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Automatic imitation effects are influenced by experience of synchronous action in children

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Abstract

By their fourth year children are expert imitators but it is unclear how this ability develops. One approach suggests that certain types of experience might forge associations between the sensory and motor representations of an action that might facilitate imitation at a later time. Sensorimotor experience of this sort may occur when an infant's action is imitated by a caregiver or when socially synchronous action occurs. This learning approach therefore predicts that the strength of sensory-motor associations should depend on the frequency and quality of previous experience. Here, we tested this prediction by examining automatic imitation; i.e., the tendency of an action stimulus to facilitate the performance of that action and interfere with the performance of an incompatible action. We required children (aged between 3:8 and 7:11) to respond to actions performed by an experimenter (e.g., two hands clapping), with both compatible actions (i.e., two hands clapping) and incompatible actions (i.e., two hands waving) at different stages in the experimental procedure. As predicted by a learning account, actions thought to be performed in synchrony (i.e., clapping/waving) produced stronger automatic imitation effects when compared to actions where previous sensorimotor experience is likely to be more limited (e.g., pointing/hand closing). Furthermore, these automatic imitation effects were not found to vary with age, as both compatible and incompatible responses quickened with age. These findings suggest a role for sensorimotor experience in the development of imitative ability.

Keywords: automatic imitation, synchrony, associative sequence learning, social learning, sensorimotor experience.

Automatic imitation effects are influenced by experience of synchronous action in children

Copying the behavioral morphology of an action is often considered to be cognitively demanding due to the correspondence problem (i.e., the sensory mismatch when observing one's own actions and those of another, Nehaniv & Dautenhahn, 2002), and imitating actions that in some cases are unobservable to the imitator (also, known as opaque actions; e.g., facial expressions) requires a mechanism for transforming sensory information into a corresponding matching action. It has been suggested that humans are born with an inter-modal representation space where proprioceptive feedback from an action can be compared to a sensory representation of the same action, facilitating action imitation (the active inter-modal mapping hypothesis, AIM; Meltzoff & Moore, 1997). On the other hand, domain-general accounts propose that associative learning links sensory and motor representations to overcome the correspondence problem (e.g., Associative sequence learning approach, ASL, and the ideomotor approach; Heyes & Ray, 2000; Brass & Heyes, 2005). However, while experience-dependent approaches have been extensively studied in adults, few studies have tested their predictions in children.

There is no consensus in the field of developmental psychology about when infants first exhibit a capacity for imitation. However, researchers predominantly fall into one of two camps. Some believe an imitative faculty is present from birth (Meltzoff & Moore, 1997; Nagy et al., 2005; Simpson, Murray, Paukner, & Ferrari, 2014), while others believe imitative ability develops throughout the first years of life (Jones, 2009; Ray & Heyes, 2011). The observation that infants imitate facial gestures within hours of being born was first reported by Meltzoff and Moore (1977) and there have been many attempts to replicate these findings, with mixed results. Some studies report evidence of a number of actions being imitated from birth including tongue protrusion, mouth opening, finger movement, and emotional expressions (Field, Woodson, Greenberg, & Cohen, 1982; Meltzoff & Moore, 1977, 1983; Nagy et al., 2005; Nagy, Pilling, Orvos, & Molnar, 2013), while others find either selective imitation of only certain actions or no imitation at all (Anisfeld et al., 2001; Hayes & Watson, 1981; Heimann, Nelson, & Schaller, 1989; Oostenbroek et al., 2016). Studies of nonhuman primates have identified further evidence of neonatal imitation of mouth opening and tongue protrusion in chimpanzees (*Pan troglodytes*, Bard, 2007; Myowa-Yamakoshi, Tomonaga, Tanaka, & Matsuzawa, 2004), and evidence of lip-smacking and tongue protrusion imitation in three-day old rhesus macaques (*Macaca mulatta*, Ferrari et al., 2006; however, note that there was no evidence of neonatal imitation of these actions when infants were one, seven or 14 days old, and no evidence was found of mouth opening or hand opening imitation). This evidence from nonhuman primates lends some weight to the notion of an evolved and innate action matching system that is at least sensitive to certain actions.

These empirical findings are granted different weight in reviews of the evidence, as both early (Anisfeld, 1996; Meltzoff, 1996) and contemporary reviews (Lodder et al., 2014; Ray & Heyes, 2011; Simpson et al., 2014) often draw conflicting conclusions about the presence of an innate imitative ability. While a consensus answer to the neonatal imitation question is not forthcoming some have suggested that overconfidence in neonatal imitation may distract from the empirical study of how imitative ability develops throughout infancy (Jones, 2007). Indeed, regardless of the presence or absence of innate imitative ability it is important to consider both predispositions to imitation and also the influence of ontogenetic processes.

An ability to imitate at birth does not preclude the involvement of learning processes later in development. In fact, some argue that evidence of imitative ability diminishing over the first few months (Ferrari et al., 2006; Fontaine, 1984) suggests that neonatal imitation may be a specific adaptation for early bonding and a different imitation faculty develops later to facilitate learning (Oostenbroek, Slaughter, Nielsen, & Suddendorf, 2013). There are few studies of the development of imitation in infancy, a deficiency that Jones (2007) attributes to the widely held belief that infants imitate from birth, however, early work in the field of developmental psychology suggested imitation develops with time.

Before Metlzoff and Moore’s seminal work on neonatal imitation, Jean Piaget (1962) proposed a stage model of imitation that did not presuppose any innate imitative ability. By studying his own children Piaget described the development of imitation throughout the first two years. While no evidence of intentional imitation was noted in the first months of life, after six months, all of Piaget’s children imitated actions present in their behavioral repertoires that were not opaque to themselves. Subsequently, Piaget noted that imitation of opaque actions developed through practice, with imitation of sound-producing-actions (i.e., clapping) preceding other actions (Piaget suggested that sounds might act as indices that allow the mapping of an observed action performed by another onto the unobservable action performed by the infant; 1962). Before performing novel actions, Piaget’s children made approximate attempts at imitating these actions, and actions were only imitated when they were in some way analogous to actions already in the infant’s repertoire. In the second year, Piaget observed these imitative attempts become more exact but often retaining some level of gradual approximation, or training, before expert imitation was achieved. Finally, in the middle of the second year, more advanced imitative ability was noted, and Piaget described how the experimentation observed in the earlier stages became internalized, facilitating quicker imitation of novel actions. While the generalizability of these findings is limited by the preliminary nature of these case studies, this work is still the most detailed longitudinal account of the development of imitative ability in infancy, and suggests that the imitative faculty develops gradually.

More recent observations align quite closely with Piaget’s earlier reports. Jones (2007) conducted a cross-sectional study of imitative behavior in 162 infants from six months of age to 20 months. Eight actions were modelled by a parent and were categorized according to certain properties, including whether the actions were visible when being performed, or whether the actions produced a sound. Reliable imitation of any kind was not identified at six months, and actions that produced sounds were first imitated between eight and 12 months of age. Actions that were silent and unobservable by the infant performing them were the final actions to be reliably imitated (interestingly, one of these actions was tongue protrusion which was not imitated reliably until 16 months). Other studies support the idea that imitative ability develops throughout the 2nd year. Nielsen and Dissanayake (2004) found that infants start imitating synchronous actions around 18 months of age. Masur and Rodemaker (1999) found that at one year of age infants are already imitating actions performed on objects, but that intransitive actions only begin to be imitated consistently at around 17 months. These findings paint a different picture of imitation in infants and how it may develop throughout infancy. Regardless of whether imitation is innate or learned it is clear that imitation in the first years of life is limited in its diversity, however, by the age of three it is widely recognized that children are highly competent imitators, often over-imitating unnecessary actions to achieve outcomes (Horner & Whiten, 2005; McGuigan, Whiten, Flynn, & Horner, 2007; Piaget, 1962). If imitation develops throughout infancy, it is necessary to explain what shape this learning may take.

The Associative Sequence Learning (ASL) approach was developed by Ray and Heyes in 2000 to describe the cognitive process facilitating imitative learning, and this model has subsequently been adapted to describe the development of mirror neurons (Catmur, Walsh, & Heyes, 2009; Heyes, 2010; see also ideomotor theory which has been descibed as being largely compatible with the ASL view, e.g., Brass & Heyes, 2005). The ASL theory proposes that an imitator develops links between sensory and motor representations of actions through experience. This experience occurs whenever sensory and motor representations are available at the same time, for example, when someone performs an action they can see, or during synchronous social interactions (Heyes & Ray, 2000). These sensory-motor associations are created prior to imitation, and facilitate imitation when an action is observed at a later time. Other stimuli may facilitate the link between sensory and motor action units, for example, the vocalized word “smile” may become associated with both the performance of a smile and the observation of someone else smiling, facilitating an indirect association between sensory and motor representations of an action (analogous to the indices described by Piaget). It may be that this indirect route to forming an association might be especially important when an action is opaque (e.g., facial expressions). More recently, the ASL approach has been applied to explain mirror neurons where sensory and motor representations are instead discussed as sensory and motor neurons (Heyes, 2010). Connections between neurons develop through sensorimotor experience and after an association has been created a motor neuron may fire solely upon seeing an action being performed. This model is gathering empirical support from studies of adult humans through the analyses of automatic imitation effects.

Automatic imitation is a stimulus-response compatibility effect that is detected when the presentation of an action stimulus (e.g., a picture of a hand opening) facilitates the performance of that action and interferes with the execution of an opposite action (e.g., closing a hand; for a review see Heyes, 2011). This automatic imitation effect may be a behavioral indicator of the associations between sensory and motor representations of an action (or mirror neuron activity), and the effect has been reliably identified in a number of studies (e.g., Boyer, Longo, & Bertenthal, 2012; Brass, Bekkering, Wohlschläger, & Prinz, 2000; Heyes, Bird, Johnson, & Haggard, 2005; Stürmer, Aschersleben, & Prinz, 2000). Automatic imitation has been employed to test assumptions of the ASL hypothesis (Heyes et al., 2005; Press, Gillmeister, & Heyes, 2007). For example, a number of studies have demonstrated automatic imitation effects are reduced significantly or reversed following training sessions where participants are required to respond to action stimuli with incompatible actions (e.g., closing their hand upon seeing a hand open; Gillmeister, Catmur, Liepelt, Brass, & Heyes, 2008; Heyes et al., 2005). Similar results have been noted in studies of mirror neuron activity (Catmur et al., 2008; Catmur, Mars, Rushworth, & Heyes, 2011). For example, Catmur and colleagues (2008) found that after training participants to move their foot after seeing a hand move (and vice versa), activation in brain areas associated with mirror neuron function for specific actions (e.g., hand movement) were activated by seeing moving images of the other effector (e.g., foot movement). This suggests that experience of contiguous sensory-motor activity forges connections between representations of actions that can be observed at the neurophysiological level, even if the sensory and motor actions are different. Support for the ASL model is growing based on experimental studies with adults; however, for the model to be useful it must take into account the real social experience of infants and children, and explain whether this experience can facilitate the development of imitation.

A crucial aspect of the ASL approach to imitation is that experience is essential for connections between sensory and motor representations to form, and while this has been explored in laboratory settings through training protocols (Gillmeister et al., 2008; Heyes et al., 2005) it is less clear whether this type of experience is common in an infant's environment. A few studies have examined imitation of both parents and infants in naturalistic play settings. Pawlby (1977) observed mother-infant interactions between the ages of four and eight months and found that approximately 16% of interactions involved some form of imitation by the mother. More recently, Kokkinaki and Vitalaki (2013) found that three to four imitative interactions (including both actions and vocalizations) took place every ten minutes between caregivers and infants with children aged two to 10 months, with 66-79% of imitative interactions performed by the caregiver. Similarly, parents have been found to imitate a child's vocalization once every four to five minutes (Kokkinaki & Kugiumutzakis, 2000), and an earlier study reports that 41-57% of non-cry vocalizations were matched between infants and mothers, primarily driven by mothers imitating infants (Papousek & Papouskek, 1989). While this research demonstrates that a substantial amount of synchronous and imitative experience takes place during an infant’s development, some authors have questioned whether the experience observed in free-play scenarios is adequate for the development of imitative ability (Simpson et al., 2014). Nevertheless, knowing that imitative or synchronous experience occurs during infancy the next step is to observe the effect of this type of interaction on behavior.

In the current study we aimed to test specific predictions of the ASL approach with children. Taking inspiration from previous studies of automatic imitation in adults and animals (Range, Huber, & Heyes, 2011; Stürmer et al., 2000) a method for assessing behavioral phenomena similar to automatic imitation in children aged between three and seven was developed. The decision to study children already possessing imitative ability was largely due to a methodological necessity; in this study children were required to perform different actions after seeing an action stimulus, and previous studies have found that young children (aged three-four) struggle with this task (see pilot study reported in Simpson & Riggs, 2011). The task used in this study required participants to make one of two actions in response to an action performed by an experimenter. Four different actions were used: hand clapping, hand waving, hand closing (i.e., making a fist), and finger pointing. One game required participants to clap or wave, while the other game required participants to create a fist or point. In compatible conditions participants were asked to respond with the same action as the experimenter, and during incompatible conditions they were asked to perform the opposite action. Each participant experienced all iterations of the game. We expected strong stimulus-response compatibility effects as suggested by previous research on automatic imitation (Brass, Bekkering, & Prinz, 2001; Stürmer et al., 2000), however, the primary aim of our study was to predict specific automatic imitation effects based on the ASL hypothesis.

Note, we describe the stimulus-response compatibility effects under investigation in this article as *automatic imitation*, however, this term, as defined in the broader cognitive literature, is operationally different, occurring only when compatibility effects are influenced by task-irrelevant stimuli; that is, when participants are required to respond discriminatorily to non-action stimuli (e.g., shapes, colors, etc.), and so compatibility effects induced by task-irrelevant action stimuli are "automatic" in the sense of being unrelated to the task-requirements. In the current study, on the other hand, the stimulus-set and response-set are the same (i.e., children respond with action responses to compatible or incompatible action stimuli), and so the compatibility effect cannot be said to be automatic in the same sense. In the comparative literature, however, the term automatic imitation is used more broadly, and also refers to contexts where animals learn to respond to action stimulus-response associations more easily when the stimulus (e.g., a hand action) is congruent with the reinforced response (e.g., a paw action; Range, et al., 2011; Mui, Haselgrove, Pearce, & Heyes, 2008). The compatibility effects examined in the current study, while operationally different from the adult and comparative literature, still relate specially to the imitative domain (i.e., action and response sets consist of the same actions), and any delays or mistakes caused by the task-instructions will be unintentional. Furthermore, we predict that underlying mechanism resulting in the any potential differences across action-sets observed in our own study would be the same as those mechanisms driving the effects found in adult studies, and therefore we chose to use the same term, automatic imitation, when describing this stimulus- response compatibility effect.

The action sets used in this study were chosen based on two criteria. First, all actions had to be simple to perform. Second, it was expected that children would have more experience of performing two of the actions in a socially synchronous or imitative context. To our knowledge, no previous study has described the frequency of specific synchronized behavior in childhood and therefore these actions were chosen through a thoughtful consideration of actions regularly imitated during social interactions. Clapping and waving, for example, are performed socially during applause and when saying goodbye respectively. Indeed, clapping specifically is often described as occurring in a group context (e.g., Repp, 1987). On the other hand, pointing and making a fist are not socially synchronous or imitated behaviors. While a rich literature describes the varied function of pointing as a communicative gesture (e.g., Kita, 2003; Tomasello, Carpenter, & Liszkowski, 2007) this gesture is seldom, if ever, described as occurring in imitative contexts. Rather, a typical interaction involves the use of language and results in a social partner's attention being guided towards a referent (Butterworth, 2003).

Our first prediction based on the ASL approach to imitation is that automatic imitation effects (i.e., the difference in reaction time between imitating actions and performing different actions) will be greater for actions that have been performed in synchrony in past interactions. The ASL approach predicts that external stimuli may facilitate the association of visual and motor properties of an action. We may then predict that an automatic imitation effect may be stronger for an action that produces other non-visual stimuli. The only action that produces a non-visual stimulus is clapping which also produces sound, and so we predict that the automatic imitation effect will be greatest for this action. Finally, if automatic imitation effects develop through imitative or synchronous experience, it follows that short periods of counter-imitative experience preceding imitation trials will increase reaction time when imitating. If this is the case we should find that when incompatible experimental trials precede imitative trials that automatic imitation effects will be suppressed. It is difficult to predict whether, or how, age might affect automatic imitation. For example, it might be expected that cumulative effects of social sensorimotor experience throughout development might facilitate quicker reaction time on imitative trials in older children while making it more difficult to inhibit imitative responses during counter imitative-trials; this might lead to an increase in automatic imitation through development. However, children get better at inhibiting imitative responses as they develop (Simpson & Riggs, 2011), which may lead to quicker reaction times when counter-imitating, subsequently reducing automatic imitation effects in older children. These developmental effects together may cancel themselves out leading to a stable automatic imitation effect throughout development with overall quicker reaction times for both imitative and counter-imitative responses. Due to the uncertainty over the direction of these effects, age related variation will be examined without a priori hypotheses.

Methods

Participants

Participants were 101 children aged between three and seven. Twenty-nine participants were excluded from the analyses for either not finishing the research session, for not performing more than 60% correct responses in any one of the four conditions, for not paying attention to the experimenter during the stimulus presentation, or for having parents or guardians interfere in their responses (mean age of excluded participants = 4.33 years, standard deviation, SD = 1.24 years). Seventy-two participants were included in the initial analysis; mean age was 5.74 years (SD = 1.29 years) and 39 participants were female (see analysis section for further information in inclusion criteria). Participants were recruited at the XXXX, UK in July 2013, and voluntarily completed research sessions for rewards of stickers. Ethical approval was granted by the University of XXXX ethics committee for the project titled “Automatic imitation in children”, and consent was given by the child’s parent or guardian before the session began.

Design

Over the course of a research session four different games were played using two different sets of actions. For two of the games, participants had to produce actions that are commonly imitated or performed in synchrony during social interaction (we will refer to these actions as the Commonly Imitated Set, or CIS). The actions chosen for the CIS were “wave” and “clap” (see Figure 1, A-B), as children are likely to clap their hands in synchrony during applause, and waving is also a socially synchronous behavior performed when waving goodbye. The actions performed in the other action set (which we will call the Rarely Imitated Set, or RIS) were “point” and “fist” (see Figure 1, C-D), as these actions are not considered to be socially-coordinated.

Using a stimulus-response compatibility paradigm two different games were played with each action set; both games required the participant to respond to the actions performed by the experimenter. One game required the participant to watch the actions of the experimenter and respond with the same action (compatible response rule), and the other game required the participant to perform the alternate action (incompatible response rule). To be included in the analysis a participant had to complete both actions sets with both response rules.

Procedure

During a research session the experimenter and participant sat facing each other across a table. Two sheets of A4 paper were attached to the table in front of both the participant and the experimenter (see Figure 1). At the beginning of the session the experimenter explained that a game was to be played and to begin the child must place their hands flat on the sheet of paper.

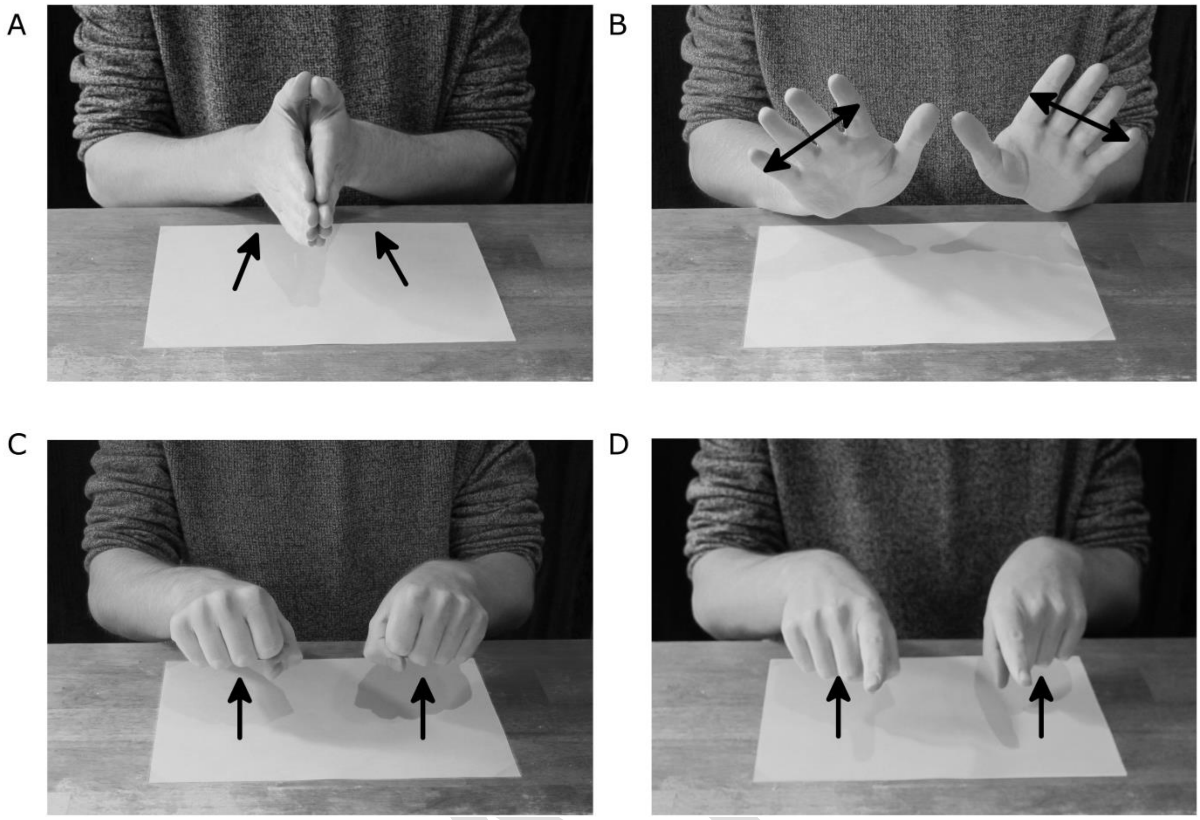

Figure 1. Action stimuli used in study; arrows indicate movement. Actions A (clap) and B (wave; note that an open hand wave was always demonstrated) are part of the commonly imitated set of actions while actions C (fist) and D (point) made up the rarely imitated action set.

The experimenter demonstrated the two actions to be performed in the first game and asked the participant if they were also able to perform each of the two actions: E.g., “Can you wave your hands like this”. Next, the experimenter explained the response rule for each of the two actions and asked the participant to demonstrate a response: E.g., “In this game if you see me wave my hands (*experimenter waves his hands*), you do the different action, the opposite action, and you clap your hands (*experimenter claps his hands*). So, if I do this (*experimenter waves his hands*) what do you do?” After explaining the response rules for both actions the participant’s understanding of the rules was tested by asking the child to respond to both actions in order. If the participant performed an incorrect response the rules were repeated and a further two trials tested comprehension. Correct responses during this pre-test phase were rewarded with verbal praise, and if both responses were correct the child progressed to the testing phase. If the child did not perform two consecutive correct responses after four pre-test trials the child progressed to the testing phase nonetheless. If these children passed the criteria for inclusion (see below), their data was included in the analysis.

The testing phase consisted of ten response trials presented in a pseudorandomized order. Children were told to react as quickly as possible. To begin a trial both experimenter and participant placed their hands flat on the sheet of paper; if the child did not have their hands on the paper they were prompted to do so (e.g., “hands flat”, “hands on the paper”). The experimenter would rapidly perform an action, return his hands to the starting position, and wait for the child to respond. During this testing phase correct responses were not praised and incorrect responses were not corrected by the experimenter. If an incorrect action was performed the experimenter would wait for approximately two seconds for the child to change their action. Between trials, children were encouraged to prepare themselves for the next trials with various verbal cues including “hands flat”, “ready”, and “next one”. After the tenth trial the child was praised for his or her performance, and told that the game was to be played again but with different rules. The procedure described above was then repeated but with the response rules reversed. After completing ten test trials with both response rules, the same overall process was repeated with the different action set. The order of the games was counterbalanced for both response rule and action set. However, due to the removal of some participants (see criteria below), for the CIS the compatible trials took place first for 35 of 72 participants, while for the RIS, 38 participants received the compatible condition first.

Video Coding

All sessions were recorded on a Sony CX405 camcorder, and each trial was coded frame-by-frame to measure reaction time. Each session was recorded at 25 frames per second (fps; interlaced), however, interlaced video allows for greater temporal resolution by overlapping adjacent frames to create a perceived resolution of 50 frames per second. The videos were coded at this higher rate of temporal resolution, and frame measurements were subsequently converted into second (s) measurements for analysis, and all measurements are reported to the nearest significant digit (i.e., 20 milliseconds).

To assess whether a participant had understood the rules we recorded how many correct responses the participant performed in each condition including trials where the participant may have initially performed the wrong action before quickly changing to the correct response (we included these corrected trials, as we felt that this change of action indicated that the child understood the rule for that trial). However, we also recorded the number of "mistakes" made per condition, considering both incorrect trials and corrected trials. We felt this measure better captured an automatic response to a stimulus, and therefore was relevant to the study of automatic imitation. This measure of mistakes was analyzed when examining automatic imitation effects.

A measure of reaction time started once an action was completed by the experimenter and ended once the completion criteria was met by the participant (see Table 1 for definitions of action completion), and these measures were kept consistent across all participants. Reaction time measurements were not taken for trials when an incorrect response was performed, whether this incorrect response was corrected or not. As actions were sometimes performed quicker by one of the participant's hands, the measurement of reaction time ended once the action was completed by one hand in the case of all actions other than clapping.

Table 1

Definitions used to begin and end a measurement of reaction time on a given trial.

Action	**Action Completion Criteria**
Wave	Hands first change direction of movement (i.e., if hands were moving inwards, measurement began once hands began moving away from each other)
Clap	Hands make contact.
Point	Pointing finger visibly extended from the rest of the fingers
Close hand	Fingers are closed and pressed into the palm

Data analyses

To be included in the analyses participants had to perform correct responses on 60% of trials within each condition. This criterion was used to ensure that each participant had understood the rules of each condition (see above). If the participant met this criterion, their total number of mistakes made per condition (i.e., across action set and response rule) was analyzed using a repeated measures ANOVA.

Reaction time (RT) was also examined. For each participant, an average RT score was calculated for each condition (i.e., CIS-Compatible, CIS-Incompatible, RIS-Compatible, and RIS-Incompatible), considering only RTs for correct trials. Trials where mistakes were made were not included, as were RTs that fell outside 2 SD of the mean RT for each condition. If, after excluding trials due to mistakes and outlying RTs, there were less than six data-points for each of the four conditions the participant's data was not included in the RT analysis. Overall, data from 55 participants was analyzed (mean age = 5.86; SD = 1.31). These inclusion criteria were set to ensure that the average RT for a given condition was representative of an unbiased response on each condition of the task. To examine the effect of rule-order, a measure of automatic imitation was calculated for each action set, taking the average RT in the compatible condition and subtracted it from the average RT in the incompatible condition. Correlations between age and automatic imitation effects for both actions, as well as average RT for each condition were also examined.

Automatic imitation effects were also calculated for each of the four actions (i.e., the difference in reaction time to specific action stimuli when responding in compatible or incompatible conditions), except in this case, as each participant responded to five presentations of each stimulus in each condition, the criterion for inclusion was three or more correct responses to each stimulus in each condition. Overall, data from 43 participants was analyzed (mean age = 5.95, SD = 1.27). Again, this inclusion criterion helped establish that RTs were representative of participant's response to a given action stimulus, however, note that this average score will in each case be based upon only three to five responses.

To examine RT data from all 72 participants, a complementary analysis was performed with RT on each trial examined using a Linear Mixed Model (LMM) with participant and condition (i.e., action set/response rule) included as random effects to account for repeated observations within participants. This additional analysis was performed to examine interactions between dependent variables and to demonstrate that when all variables are included in the same analyses (in comparison to the individual analyses reported below) that the same general findings hold. This analysis and the model details can be found in the supplementary materials.

Statistical Software

All statistical analyses were performed using SPSS 23 and R (R Core Team, 2014; we used the Rstudio environment; RStudio Team, 2014), and all figures were created using the ggplot2 package in R (Wickham, 2009). The LMM was developed using the “lme4” package (Bates et al., 2015), and Wald chi-square tests for this model was calculated using the “car” package (Fox et al., 2016).

Results

Overall Automatic Imitation Effects

To examine the overall effect of the two response rules and two action sets on mistakes, a 2X2 repeated-measures analysis of variance (ANOVA) was performed with all 72 participants. A main effect of response rule was identified (F(1, 71) = 21.28, p <.001; η_p^2= .23) with an estimated 0.72 fewer mistakes made when responding with compatible responses (standard error, SE = 0.16, CIs= 0.41 – 1.02). Also, a main effect of action set was found (F(1, 71)= 51.18, p <. 001; η_p^2 = .42) with an estimated 1.17 more mistakes (SE = .16; CIs = .85 – 1.50) in the RIS (M = 2.08) when compared with the CIS (M = 0.90). An interaction between action set and response rule was not identified (F(1,71) = 0.20, p = .657; η_p^2 < .01).

A 2X2 ANOVA examined the effect of condition on reaction time (RT) using data from the 55 participants that reached the inclusion criteria (see data analysis section above for details; also, see the Supplementary Materials for a Linear Mixed Model examining trial RT with all 72 participants). A main effect of response rule was identified (F(1, 54) = 350.65, p <.001; η_p^2 = .87) with compatible trials performed an estimated 0.56 s quicker on average than incompatible trials (standard error, SE = 0.02, CIs = 0.50 – 0.62). A main effect of action set was also found (*F*(1, 54) = 5.57, *p* = .022; η_p^2= .09) with an estimated mean difference of 0.06 s (SE = 0.02; CIs = 0.01 – 0.12) between the CIS (M = 1.10 s) and the RIS (M = 1.04 s). A significant interaction between action set and response rule was also identified (*F*(1, 54) = 22.08, *p* < .001; η_p^2= .29), suggesting automatic imitation (i.e., RT difference between compatible and incompatible responses rules) varied across action set; indeed, the average automatic imitation effect in the CIS was 0.66 s, and 0.44 s in the RIS. Examining these differences further, we found that compatible responses were not significantly quicker in the CIS (M = 0.76 s) when compared to those in the RIS (M = 0.80 s; *t*(54)= -1.18, *p* = .242), however, incompatible responses in the CIS (M = 1.42 s) were significantly slower than those in the RIS (M = 1.26 s; *t*(54)= 4.31, *p* < .001; see Figure 2).

Stimuli Effects

To examine the automatic imitation effects associated with specific action stimuli we subtracted average RT for compatible responses from average RT for incompatible responses for each action. Comparing these automatic imitation effects, we identified a significant effect of stimulus (*F*(2.67, 112.29) = 11.37, *p* < .001; η_p^2= .21; Mauchly's test indicated that the assumption of sphericity was violated so degrees of freedom were corrected using Huynh-Feldt estimates, ε = .89). Post-hoc comparisons with Holm-Bonferroni corrections identified that the automatic imitation (AI) effect for the clap stimuli (M = 0.72 s, SE = 0.06) was significantly greater than the AI effect for the wave (M = 0.58 s, SE = 0.04; p = .046), point (M = 0.46 s, SE = 0.04; p <.001), and fist stimuli (M = 0.44 s, SE = 0.04; p < .001). Waving stimuli resulted in a significantly greater AI effect when compared with fist stimuli (*p* = .036), and point stimuli (*p* = .036), and there was no difference in AI effect between the point stimuli and fist stimuli (*p* = .755).

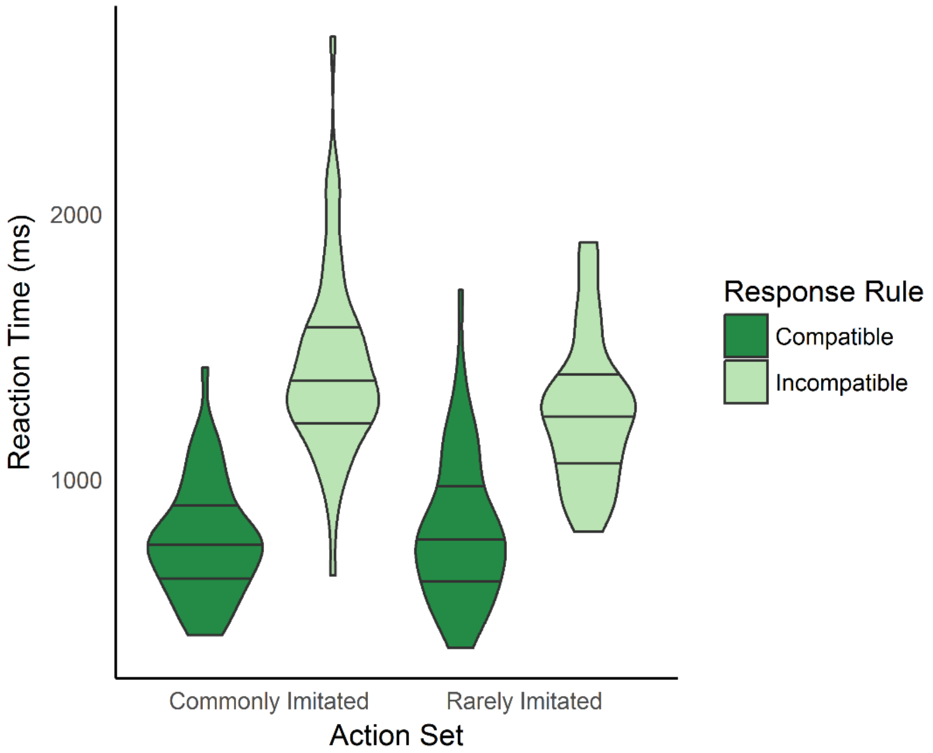

Figure 2. Violin plots for each response rule (Compatible and Incompatible), for each action set (Commonly Imitated Set and Rarely Imitated Set). Horizontal lines represent the median and interquartile range for each condition and the width of the plot represents the kernel probability density of the data for each condition.

To examine what was driving these AI differences we examined RTs for compatible and incompatible responses for each stimulus separately. We performed two one-way repeated measures ANOVAS, one for compatible rules and one for incompatible rules, with action stimulus as the independent variable. In both cases, Mauchly's tests indicated that the assumption of sphericity was violated ($X^2(5)_{\text{compatible}} = 42.40$, $p < .001$; $X^2(5)_{\text{incompatible}} = 22.83$, $p < .001$), so degrees of freedom were corrected using Greenhouse-Geisser estimates for both compatible actions ($\varepsilon = .58$) and incompatible actions ($\varepsilon = .74$; see Field, 2016). We found no significant effect of stimulus type for compatible responses ($F(1.75, 73.65) = 2.30$, $p = .114$;

η_p^2 = .05; see Figure 3), but a significant effect of stimulus type for incompatible responses (F(2.21, 92.64) = 9.15, p < .001; η_p^2= .18, see Figure 3). Note that while this might suggest that incompatible trials are driving the automatic imitation effects, these individual action comparisons cannot explain the effect given baseline performance times for actions may vary based upon motoric difficulty, for example. Thus, conclusions based upon these comparisons are speculative.

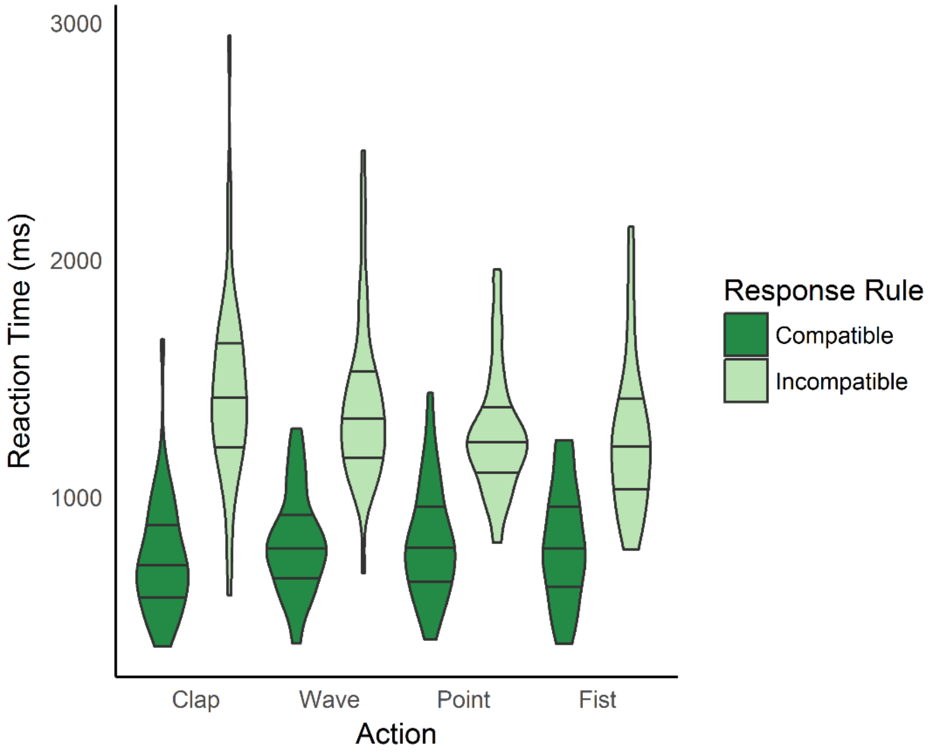

Figure 3. Violin plots representing RTs to each response rule (compatible and incompatible) for each action stimulus. Horizontal lines represent the median and interquartile range for each condition and the width of the plot represents the kernel probability density of the data.

When responding with incompatible actions, post-hoc tests with Holm-Bonferonni corrections identified significantly slower average RTs to clap stimuli (M = 1.46 s, SE = 0.06) when compared with point (M = 1.26 s, SE = 0.04; *p* = .010) and fist stimuli (M = 1.24 s, SE = 0.04; *p* < .001). Incompatible responses to wave stimuli (M = 1.40 s, SE = 0.06) did not significantly differ in comparison to average RTs to clap stimuli (*p* = .308), but were significantly slower than responses to point (*p* = .033) and fist stimuli (*p* = .016). No RT differences were found in incompatible responses to point and fist stimuli (*p* = .483).

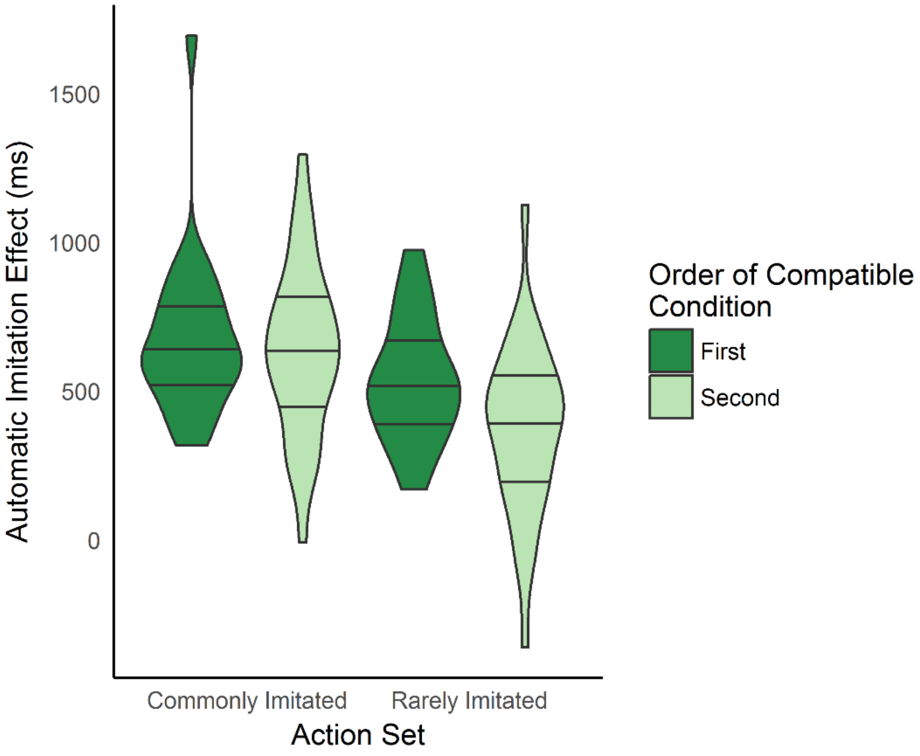

Figure 4. Violin plots representing the automatic imitation effect (i.e., difference between average RT in the incompatible and compatible conditions) for each action set (Commonly Imitated Set and Rarely Imitated Set), when compatible rules are performed first, and second. Horizontal lines represent the median and interquartile range for each condition and the width of the plot represents the kernel probability density of the data for each condition.

Order Effects

We examined whether the order that response rules were completed had an effect on automatic imitation by comparing the automatic imitation effects found when compatible responses were performed first and when they were performed second. For the CIS, we found no significant difference in AI effects dependent on whether compatible responses were performed first (M = 0.68 s, SE = 0.06), or second (M = 0.64 s, SE = 0.06; $t(53) = 0.48$, $p = .632$; *Cohen's d* = 0.13; see Figure 4). However, for the RIS, when compatible responses were performed first, the AI effect (M = 0.54 s, SE = 0.04) was significantly larger than when the compatible responses were performed second (M = 0.38 s, SE = 0.06; $t(53) = 2.35$, $p = .023$; *Cohen's d* = 0.64; see Figure 4). However, comparing the effect-sizes from these two tests identifies no significant difference between these results (Z= 1.32, p = .188). Furthermore, when a three-way interaction between the automatic-imitation effect, order of rules, and action set was examined using a Linear Mixed Model, a significant interaction was not found ($X^2(1) = 2.21$; p = 0.137; see Table 1, Supplementary Materials), again, suggesting that while order effects are different across conditions, this difference is not statistically significant.

Age effects

Age was not significantly correlated with AI effect in either the commonly imitated action set ($r = -.11$, $p = .432$) or the rarely imitated action set ($r = .06$, $p = .681$), and any difference between AI effects (calculated by subtracting a participant's AI effect in the RIS from the CIS effect), similarly, did not vary across age ($r = -.14$, $p = .311$). RTs to compatible rules in both action conditions quickened with age ($r_{cis} = -.50$, $p < .001$; $r_{ris} = -.45$, $p < .001$; see Figure 5), and similarly, incompatible responses quickened with age ($r_{cis} = -.40$, $p = .003$; $r_{ris} = -.39$, $p = .004$; see Figure 5). As all RTs were strongly correlated with age, we performed a correlation between AI effects for both action sets and age while partialling out the effect of a participant's mean RT performance; we found no relationship between age and the AI effect for the commonly imitated set (*r* = .20, *p* = .158), or rarely imitated actions (*r* = .07, *p* = .629).

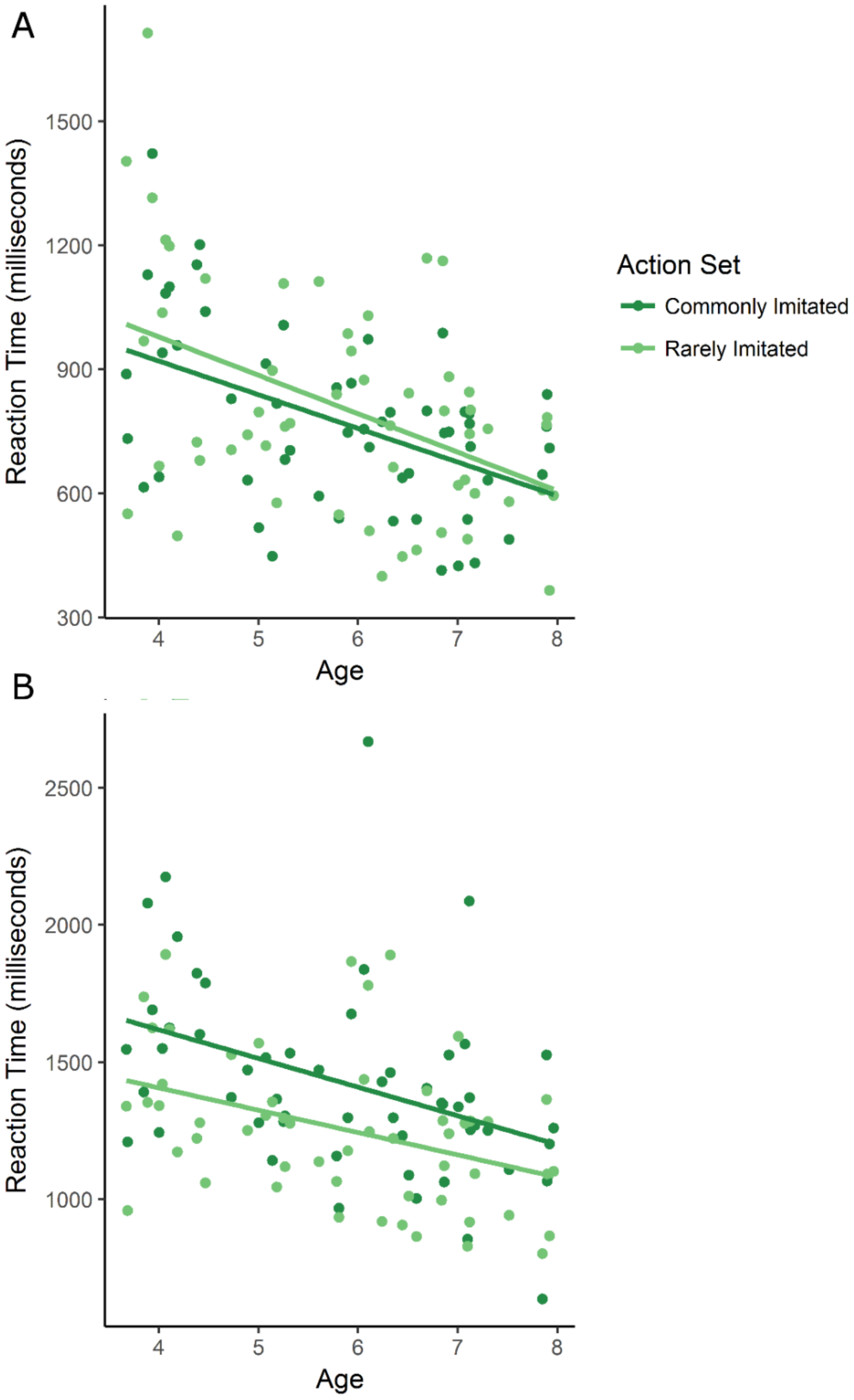

Figure 5. Participant’s average reaction time as a function of age when responding in (A) compatible trials and (B) incompatible trials for both commonly imitated actions (dark green/grey) and rarely imitated actions (light green/grey). Lines represent the linear regression lines for the predicted effect of age on reaction time for each condition and action set.

Discussion

This study of automatic imitation specifically tests predictions of the ASL model of imitation in children. Unsurprisingly, given the impressive imitative skills of children from the age of three we found a significant automatic imitation effect for both sets of actions when examining reaction time (see Figure 2), and the number of mistakes made in each condition. However, it is the difference in automatic imitation effects between action sets that is of the most interest. The ASL model, as well as the ideomotor approach (Brass & Heyes, 2005), predicts that associations between sensory and motor representations of actions are formed through experience and so actions that receive more of this particular type of sensorimotor experience should be quicker to imitate and more difficult to inhibit. Commonly imitated actions were not imitated quicker than rarely imitated actions overall, however, incompatible responses to commonly imitated actions were significantly slower than incompatible responses to rarely imitated actions. This resulted in a significantly greater automatic imitation effect in the commonly imitated set when examining reaction times. However, note that while this result may suggest that incompatible trials are driving the AI effect, as each action has its own level of motoric difficulty, this may not be the case; for example, a clap may take longer to complete than a point in general, however, when imitating, the advantage granted clapping may be greater than that afforded pointing and so RTs are instead comparable in this condition). This finding supports an experiential account of imitation, demonstrating that inhibition of a learned imitative response varies in line with predictions of previous social sensorimotor experience.

Overall, more mistakes were made when participants were required to respond with incompatible actions, and more mistakes were made when responding to rarely imitated actions. However, there was no interaction between response rule and action set, suggesting the automatic imitation effect measured in this context did not vary in line with predictions of synchronous experience. While inconsistent with the reaction time analysis, the failure to find a significant effect here may be driven by a tradeoff between speed and accuracy that is found in choice reaction-time paradigms (Wood & Jennings, 1976). Also, it is unclear why more mistakes were made overall in the rarely imitated set, but as the reaction time analyses only considered correct trials, this difference is unlikely to impact these findings.

Further evidence in support of a domain-general account is provided by our finding that the greatest automatic imitation effect was found when responding to clapping stimuli, an observation that is predicted by the ASL model's account of environmental stimuli facilitating the connection between sensory and motor representation of an action. Environmental stimuli are thought to bridge cognitive representations in cases where actions may not provide sensory feedback (Ray & Heyes, 2011); and in cases where sensory information is available, auditory stimuli may act to provide a more complex network of associations. This interpretation corresponds with evidence of audio-visual mirror neurons identified in monkeys that fire when performing an action, seeing an action, and hearing an action (Keysers et al., 2003). If automatic imitation is indeed a behavioral effect of mirror neuron activity formed through associative processes, we may expect this more pronounced effect when motor actions have become associated with multiple stimuli over different modalities. Other actions performed in this study also involve the proprioceptive modality of course, but only when performed. Clapping on the other hand, incorporates both the visual and auditory sensory modality during performance as well as social perception. While it is known that reaction times to multisensory stimuli are quicker than reaction times to a single stimulus (Andreassi & Greco, 1975;

Hershenson, 1962), here, we see differences in automatic imitation effects driven by slower reaction times when responding with an incompatible action suggesting a compatibility-specific effect. If reaction times were quicker for both compatible and incompatible trials, we could conclude that bimodal stimulation alone may drive this stimulus specific effect, however, here we see an interaction between bimodality and compatibility. To our knowledge, studies of bimodal stimuli presentation have not examined the inhibition of a prepotent response to a bimodal stimulus but if associative processes underlie advantages when responding to bimodal stimuli in reaction paradigms, we would predict that responses would be more difficult to inhibit when compared to a unimodal case. Also, it may be possible that of all the actions used as stimuli, clapping is by chance the action performed in synchrony the most often, leading to the observed effect. This interpretation, while compatible with the ASL view of imitation, incorporates a conceptually different mechanism. Future studies could easily differentiate between these two interpretations by manipulating the degree of experience participants receive as well as the degree of intermodal sensory information available during learning and subsequent inhibition of responses to novel associative stimuli. This protocol could isolate the role of both experience and stimulus complexity in imitative learning.

Partial support for the ASL view of imitation is found when examining the effect of counter-imitative experience preceding imitative action. Overall, it was found that a short session of counter-imitative training significantly reduced the automatic imitation effect for rarely imitated actions but not for commonly imitated actions. Previous research has eliminated automatic imitation effects entirely through counter-imitative training (Heyes et al., 2005), while here we merely reduce it. However, the training received in this study (approximately 12 trials including practice trials) is not comparable to the training in other studies (e.g., 6 blocks of 72 trials, Heyes et al., 2005). While simple order effects are common in experimental paradigms of this sort, we feel it is important to highlight that imitative compatibility effects are not immune to such effects. Furthermore, while we didn’t predict that the order of response rule would vary across actions sets, this finding is consistent with an experiential account, as an automatic imitation effect might be resistant to counter-imitative experience when strong sensory-motor associations have been formed. However, it is important to note that while an order effect was only found for automatic imitation effects in the rarely imitated action set (see Figure 4), this effect was not significantly different from the null result found in the commonly imitated set, and so conclusions concerning this difference are speculative.

While older participants responded more quickly for both response rules within each action set, no change in automatic imitation was found over development. This is not necessarily surprising. As previously mentioned, based on the ASL approach one might predict that an automatic imitation effect would increase with age as cumulative experience would lead to increased inter-representational connectivity. However, in the paradigm explored here we are dealing with two effects: An imitation effect and an inhibitory effect, since reacting to an action stimulus with a different action necessitates the inhibition of imitation. Previous studies of inhibition in children have found that the ability to inhibit prepotent responses increases with age (Simpson & Riggs, 2011). With this in mind, as children age we might expect that experience would contribute to greater sensorimotor co-ordination resulting in quicker reaction times in imitative trials, and developing inhibitory control should reduce reaction times when responding to incompatible stimuli. If this is the case it is not surprising that we see a consistent automatic imitation effect throughout development. It could be argued that the automatic imitation effect reported here is solely a result of a higher memory load required to react to incompatible rules (i.e., the “different action” has to be remembered for an incompatible rule, while this information is readily available in the stimulus in the compatible condition). Indeed, under the present paradigm automatic imitation is likely to function in conjunction with working memory and other inhibitory effects, but as this study is more orientated towards examining the extent of automatic imitation across different contexts where memory load and inhibitory context are kept constant, we believe this interaction does not affect our conclusions. Nonetheless, future studies with children should attempt to isolate automatic imitation effects.

It could be argued that the effect of action-set on automatic imitation is driven solely by the fact that one action in the CIS produced a sound, while neither action in the RIS produced sound. Under this interpretation, the difference in automatic imitation observed between sets is not driven by previous experience of synchrony but by an interaction between action- and sound-compatibility. While a valid observation, a similar argument could be made for any perceptual feature unique to a specific action, and in this study we did not aim to, and could not, control for every perceptual feature across actions sets, and indeed, retaining ecological validity of actions was an important goal of this study. Nonetheless, if a discrepancy in sound production was the sole driver of the stronger compatibility effect in the CIS, this would be an important example of how action planning is strongly inhibited when the sound, and indeed absence of sound (in the case of the wave stimulus), does not correspond with the sound produced by an action to be performed, and more work is needed for this effect to be fully understood. However, even if sound-compatibility was the primary driver of the difference across action-sets, the initial development of a link between the perceptual and motor representations of an action (so called event codes, see Hommel, 2004; or common codes, see Prinz, 1997) would be facilitated by the previous experience of that action in both asocial and social contexts. The performance of an action in synchrony with others, for example, would help develop a richer stimulus-set with which to facilitate action planning at a later stage, and sound production would just be one element of the event code. Sound-compatibility may be an important driver of this compatibility-effect, even potentially the sole driver, however, it is not possible to disentangle the effect of previous experience of synchronous action from specific stimulus-components of an action (e.g., sound) from this data. Only future empirical work with this paradigm will identify the impact of each stimulus-element on these compatibility effects and how prior social experience interacts with these stimuli-effects.

It is important to note here that the theoretical perspectives that account for action planning in the asocial domain described by Prinz (1997) and others (e.g., Hommell, 2004), are largely consistent with the account that examines this effect in the social domain (e.g., the ASL approach to imitation). In fact, following from this perspective, it could be argued that different automatic imitation effects are driven by the mere frequency of action performance, rather than social experience (e.g., imitative or synchronous action). Indeed, an experiential view of imitation does not necessarily require experience to be social in nature. For example, associations between sensory and motor representation of the same actions can develop through self-observation (Heyes, 2011). While to our knowledge there is no observational work comparing the baseline frequency of different actions performed by children, we cannot think of a reason for why a simple action like the closing of a hand or a frequently used communicative gesture like pointing (Cochet & Vauclair, 2010), would be performed less often than waving or clapping. Importantly, the differences identified in this study are not solely related to the motor performance of these actions but the sensory context preceding their performance which is specifically social in nature, and so these results are directly applicable to the domain of social imitation, rather than action performance alone.

We acknowledge that a limitation of our study is that our assumptions regarding previous social experience were not based upon observations of adult-child or peer interactions, but instead, upon a priori consideration of specific behaviors that are known to be coordinated in time through social convention. As mentioned in the introduction, clapping (as performed in applause for example) and waving (as performed as a greeting/departure display) have specific social significance in the country where this study was performed that will lead to actions being performed synchronously (or at least, resulting in these actions being temporally clustered), while hand closing and pointing gestures do not occur in this socially synchronous context, at least in the same extent. For example, to our knowledge, there is no cultural-practice in the UK of pointing in synchrony with others, and descriptions of pointing in the developmental literature define pointing occurring in communicate contexts where copying or synchronous action is not typical. We acknowledge that in a communicatory context a complementary pointing action may be used to clarify a specific referent, but a pointing bout is likely to end once the goal of the gesture has been completed (i.e., once attention has been guided to a referent). However, this is an empirical question that should be examined through naturalistic observational, and future work should examine a broader range of behaviors and the social contexts in which they occur in normal interaction. Indeed, this observational work could inform specific predictions concerning imitation effects across actions, and allow further testing of key predictions of an experiential approach. Further, to complement this ecological approach to the development of imitative ability, experimental avenues could manipulate levels of synchronous experience before testing imitative ability in children. This experimental perspective has had some success in revealing the importance of experience in automatic imitation in adults (Catmur et al., 2008; Press, Gillmeister, & Heyes, 2007), but this role in children has yet to be thoroughly explored.

While early work in the field of developmental psychology presented a detailed description of the development of imitation in infancy (Piaget, 1962), recent work on this subject is sparse. It is crucial to consider developmental approaches to imitation as even an innate imitative system must interact with the environment to generate adaptive behavioral responses. From this perspective an associative model complements innate dispositions. In fact, to account for the vast difference in imitative ability between humans and other animals (e.g., Whiten, Horner, & Marshall-Pescini, 2005) the ASL account must recognize innate differences in motivation or attention to account for the unique routes human development takes (Heyes, 2012). The strength of a good theory rests on the reliability and validity of its predictions. There is no doubt that the ASL model of imitation has need for further empirical support, but converging evidence from cognitive (Heyes et al., 2005), neuroscientific (Catmur et al., 2008), comparative (Range et al., 2011), and now developmental fields suggests that this model is reliable in varied contexts. For a thorough understanding of the development of imitation, future research should examine the predictive power of this model in younger children that are still developing their imitative skills. This study marks a first step towards realizing that goal.

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