error group as children needed to temporarily store ongoing responses as correct or incorrect and update the representation of each item's serial order in the sequence with each successive trial. What we did not control for were individual differences in *sustained* (or controlled) attention (Sarter, Gehring, & Kozak, 2006). It may be that social input enhances sustained attention, explaining why practice groups that involved social input performed best. Answering this question will not be easy, however, because it will require distinguishing between general attention (e.g., orientation, identification), which was controlled in the current study (i.e., Spatial Trial-and-Error, Item Imitation practice) and sustained attention, which was not. Future studies could also include independent measures of IQ and speed of processing.

Natural pedagogy hypothesis

According to the natural pedagogy hypothesis (Csibra & Gergely, 2009), social learning is mediated by a dedicated communication system that allows humans to transmit generic knowledge via ostensive cues such as eye gaze and pointing that direct and focus attention on relevant information. Specifically, these studies have reported that imitation practice in one task domain, object imitation, improves imitation performance in another task domain, gestural imitation (Cardon & Wilcox, 2011; Ingersoll & Lalonde, 2010; Ingersoll & Schreibman, 2006). The results of the current study provided some partial support for this hypothesis. Practicing Item Imitation significantly improved from pre- to post-practice testing. However, practicing Item Imitation did not significantly improve relative to the Free Play group, which did not practice at all. Furthermore, when examining the practice effects, social input was associated with better post-practice test imitation as well. Given that Spatial Trial-and-Error practice had no significant effect on Spatial Imitation, the significant effect of Item Imitation practice on Spatial Imitation suggests that the effect of social communication and imitation-specific processes may be additive, where one mechanism (social communication) may gather the relevant information and another mechanism (imitation specific) transforms that information into a matching response.

MIM hypothesis

Finally, Subiaul (2010) proposed that imitation learning is mediated by multiple, domain-specific copying mechanisms. According to this multiple imitation mechanism hypothesis, there are different imitation mechanisms, each specialized for copying responses in different domains and tasks. An extension of this hypothesis, the mosaic social learning (MSL) hypothesis (Subiaul, Patterson, et al., 2016), posits that some social learning mechanisms are more domain and task general (e.g., emulation, natural pedagogy), whereas other forms of social learning, such as spatial imitation, are domain and task specific. The MIM hypothesis predicts that *only* Spatial Imitation practice should significantly improve spatial imitation performance relative to a Free Play control. The results from the current study are consistent with the predictions of the MIM and MSL hypotheses that domain- *and* task-specific imitation practice produces the most robust effect on imitation performance. However, results failed to support the prediction that only Spatial Imitation practice can improve spatial imitation performance given that Item Imitation practice also proved to be beneficial, albeit less so.

Could differences between groups be explained by different learning goals?

It is possible that children in each practice group learned different goals, and those task-specific goals may explain the differences between practice groups. For example, children in the Item Imitation and Spatial Imitation practice groups may have learned a social goal, *imitate the model.* Such an orientation to the model's actions could explain why these two practice groups produced the most robust transfer. In contrast, children in the Spatial Trial-and-Error group could have learned a different goal, *order items spatially.* Because there was no model, children in this group must have developed sequencing goals having to do with holding in memory correct responses (A) and avoiding incorrect sequences (A → C). But notice how, despite the differences in the types of learning goals or strategies that children may have developed (one that was social and another that was asocial), both goal-types should improve performance in the Spatial Task. Moreover, such social or sequencing goals would represent different subgoals to the ultimate goal, *find Jumping Man.* This ultimate goal was established at the outset and held constant across groups. Given these procedures, it is unlikely that differences in subgoals alone explain the observed differences between practice groups.

Are observed effects additive?

Both spatial WM (i.e., general learning hypothesis) and social communicative (i.e., natural pedagogy) processes, along with specialized copying mechanisms, may be shared components of imitation that *additively*—but not individually—contribute to imitation across domains. Consistent with this hypothesis is that when the benefits of Item Imitation and Trial-and-Error practice conditions are combined, they are nearly identical to the mean benefit of Spatial Imitation practice (cf. Fig. 2B). However, if the post-practice testing effect on Spatial Imitation was additive, it was very uneven. Recall that the effect of Item Imitation practice (involving a *different* task) was more than twice that of Spatial

Trial-and-Error practice (involving the *same* task). Such a large gap between the contributions of social- and content-specific training indicates that social information is not only privileged but also more malleable than individual experience, which is either discounted relative to social experience or non-transferrable between asocial and social domains. However, the preference for social knowledge over asocial—firsthand—knowledge may change during the course of development. It might be that preschoolers who are just beginning to be introduced to more formal pedagogical settings might have been most sensitive to the social input in the imitation conditions (McGuigan et al., 2017). One way to test this would be to investigate whether there are age-related changes in the sensitivity or salience of such pedagogical cues by testing older children and adults in this paradigm.

Future directions and implications

Further investigation of these findings is warranted. Of course, there are many possible practice groups that we could have included to identify and better characterize the core mechanisms of imitation learning. For example, practicing other domain-general—executive—processes, such as inhibition, set shifting, and cognitive control, may increase Spatial Imitation learning. Including other social-cognitive and communication practice groups would be useful. To distinguish between different sociocognitive mechanisms, a future study could include a ghost demonstration condition where the steps of the sequence are demonstrated by the computer rather than by a person. Previous studies have shown that ghost conditions prime social cognitive percepts, specifically percepts of animacy and agency (Biro & Leslie, 2007; Subiaul, Vonk, & Rutherford, 2011). But critically, ghost controls lack natural pedagogical cues. If natural pedagogical cues represent component processes of imitation, eliminating such cues should also eliminate any benefit during post-testing. Alternatively, if imitation-specific mechanisms mediate imitation independent of natural pedagogical cues, we might expect that spatial ghost practice should significantly benefit spatial imitation performance during post-testing (cf. Zimmermann, Moser, Lee, Gerhardstein, & Barr, 2017).

Beyond shedding light on the cognitive structure of imitation, these findings also have important implications for early educational settings where touchscreen apps are increasingly employed in the classroom and are often assumed to lead to self-directed learning, particularly in science, technology, engineering, and math. The finding that item imitation learning or spatial trial-and-error learning did not result in high levels of transfer to spatial imitation might be surprising to educators. Yet understanding *why* is critical to making better predictions in educational settings and success of early education programs.

Despite the fact that young children are proficient with touchscreen devices (Moser et al., 2015; Zimmermann et al., 2017), these findings suggest that during early childhood directed social learning may be especially beneficial for children mastering novel concepts. These findings also suggest that imitation learning may be content specific, a key characteristic of the early memory system (see Barr & Brito, 2014). It is possible that a lack of generalizability between Spatial Trial-and-Error practice and Spatial Imitation may be due in part to the cognitive architecture of imitation during early childhood, requiring task- and domain-specific practice to improve outcomes. For example, future practice studies might examine whether practicing object-based imitation tasks with a significant spatial component (e.g., where objects must be related to specific points in space) improves performance on a task like the more abstract Spatial Task used here and vice versa. These types of studies may allow us to make better predictions about the generality of imitation practice effects in different contexts. These studies should also control for individual differences, such as IQ, that might contribute to outcomes. Educators and app developers will need to consider how different domains overlap in order to maximize pre-academic skill learning required for language/literacy (item learning) and spatial skills/mathematics (spatial learning).

These results may also have clinical implications for populations with imitation deficits. Existing interventions, although effective, are time intensive and costly (Weinmann et al., 2009). The imitation practice conditions used in the current study were brief and targeted and could be efficacious for populations with limited language skills and a variety of cognitive impairments. In short, a better understanding of the component cognitive processes underlying imitation performance and an appreciation for how such processes may differ across task domains may ultimately shed light on the relationship between domain-general and domain-specific cognitive processes. Such knowledge may have important practical benefits, resulting in more precise diagnostic measures as well as more efficacious cognitive interventions.

References

American Psychiatric Association (2013). *Diagnostic and statistical manual of mental disorders–fifth edition: DSM-5*. Washington, DC: Author.

Baddeley, A. (1986). *Working memory*. Oxford, UK: Oxford University Press.

Baddeley, A. (1996). The fractionation of working memory. *Proceedings of the National Academy of Sciences of the United States of America, 93*, 13468–13472.

Baddeley, A. (1998). The central executive: A concept and some misconceptions. *Journal of the International Neuropsychological Society, 4*, 523–526.

Baddeley, A. (2012). Working memory: Theories, models, and controversies. *Annual Review of Psychology, 63*, 1–29.

Barr, R. (2002). Imitation as a learning mechanism and research tool: How does imitation interact with other cognitive functions? *Developmental Science, 5*, 16–18.

Barr, R., & Brito, N. (2014). From Specificity to Flexibility: Developmental Changes during Infancy. In P. Bauer & R. Fivush (Eds.), *Wiley-Blackwell Handbook on the Development of Children's Memory* (pp. 453–479). Chichester: John Wiley and Sons.

Barr, R., Dowden, A., & Hayne, H. (1996). Developmental changes in deferred imitation by 6- to 24-month-old infants. *Infant Behavior and Development, 19*, 159–170.

Barr, R., & Hayne, H. (2000). Age-related changes in imitation: Implications for memory development. In C. Rovee-Collier, L. Lipsitt, & H. Hayne (Eds.). *Progress in infancy research* (Vol. 1, pp. 21–67). Mahwah, NJ: Lawrence Erlbaum.

Bauer, P. J. (1992). Holding it all together: How enabling relations facilitate young children's event recall. *Cognitive Development, 7*, 1–28.

Bauer, P. J., & Mandler, J. M. (1992). Putting the horse before the cart: The use of temporal order in recall of events by one-year-old children. *Developmental Psychology, 28*, 441–452.

Bekkering, H., Wohlschlager, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *Quarterly Journal of Experimental Psychology A, 53*, 153–164.

Bird, G., Brindley, R., Leighton, J., & Heyes, C. (2007). General processes, rather than "goals", explain imitation errors. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 1158–1169.

Bird, G., & Heyes, C. (2005). Effector-dependent learning by observation of a finger movement sequence. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 262–275.

Bird, G., Osman, M., Saggerson, A., & Heyes, C. (2005). Sequence learning by action, observation and action observation. *British Journal of Psychology, 96*, 371–388.

Biro, S., & Leslie, A. M. (2007). Infants' perception of goal-directed actions: Development through cue-based bootstrapping. *Developmental Science, 10*, 379–398.

Cardon, T. A., & Wilcox, M. J. (2011). Promoting imitation in young children with autism: A comparison of reciprocal imitation training and video modeling. *Journal of Autism and Developmental Disorders, 41*, 654–666.

Carpenter, M., Call, J., & Tomasello, M. (2002). Understanding "prior intentions" enables two-year-olds to imitatively learn a complex task. *Child Development, 73*, 1431–1441.

Carpenter, M., Pennington, B. F., & Rogers, S. J. (2002). Interrelations among social-cognitive skills in young children with autism. *Journal of Autism and Developmental Disorders, 32*, 91–106.

Catmur, C., & Heyes, C. (2013). Is it what you do, or when you do it? The roles of contingency and similarity in pro-social effects of imitation. *Cognitive Science, 37*, 1541–1552.

Charman, T., Swettenham, J., Baron-Cohen, S., Cox, A., Baird, G., & Drew, A. (1997). Infants with autism: An investigation of empathy, pretend play, joint attention, and imitation. *Developmental Psychology, 33*, 781–789.

Cooper, R. P., Cook, R., Dickinson, A., & Heyes, C. (2013). Associative (not Hebbian) learning and the mirror neuron system. *Neuroscience Letters, 540*, 28–36.

Corsi, P. M. (1972). Human memory and the medial temporal region of the brain. Unpublished doctoral dissertation, McGill University.

Csibra, G., & Gergely, G. (2009). Natural pedagogy. *Trends in Cognitive Science, 13*, 148–153.

Dawson, G., & Adams, A. (1984). Imitation and social responsiveness in autistic children. *Journal of Abnormal Child Psychology, 12*, 209–225.

Elman, J. L. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.

Fodor, J. A. (2000). *The mind doesn't work that way: The scope and limits of computational psychology*. Cambridge, MA: MIT Press.

Galef, B. G. (1988). Imitation in animals: History, definition, and interpretation of data from the psychological laboratory. In Z. Galef (Ed.), *Social learning: Psychological and biological perspectives* (pp. 3–28). Hillsdale, NJ: Lawrence Erlbaum.

Happe, F., Cook, J. L., & Bird, G. (2017). The structure of social cognition: In(ter)dependence of sociocognitive processes. *Annual Review of Psychology, 68*, 243–267.

Harnick, F. S. (1978). The relationship between ability level and task difficulty in producing imitation in infants. *Child Development, 49*, 209–212.

Heyes, C. (2012a). Grist and mills: On the cultural origins of cultural learning. *Philosophical Transactions of the Royal Society B: Biological Sciences, 367*, 2181–2191.

Heyes, C. (2012b). What's social about social learning? *Journal of Comparative Psychology, 126*, 193–202.

Heyes, C. (2016a). Homo imitans? Seven reasons why imitation couldn't possibly be associative. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*. https://doi.org/10.1098/rstb.2015.0069.

Heyes, C. (2016b). Who knows? Metacognitive social learning strategies. *Trends in Cognitive Science, 20*, 204–213.

Heyes, C., & Pearce, J. M. (2015). Not-so-social learning strategies. *Proceedings of the Royal Society B: Biological Sciences, 282*. https://doi.org/10.1098/rspb.2014.1709.

Hobson, R. P., & Hobson, J. A. (2008). Dissociable aspects of imitation: A study in autism. *Journal of Experimental Child Psychology, 101*, 170–185.
Hobson, R. P., & Lee, A. (1999). Imitation and identification in autism. *Journal of Child Psychology and Psychiatry, 40*, 649–659.
Hopper, L. M. (2010). "Ghost" experiments and the dissection of social learning in humans and animals. *Biological Reviews of the Cambridge Philosophical Society, 85*, 685–701.
Hothorn, L. A., & Gerhard, D. (2009). Statistical evaluation of the in vivo micronucleus assay. *Archives of Toxicology, 83*, 625–634.
Hothorn, T., Hornik, K., van de Wiel, M. A., & Zeileis, A. (2008). Implementing a class of permutation tests: The coin package. *Journal of Statistical Software, 28*(8). https://doi.org/10.18637/jss.v028.i08.
Ingersoll, B., & Lalonde, K. (2010). The impact of object and gesture imitation training on language use in children with autism spectrum disorder. *Journal of Speech, Language, and Hearing Research, 53*, 1040–1051.
Ingersoll, B., & Schreibman, L. (2006). Teaching reciprocal imitation skills to young children with autism using a naturalistic behavioral approach: Effects on language, pretend play, and joint attention. *Journal of Autism and Developmental Disorders, 36*, 487–505.
Kanwisher, N. (2010). Functional specificity in the human brain: A window into the functional architecture of the mind. *Proceedings of the National Academy of Sciences of the United States of America, 107*, 11163–11170.
Kemps, E., De Rammelaere, S., & Desmet, T. (2000). The development of working memory: Exploring the complementarity of two models. *Journal of Experimental Child Psychology, 77*, 89–109.
Kessels, R. P., van den Berg, E., Ruis, C., & Brands, A. M. (2008). The backward span of the Corsi Block-Tapping Task and its association with the WAIS-III Digit Span. *Assessment, 15*, 426–434.
Lee Swanson, H., Orosco, M. J., & Lussier, C. M. (2015). Growth in literacy, cognition, and working memory in English language learners. *Journal of Experimental Child Psychology, 132*, 155–188.
Lonigan, C. J., Lerner, M. D., Goodrich, J. M., Farrington, A. L., & Allan, D. M. (2016). Executive function of Spanish-speaking language-minority preschoolers: Structure and relations with early literacy skills and behavioral outcomes. *Journal of Experimental Child Psychology, 144*, 46–65.
McGuigan, N., Burdett, E., Burgess, V., Dean, L., Lucas, A., Vale, G., & Whiten, A. (2017). Innovation and social transmission in experimental micro-societies: Exploring the scope of cumulative culture in young children. *Philosophical Transactions of the Royal Society B: Biological Sciences, 372*. https://doi.org/10.1098/rstb.2016.0425.
Meltzoff, A. N. (1988). *The human infant as Homo imitans*. Hillsdale, NJ: Lawrence Erlbaum.
Meltzoff, A. N. (2007). "Like me": A foundation for social cognition. *Developmental Science, 10*, 126–134.
Morgan, T. J., Laland, K. N., & Harris, P. L. (2015). The development of adaptive conformity in young children: Effects of uncertainty and consensus. *Developmental Science, 18*, 511–524.
Moser, A., Zimmermann, L., Dickerson, K., Grenell, A., Barr, R., & Gerhardstein, P. (2015). They can interact, but can they learn? Toddlers' transfer learning from touchscreens and television. *Journal of Experimental Child Psychology, 137*, 137–155.
Nehaniv, C. L., & Dautenhahn, K. (2002). The correspondence problem. In C. L. Nehaniv & K. Dautenhahn (Eds.), *Imitation in animals and artifacts* (pp. 41–61). Cambridge, MA: MIT University Press.
Oei, A. C., & Patterson, M. D. (2014). Are videogame training gains specific or general? *Front Syst Neurosci, 8*, 54.
Over, H., & Carpenter, M. (2012). Putting the social into social learning: Explaining both selectivity and fidelity in children's copying behavior. *Journal of Comparative Psychology, 126*, 182–192.
Posner, M. I., Petersen, S. E., Fox, P. T., & Raichle, M. E. (1988). Localization of cognitive operations in the human brain. *Science, 240*, 1627–1631.
Rendell, L., Fogarty, L., Hoppitt, W. J., Morgan, T. J., Webster, M. M., & Laland, K. N. (2011). Cognitive culture: Theoretical and empirical insights into social learning strategies. *Trends in Cognitive Science, 15*, 68–76.
Rogers, S. J., & Pennington, B. F. (1991). A theoretical approach to the deficits in infantile autism. *Developmental Psychopathology, 3*, 137–162.
Rossi-Arnaud, C., Pieroni, L., Spataro, P., & Baddeley, A. (2012). Working memory and individual differences in the encoding of vertical, horizontal and diagonal symmetry. *Acta Psychology (Amsterdam), 141*, 122–132.
Rumiati, R. I., & Tessari, A. (2002). Imitation of novel and well-known actions: The role of short-term memory. *Experimental Brain Research, 142*, 425–433.
Rumiati, R. I., Weiss, P. H., Tessari, A., Assmus, A., Zilles, K., Herzog, H., & Fink, G. R. (2005). Common and differential neural mechanisms supporting imitation of meaningful and meaningless actions. *Journal of Cognitive Neuroscience, 17*, 1420–1431.
Sarter, M., Gehring, W. J., & Kozak, R. (2006). More attention must be paid: The neurobiology of attentional effort. *Brain Research Reviews, 51*, 145–160.
Smith, I. M., & Bryson, S. E. (1998). Gesture imitation in autism I: Nonsymbolic postures and sequences. *Cognitive Neuropsychology, 15*, 747–770.
Stone, W. L., Ousley, O. Y., & Littleford, C. D. (1997). Motor imitation in young children with autism: What's the object? *Journal of Abnormal Child Psychology, 25*, 475–485.
Subiaul, F. (2010). Dissecting the imitation faculty: The multiple imitation mechanisms (MIM) hypothesis. *Behavioural Processes, 83*, 222–234.
Subiaul, F., Anderson, S., Brandt, J., & Elkins, J. (2012). Multiple imitation mechanisms in children. *Developmental Psychology, 48*, 1165–1179.
Subiaul, F., Lurie, H., Romansky, K., Klein, T., Holmes, D., & Terrace, H. (2007). Cognitive imitation in autism. *Cognitive Development, 22*, 230.
Subiaul, F., Patterson, E. M., & Barr, R. (2016). The cognitive structure of goal emulation during the preschool years. *British Journal of Developmental Psychology, 34*(1), 132–149.
Subiaul, F., Patterson, E. M., Schilder, B., Renner, E., & Barr, R. (2015). Becoming a high-fidelity—*super*—imitator: What are the contributions of social and individual learning? *Developmental Science, 18*, 1025–1035.
Subiaul, F., Vonk, J., & Rutherford, M. D. (2011). The ghosts in the computer: The role of agency and animacy attributions in "ghost controls". *PLoS One, 6*(11), e26429.
Subiaul, F., Zimmermann, L., Renner, E., Schilder, B., & Barr, R. (2016). Elemental imitation mechanisms in preschool age children. *Journal of Cognition and Development, 7*, 221–243.

Thorndike, E. L., & Woodworth, R. S. (1901). The influence of improvement in one mental function upon the efficiency of other functions. *Psychological Review, 8*, 247–261.
Tomasello, M., & Carpenter, M. (2007). Shared intentionality. *Developmental Science, 10*, 121–125.
Uzgiris, I. C. (1981). Two functions of imitation during infancy. *International Journal of Behavioral Development, 4*, 1–12.
Vanvuchelen, M., Roeyers, H., & De Weerdt, W. (2011a). Development and initial validation of the Preschool Imitation and Praxis Scale (PIPS). *Research in Autism Spectrum Disorders, 5*, 463–473.
Vanvuchelen, M., Roeyers, H., & De Weerdt, W. (2011b). Imitation assessment and its utility to the diagnosis of autism: Evidence from consecutive clinical preschool referrals for suspected autism. *Journal of Autism and Developmental Disorders, 41*, 484–496.
Weinmann, S., Schwarzbach, C., Begemann, M., Roll, S., Vauth, C., Willich, S. N., & Greiner, W. (2009). Behavioural and skill-based early interventions in children with autism spectrum disorders. *GMS Health Technology Assessment, 5*. https://doi.org/10.3205/hta000072.
Williams, J. H. G., Whiten, A., & Singh, T. (2004). A systematic review of action imitation in autistic spectrum disorder. *Journal of Autism and Developmental Disorders, 34*, 285–299.
Wood, L. A., Harrison, R. A., Lucas, A. J., McGuigan, N., Burdett, E. R., & Whiten, A. (2016). "Model age-based" and "copy when uncertain" biases in children's social learning of a novel task. *Journal of Experimental Child Psychology, 150*, 272–284.
Young, G. S., Rogers, S. J., Hutman, T., Rozga, A., Sigman, M., & Ozonoff, S. (2011). Imitation from 12 to 24 months in autism and typical development: A longitudinal Rasch analysis. *Developmental Psychology, 47*, 1565–1578.
Zentall, T. R. (1996). An analysis of imitative learning in animals. In C. Heyes & B. Galef (Eds.), *Social learning in animals: The roots of culture* (pp. 221–238). San Diego: Academic Press.
Zentall, T. R. (2012). Perspectives on observational learning in animals. *Journal of Comparative Psychology, 126*, 114–128.
Zimmermann, L., Moser, A., Lee, H., Gerhardstein, P., & Barr, R. (2017). The ghost in the touchscreen: Social scaffolds promote learning by toddlers. *Child Development, 88*, 2013–2025.