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Cognitive development of imitation of intransitive gestures: an analysis of hand and finger errors

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ABSTRACT

The dual-route model proposes that imitation of meaningful gestures relies on a lexical route whereas imitation of meaningless gestures relies on a sub-lexical route. The aim of the present study was to investigate the development of imitation of intransitive meaningful and meaningless gestures in children from 6 to 9 years old by exploring hand and finger errors. Despite lower performance, children showed similar patterns than adults with better imitation of meaningful compared to meaningless gestures. Concerning body part errors, children made more errors than adults. Moreover, children produced more hand errors than adults for meaningful gestures whereas they were no difference for meaningless gestures. These results suggest that the two routes are present but are still maturing. Moreover, several specific and non-specific factors may have impacted imitation skills. Further studies are needed to disentangle the role of these factors in imitation of intransitive gestures during development from childhood to adulthood.

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Imitation; intransitive gestures; lexical route; sub-lexical route; development

1. Introduction

Among all the actions performed by humans, the literature classically distinguishes between transitive/object-related actions (e.g. hammering) and intransitive actions, which do not involve objects but typically convey communicative content (e.g. waving goodbye). Intransitive actions are separated into meaningful (MF) and meaningless (ML) gestures according to several reports of patients showing selective impairments for imitating these gestures (e.g. Bartolo et al., 2001; Goldenberg & Hagmann, 1997; Tessari et al., 2006). These neuropsychological findings are classically interpreted in the light of the dual-route model (Cubelli et al., 2000; Rothi et al., 1991). According to this model, imitation of transitive and intransitive gestures is subserved by both a lexical route (or semantic route; Tessari & Rumiati, 2004), through which gestures are processed by access to their meaning in the semantic memory and a sub-lexical route (or direct route; Tessari & Rumiati, 2004) through which visual stimuli are translated into corresponding motor actions, that is, by-passing semantic memory. Imitation of MF gestures relies on the lexical route, and imitation of ML gestures relies on the sub-lexical route.[1] The dual-route model has been well documented in healthy adults (Rumiati et al., 2005, 2009, 2002; Tessari & Rumiati, 2004) and in brain-damaged patients (Achilles et al., 2016; Mengotti et al., 2013; Tessari et al., 2006, 2021). However, few data are available on the development of these two routes in healthy children.

Studies exploring the ability to imitate intransitive gestures in children focused on neurodevelopmental disorders, such as autism spectrum disorders, and considered the production of healthy children as control performance (e.g. Mostofsky et al., 2006; Vanvuchelen et al., 2007).

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[1]The sub-lexical route can support both MF and ML gestures, only when they are presented in the same block of stimuli (Tessari et al., 2006; Tessari & Rumiati, 2004).

However, studying the imitation of intransitive gestures in healthy children can give valuable information in the early development of lexical and sub-lexical routes. In a previous work that explored the development of imitation of MF and ML transitive and intransitive gestures in pre-school children (Sebastianutto et al., 2017), children from the age of 3 showed a similar pattern of performance as adults with a better imitation of MF gestures compared to ML gestures (see also Carmo & Rumiati, 2009 for similar data in healthy adults). These results indicate that the lexical route is at work early in development (i.e. first years of life; Nielsen & Slaughter, 2007). As an imitation of MF gestures relies on the semantic system according to the dual-route model, the lower performance in children compared to adults may be mainly explained by a more restricted repertory of known gestures in children. Concerning the sub-lexical route, which translates visual input to motor outputs, several studies have reported that it may not be as direct as previously assumed (for a discussion, see Goldenberg, 2013), and could include intermediate cognitive steps, like visuo-motor conversion mechanism (Cubelli et al., 2000), body knowledge (Buxbaum et al., 2000; Goldenberg, 1995, 1997; Schwoebel & Coslett, 2005), motor imagery (Lesourd et al., 2017) or working memory (Rumiati & Tessari, 2002; van Leeuwen et al., 2009). Thus, if ML gestures in children are worse imitated than in adults, it may be explained by the fact that several cognitive mechanisms are not mature. For instance, the body schema is not innate but rather develops progressively until the age of 8 and beliefs concerning another body become mature later, from 8 to 10 years old (Assaiante et al., 2014). Similarly, working memory capacities continue to mature from school years to late adolescence (Cowan, 2016; Ferguson et al., 2021).

The fact that children and adults showed similar patterns of performance in the imitation of intransitive gestures does not mean that they made the same kind of errors. When imitating intransitive gestures, spatial errors are the most represented in both adults (Carmo & Rumiati, 2009) and children (Mostofsky et al., 2006), but the difference between hand and finger errors are rarely explored. This is of particular importance as it is assumed that imitation of hand and finger postures is relying upon distinct neurocognitive mechanisms. Several neuropsychological studies in LBD patients with left-brain damage reported a dissociation between imitation of hand posture and finger posture (Achilles et al., 2016, 2019; Goldenberg, 1999, 2001). A deficit of imitation of finger postures has also been associated with frontal lesions, whereas a deficit of imitation of hand posture was associated with the parietal lesion (Goldenberg & Karnath, 2006; for a review, see Lesourd et al., 2018; but see Achilles et al., 2017 for contradictory findings). In LBD patients with an imitation deficit, it has been observed that imitation of ML finger postures was more impaired than MF finger postures (Achilles et al., 2016, 2019). More recently, these results were confirmed and extended in LBD patients, where no differences were found between imitation of MF hand and MF finger postures, whereas more errors were made during imitation of ML finger postures compared to the imitation of ML hand postures (Tessari et al., 2021). The absence of difference between MF hand and finger postures may be explained because MF gestures are processed as a whole and are retrieved from semantic long-term memory, independently of the body part involved. In contrast, ML gestures are processed through the direct route, and ML finger posture may be more difficult to produce than ML hand posture, the former being more cognitively demanding than the latter.

The aim of the present work was to investigate quantitatively and qualitatively the development of imitation of intransitive gestures in the dual-route model framework by exploring particularly hand and finger errors. A similar pattern of imitation between young children (3–5 years old) and adults has been observed, that is, better performance for imitation of MF gestures than for ML gestures (Sebastianutto et al., 2017), but this study did not investigate hand and finger errors.

In an imitation task of MF and ML intransitive gestures, we first expect to extend the results obtained with pre-school children with children from 6 to 9 years old, that is better performance with MF than ML gestures as in adults (i.e. higher accuracy and faster initiation reaction times) (Carmo & Rumiati, 2009). Concerning hand and finger errors, as an imitation of ML gestures is taxing important cognitive resources and is calling upon the direct route, which includes several cognitive processes which are not mature at 6–9 years old, we assume to observe more errors of hand and finger postures in children compared to adults. We should also observe a greater difference between hand and finger postures in children than in adults, with more finger errors in children. However, in a context of low cognitive resources, we may also observe an important amount of hand errors in children during the imitation of ML gestures. Imitation of MF gestures relies upon the lexical route, and MF gestures are retrieved from semantic long-term memory; thus, we may observe relatively similar performance between MF hand and MF finger postures in both children and adults. Moreover, examining the association between chronological age and finger and hand errors in children may afford valuable information on the development of lexical and sub-lexical routes.

2. Method

2.1. Participants

Twenty-four children ($M_{age} = 7.33$; $SD_{age} = 1.13$; 10 females; 22 right-handers) without neurodevelopmental disorder and 24 adults ($M_{age} = 21.29$; $SD_{age} = 2.05$; 18 females; 22 right-handers), all with normal or corrected-to-normal vision, volunteered to take part in the experiment. An a priori power analysis with G*Power 3 (Faul et al., 2007) was based on children's studies and used for detecting a difference between MF and ML intransitive imitation.[2] This analysis leads to estimate size of 23 participants with a power of 95% and an alpha of 0.05. Thus, 24 subjects were included in both groups, according to the needed of the counterbalancing procedure (see Section 2.3.).

All the participants, and parents for children, gave their informed consent prior to the experiment. Each participant was tested individually in a quiet room (in a dedicated room at school for the children and in the laboratory for the adults). This study was conducted in accordance with the ethical standards of the Declaration of Helsinki.

2.2. Stimuli

Two sets of meaningful and meaningless non-reflexive intransitive actions were used. The meaningful actions were communicative gestures (e.g. "Come here!"), and the meaningless actions were derived from the meaningful actions by modifying the original relationship between the hand and the arm or between the finger configurations of the hand (see Carmo & Rumiati, 2009 for a similar procedure). Stimuli represented photographs of a female actor in front of the camera, performed the gestures that were all unimanual, non-reflexive, did not cross the body midline and were performed with the left hand of the model. Only non-reflexive gestures were selected as several recent studies pointed out an important difference in the processing of gestures produced on the body versus far from the body (Bartolo et al., 2019; Ruotolo et al., 2021). Thus, we selected for this study only non-reflexive intransitive gestures that were always presented on the peri-personal space, near the head of the model. If we had used videos instead of photographs, the pathway of the hand/arm of the model from its start point to its final position would always have been the same, as all the gestures are appearing in the same space location.

An independent matched sample of 20 children ($M_{age} = 7.55$; $SD_{age} = 1.28$; range = 6–10 years old; nine females; 17 right-handers) and 20 adults ($M_{age} = 22.90$; $SD_{age} = 8.19$; 15 females; 19 right-handers), who participated in a previous experiment, were instructed to recognise MF and ML gestures used in the present experiment. A gesture that did not reach 80% of correct recognition was excluded from the experiment. Based on this criterion, 13 MF and 13 ML gestures were selected (see Appendix). Children ($M = 89.62\%$, $SD = 0.08$) and adults ($M = 90.58\%$, $SD = 0.08$) recognise equally all the selected gestures ($t(38) = -.38$, $p = 0.71$).

2.3. Procedure

The two types of gesture (MF and ML) were presented in two separate blocks. In one block, all the gestures were meaningful, and in the other block, all the gestures were meaningless. The order of the blocks was counterbalanced across participants. Each gesture was presented only once (MF: $N = 13$ and ML: $N = 13$) in a randomised order. At the beginning of the block, participants were asked to carefully look at each photography and to reproduce each gesture with their right hand, as if they were in front of a mirror (the model always used her left hand on the pictures). Before each photography, a fixation cross was presented during 1000 ms and followed by a white screen lasting for 500 ms. At

[2]We choose to calculate an estimation of the sample size based on the results existing in children's studies instead of adults' studies, because the difference between imitation of ML and MF gestures in adults is important and may lead to a reduced sample of participants. For instance, based on the data reported by Carmo and Rumiati (2009), the estimated sample size is $n = 3$ adults with a power of 95% at an alpha of 0.05.

the start of each trial, the participants were asked to press the "space bar" of the keyboard with their right hand and to release it for imitating the gesture. Each gesture was presented on the screen until the participants released the space bar thus the gestures did not appear during the execution of the gesture. By doing this, we wanted to record the reaction times associated with the initiation of each gesture production, and we made sure that participants kept the same hand position at the beginning of each trial. After the participants had imitated a gesture, they had to press the "space bar" and the next trial was triggered.

Each experimental session was video-recorded and later scored by a judge depending on the error classification described hereafter. Each gesture clearly recognisable or containing slight errors (e.g. wrist angle slightly incorrect) was given 1 point; otherwise, 0 point. Scoring considered only the final position of the hand or fingers and did not consider hesitation, searching movements or self-corrections during the movement, nor did it consider a minor variation of the angle of the hand or of the fingers. Global accuracy was then calculated by summing "correct" gestures for each condition (with a maximum score of 13 for MF and ML) and was given in percentage for each participant. Additionally, we coded for each gesture two potential body part errors, that is, hand and finger configuration errors. A gesture containing a hand posture flagrantly incorrect, unrecognisable or transiently correct was given one error. A gesture containing incorrect finger configuration (e.g. thumb touching middle finger instead of index) was given one error. A gesture could contain both errors (i.e. hand and finger), but a gesture scored "correct" could not contain any errors. Errors were summed by condition (MF and ML gestures) for each participant.

To assess the reliability of the rating system, 20 videos (10 children and 10 adults) were evaluated by two independent raters (about 42% of the whole videos). Cohen's Kappa coefficient was calculated for global accuracy and for error type. Concerning the global accuracy, the Kappa value obtained corresponds to almost perfect strength of agreement ($K = .87$, $p < 0.001$). Cohen's Kappa calculating for each body part errors also revealed almost perfect strength of agreement (Hand error: $K = .81$, $p < 0.001$; Finger error: $K = .82$, $p < 0.001$). The rest of the videos were assessed by a single rater (ML).

Programming of the experiment and data recording were performed using PsychoPy 1.8 (Peirce, 2007).

2.4. Statistical analysis

Separate repeated measures ANOVA were performed on mean response times (RTs) and global accuracy with Meaning (MF *vs*. ML) as within-subject factor and Group (Children *vs*. Adults) as between-subject factor. Moreover, a repeated measures ANOVA was performed on error types with Meaning (MF *vs*. ML) and Body part (Hand *vs*. Finger) as within-subject factors and Group (Children *vs*. Adults) as between-subject factors. Post-hoc tests on the significant interactions were performed using paired *t*-tests (Holm's correction for multiple comparisons; Benjamini & Yekutieli, 2001). To further explore the effect of development on imitation skills, correlational analyzes (Pearson) were calculated between chronological age (in months global) and (1) accuracy and error types in the Children group (age in month). RTs deviating from 3 standard deviations from the mean were excluded from the analysis (less than 1% of the whole data).

Initial data processing and subsequent analyses were performed with RStudio version 3.2.2 (R Development Core Team, 2008). Values are given as Mean ± Standard Error Means (SEMs). The significance level was set at $\alpha < 0.05$.

3. Results

3.1. Accuracy and initiation of gesture imitation

Results for imitation accuracy and initiation RTs are reported in Figure 1. Adults were faster to initiate the imitation of intransitive gestures ($M_{adults} = 1705ms \pm 92$, $M_{children} = 2204\ ms \pm 150$, $F(1,46) = 5.86$, $p = 0.019$, $\eta_p^2 = .11$) and were also more accurate than children ($M_{adults} = 82.28\% \pm 1.61$, $M_{children} = 66.71\% \pm 1.84$, $F(1,46) = 32.35$, $p < 0.001$, $\eta_p^2 = .41$). Regardless of the group, MF gestures were initiated faster than ML gestures ($M_{MF} = 1744ms \pm 108$, $M_{ML} = 2164\ ms \pm 141$, $F(1,46) = 10.80$, $p = 0.002$, $\eta_p^2 = .19$), and their imitation was more accurate ($M_{MF} = 79.58\% \pm 1.74$, $M_{ML} = 69.42\% \pm 2.11$, $F(1,46) = 42.29$, $p < 0.001$, $\eta_p^2 = .48$). There was no interaction between Group and Meaning for initiation reaction time and accuracy ($F < 1$ and $F(1,46) = 1.20$, $p = 0.28$, respectively).

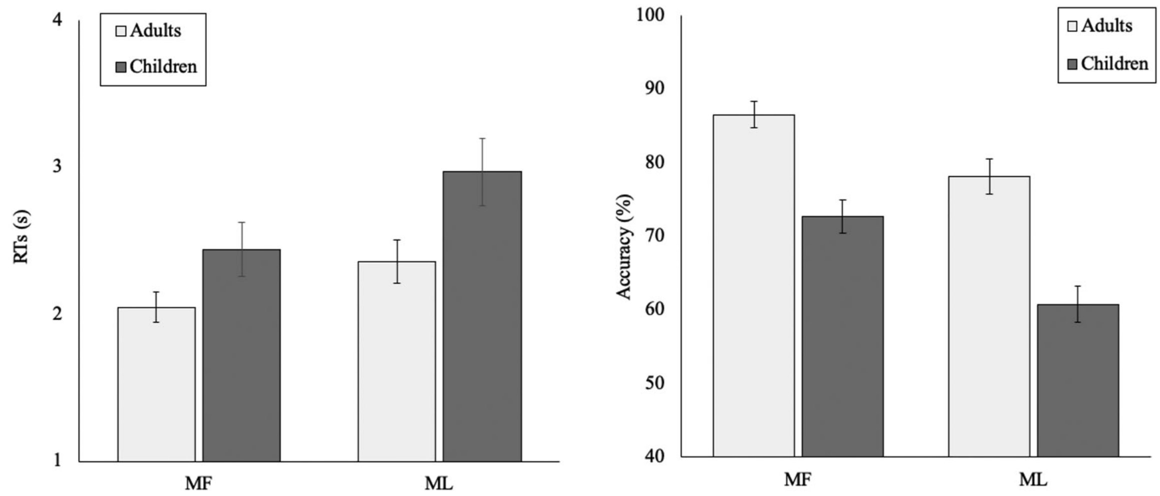

Figure 1. Initiation RTs (left panel) and accuracy (right panel) as a function of Group (Adults *vs.* Children) and Meaning (MF *vs.* ML) for imitation of intransitive gestures. MF: Meaningful; ML: Meaningless.

3.2. Body part errors analysis

Results for body part error analysis are reported in Figure 2. Adults made fewer errors than children to imitate intransitive gestures ($M_{adults} = 1.24$ errors $\pm .10$, $M_{children} = 2.23 \pm .16$, $F(1,46) = 29.95$, $p < 0.001$, $\eta_p^2 = .39$). Regardless of the group, less errors were committed for MF gestures compared to ML gestures ($M_{MF} = 1.39 \pm .13$, $M_{ML} = 2.08 \pm .14$, $F(1,46) = 26.16$, $p < 0.001$, $\eta_p^2 = .36$). There was no effect of the factor Body part, $F(1,46) = 2.48$, $p = 0.12$. There was an interaction between Group and Body part, $F(1,46) = 12.63$, $p < 0.001$, $\eta_p^2 = .22$, children produced more hand errors than adults ($M_{adults} = 1.06 \pm .13$, $M_{children} = 2.69 \pm .20$, $p < 0.001$), whereas there was no difference between children and adults for finger errors ($M_{adults} = 1.42 \pm .15$, $M_{children} = 1.77 \pm .23$, $p = 0.33$). We also found an interaction between Body part and Meaning, $F(1,46) = 50.56$, $p < 0.001$, $\eta_p^2 = .52$, regardless of the group, less finger errors were made for MF gestures compared to ML gestures ($M_{MF} = 0.77 \pm .11$, $M_{ML} = 2.42 \pm .18$, $p < 0.001$), whereas there was no difference for hand errors ($M_{MF} = 2.00 \pm .20$, $M_{ML} = 1.75 \pm .21$, $p = 0.19$). There was no interaction between Group and Meaning, $F(1,46) = 3.64$, $p = 0.063$, $\eta_p^2 = .07$. Finally, the triple interaction between Group, Meaning and Body part was significant, $F(1,46) = 5.14$, $p = 0.028$, $\eta_p^2 = .10$ (see Figure 2). Children produced more hand errors than finger errors for MF gestures ($M_{hand} = 2.83 \pm .18$, $M_{finger} = 0.67 \pm .17$, $p < 0.001$), whereas there was no difference for ML gestures ($M_{hand} = 2.54 \pm .21$, $M_{finger} = 2.88 \pm .19$, $p = 1.00$). Adults produced more finger errors than hand errors for ML gestures ($M_{finger} = 1.96 \pm .19$, $M_{hand} = 0.96 \pm .21$, $p = 0.03$) whereas there was no difference for MF gestures ($M_{finger} = 0.88 \pm .17$, $M_{hand} = 1.17 \pm .18$, $p = 1.00$). Children produced more hand errors than Adults for MF ($M_{children} = 2.83 \pm .27$, $M_{adults} = 1.17 \pm .18$, $p < 0.001$) and ML gestures ($M_{children} = 2.54 \pm .29$, $M_{adults} = 0.96 \pm .21$, $p < 0.001$). There was also a trend to significance for the difference for finger errors in ML ($M_{children} = 2.88 \pm .28$, $M_{adults} = 1.96 \pm .19$, $p = 0.058$) but not in MF gestures ($M_{children} = 0.67 \pm .14$, $M_{adults} = 0.88 \pm .17$, $p = 1.00$).

We also represented in Table 1, the repartition of errors produced by adults and children during imitation according to the pattern of gestures (i.e. hand *vs.* finger gestures) (see also Supplementary Material Figure 2). For the predominant hand pattern gestures, Children and Adults produced about three times more hand errors (58%) than finger errors (19%). Although Children made more errors than adults, there was no difference between the error distribution of the two groups ($\chi^2(1) < 1$, $p = 0.93$). Concerning predominant finger pattern gestures, Adults made about twice as many finger errors (58%) as hand errors (27%), whereas the proportion of errors was quite similar in Children (hand errors: 34% and finger errors: 27%; $\chi^2(1) = 12.23$, $p < 0.001$).

3.3. Correlational analyses in children

Concerning RTs, there was no associations between chronological age and MF gesture initiation ($r = .28$,

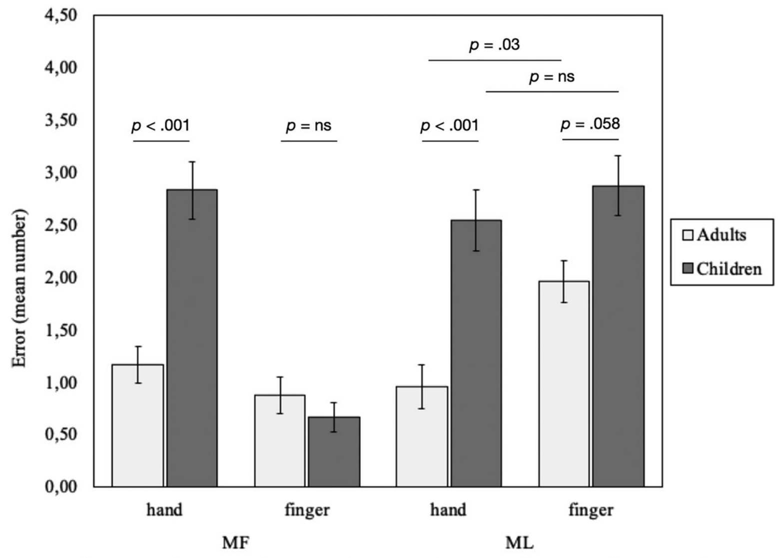

Figure 2. Errors (mean number) as a function of Group (Adults *vs*. Children), Meaning (MF *vs*. ML) and Body part (Hand *vs*. Finger) for imitation of intransitive gestures. MF: Meaningful; ML: Meaningless. Error bars represent SEM.

$p = 0.19$) and between age and ML gesture initiation ($r = .02$, $p = 0.93$). Correlations between global accuracy and chronological age are presented in Figure 3. We found a significant correlation between chronological age and ML gesture ($r = .57$, $p = 0.004$) but not with MF gesture ($r = .04$, $p = 0.85$). Concerning body part errors, there was no association between chronological age and hand errors ($r = -.07$, $p = 0.75$) or with finger errors ($r = -.35$; $p = 0.09$) for MF gestures. However, we found a significant correlation only between chronological age and hand errors ($r = -.47$, $p = 0.02$), but not between chronological age and finger errors ($r = -.21$, $p = 0.32$) for ML gestures.

3.4. Additional analysis

To test for the effect of order presentation on the meaning of gestures, we carried out an ANOVA on imitation accuracy with Meaning (MF *vs.* ML) as within factor and Order presentation (MF block first *vs.* ML block first) as between factor. The ANOVA revealed a main effect of Meaning, $F(1,46) = 41.32$, $p < 0.001$, $\eta_p^2 = .47$, indicating that MF gestures ($M = 79.58 \pm 1.74$) were better imitated than ML gestures ($M = 69.42 \pm 2.11$), but there was no main effect of the factor Order presentation $F(1,46) = 2.32$, $p = 0.13$, $\eta_p^2 = .05$. *n* was also no interaction between Order presentation and Meaning, $F < 1$.

Table 1. Table contingency of type of errors (hand *vs.* finger) produced during imitation according to the a priori gesture configuration and the group of participants.

	Gesture configuration			
	Predominant finger pattern		Predominant hand pattern	
	Hand errors	Finger errors	Hand errors	Finger errors
Children	76 (34%)	60 (27%)	37 (48%)	13 (17%)
Adults	27 (12%)	58 (26%)	21 (27%)	6 (8%)

4. Discussion

The aim of the present work was to investigate the development of imitation of intransitive gestures by testing theoretical predictions within the dual-route model concerning hand and finger errors. First, we hypothesised that children should be slower and less accurate than adults when imitating intransitive gestures, despite a similar response pattern between the two groups, that is, better performance for MF than for ML gestures. Second, in a context of low cognitive resources (i.e. in children), we predict more finger errors compared to hand errors in ML gestures in children compared to adults, but we may also hypothesis the presence of an important number of hand errors for ML gestures.

In line with the first hypothesis, although children performed globally worse and initiated their gestures slower than adults when imitating intransitive gestures, they showed a similar response pattern compared to adults with better performance for MF compared to ML gestures (Sebastianutto et al., 2017). Indeed, children imitated less

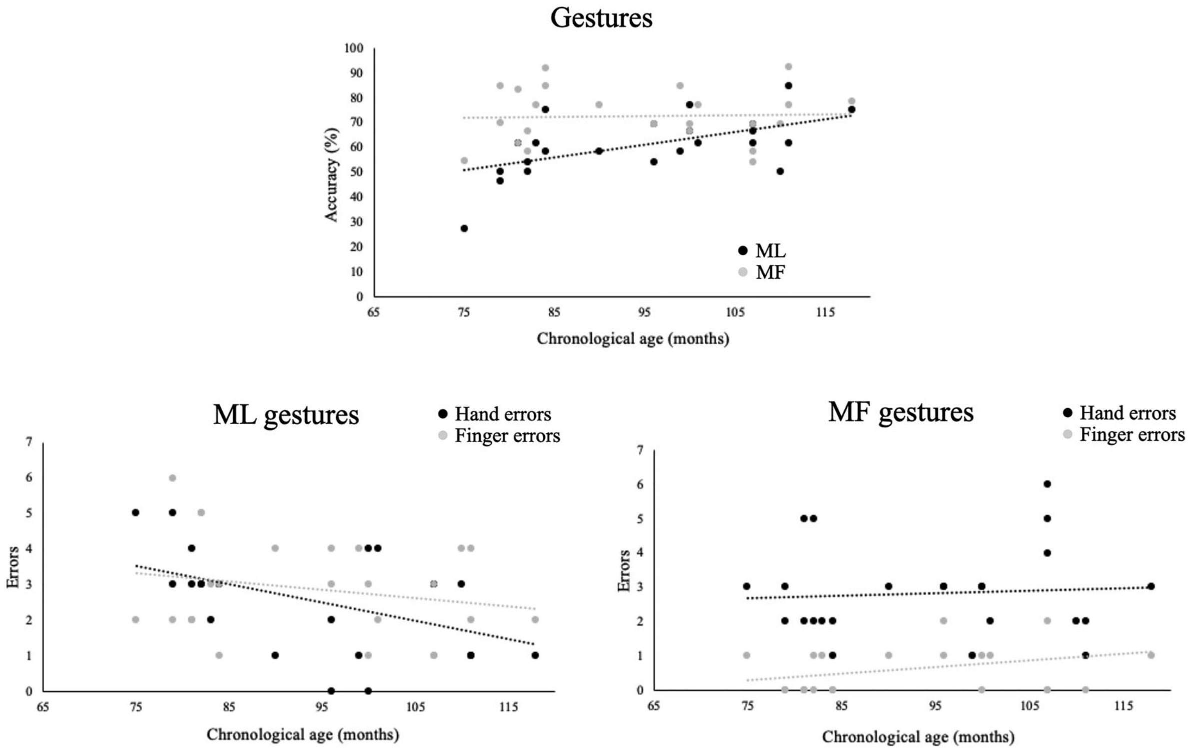

Figure 3. Correlational plots of chronological age (in months) for children with MF and ML imitation accuracy (Top), hand and finger errors for ML gestures (Bottom left) hand and finger errors for ML gestures (Bottom right).

accurate ML gestures than MF gestures and produced more errors (hand and finger). We also found that children initiated MF gestures faster than ML gestures, which is coherent with the idea that observation of known gestures may have activated a stored representation of these gestures in semantic memory and may have facilitated their initiation compared to unknown gestures (Press & Heyes, 2008; Rumiati & Tessari, 2002). The fact that children from 6 to 9 years old presented overall worse performance, but a similar imitation pattern, suggests that the two routes are present at this time of development. However, specific factors (i.e. body knowledge) or/and non-specific factors have impacted imitation performance (e.g. frontal abilities, visuo-spatial skills, working memory, etc.). To go further, we investigated the association between chronological age in children for both MF and ML gesture accuracy. Results showed a significant negative correlation between age and ML gesture accuracy, but not with MF gesture accuracy. Taken together, these results may indicate that lexical and sub-lexical routes do not develop uniformly, with a faster development for the lexical route compared to the sub-lexical route between 6 and 9 years.

The other objective of the present paper was to explore body part errors in relation with lexical and sub-lexical routes for both adults and children. For imitating ML gestures, that are assumed to be supported by the direct route (Cubelli et al., 2000; Tessari et al., 2006, 2004), we found that adults produced slightly more finger errors than hand errors, whereas such difference does not exist for MF gestures, which is in line with recent data (Tessari et al., 2021). In the children group, there was more errors than in adults, but the difference between hand and finger errors was not significant. As ML gestures are more complex to produce and therefore more resources demanding, it seems that both components of gestures are impacted in children, and not only finger parts, as we observed in adults. Processing finger postures depends on attentional resources (Goldenberg, 2001; Tanaka & Inui, 2002), while processing of hand postures rather calls on body schema (i.e. conceptual mediation; Goldenberg, 1995, 1997). As body knowledge is developing until about 10 years old, it could explain why children from 6 to 9 years old met difficulties to reproduce correctly hand postures. More surprisingly, there was significantly more hand errors than finger errors in children for MF gestures. This result seems counterintuitive, as MF gestures are supposed to be processed as a whole and retrieved from semantic long-term memory, independently of the body part involved (Tessari et al., 2021). We will now propose several hypotheses to explain the higher number of hand errors in children.

First, it has been found that hand posture was more impaired than finger posture in LBD apraxic patients (Bekkering et al., 2005; Della Sala et al., 2006; Goldenberg, 1999, 2001). Bekkering et al. (2005) explained these results by assuming that imitation should be viewed from a goal-directed rather than a body-mapping perspective, and that highest priority is given to more distal aspects of imitation rather than the means used to achieve the goal (GOADI theory; Wohlschläger et al., 2003). In this theory, imitation involves a decomposition-reconstruction process that leads to the representation of observed actions as a set of goal-directed motor patterns. The goals are hierarchically organised and include several components of actions (movement path, agent performing the action and other salient features of the actions). Each component of actions is reproduced according to its importance in the hierarchy and when processing resources are taxed, errors are likely to be committed involving primarily a misproduction of the less dominant goals. For instance, in a task where children were asked to reproduce contralateral movements (e.g. reaching left ear with right hand) or ipsilateral movements (e.g. reaching left ear with left hand; Bekkering et al., 2000), children produced ipsilateral movements in 40% of the contralateral trials (i.e. contra-ipsi error). Most of the errors consisted of touching the correct ear but with the wrong hand, suggesting that the ear defined the highest-level-goal. In our study, we could suppose that the position of the hand represented a lower goal than the configuration of the fingers when imitating intransitive gestures, which explained why children produced more hand errors than adults for MF gestures. For more complex gestures (i.e. ML) taxing important resources, the distal part of the gesture, which nevertheless represents the highest-level-goal, can also be impacted. This could explain the similar number of errors obtained between finger and hand errors for ML gestures in children.

Second, the difference between hand and finger errors in children may be explained from an ontogenetic neurocognitive perspective. In broad terms, one may ask whether the brain regions involved in the imitation of hand postures matured later than brain regions engaged in the processing of finger posture imitation. In a longitudinal study (from 5 to 20 years old) of cortical brain development, Gogtay et al. (2004) reported that higher-order associative areas mature only after lower-order sensorimotor areas, thus motor and sensory areas are the first to mature. The lateral temporal lobes are the last to mature. Goldenberg and Karnath (2006) proposed that some brain regions are dedicated to the imitation of specific body parts, that is, the left inferior frontal gyrus (opercular part) for the imitation of finger postures and the left inferior parietal lobe and the left temporo-parieto-occipital junction for the imitation of hand postures. A recent review reported that lesions in the left posterior temporal lobe and left inferior parietal lobe are associated with hand posture deficit in LBD patients, whereas finger imitation is mostly associated with frontal and subcortical lesions (Lesourd et al., 2018). These results seem to be in general agreement with what we found here (i.e. more hand errors than finger errors in children). However, in a recent study, Achilles et al. (2017) questioned these previous results in a large sample of LBD patients by showing that no reliable dissociations between hand and finger imitation could be found. They also showed that a deficit in hand and finger imitation is associated with lesions in somato-sensory and motor cortices. From this point of view, hand and finger imitation is processed by brain regions that have matured early in the development, and brain maturation could not explain on its own the present results. To sum up, this ontogenetic explanation does not seem sufficient, and further studies are needed if we want to explain the development of hand and finger imitation in association with cortical maturation.[3]

Third, some methodological choices made in the present study could have influenced the difference observed between hand and finger errors in children. We used photographs and not videos as stimuli, and one may stress that we did not test

[3]One needs to be cautious when interpreting brain-behavior relations in children from data obtained in brain-damaged adults' patients. It is likely that imitation of hand and finger postures is relying upon multiple processes widely distributed in the brain (Caspers et al., 2010; Lesourd, Osiurak, et al., 2018) that could be engaged differentially according to the level of development. Moreover, the cognitive system in children does not present the same properties as adults (i.e., Modularity; for a discussion see Karmiloff-smith et al., 2003).

imitation *per se*, the errors observed consisting only in errors of final position of the body parts. Indeed, we observed spatial errors but, of course, not kinematic errors. Then, we cannot rule out that another category of errors could have been observed. However, spatial errors (i.e. arm posture, finger posture, hand posture, etc.) are over-represented in imitation of intransitive gestures even in adults (about 60%; Carmo & Rumiati, 2009). thus, imitating intransitive gestures, even based on a photograph, may be associated with errors typically observed with videos, as we found in both adults and children. Another potential effect to consider is the order of presentation of MF and ML blocks. As MF and ML blocks were counterbalanced across participants, it could have triggered the selection of the sub-lexical route for the ML block, which could have been maintained for the MF block (Tessari et al., 2006, 2004). However, we did not find any influence of order presentation on the meaning of gestures. It is, therefore, unlikely that the presence of hand posture errors was fully explained by the maintenance of the sub-lexical route for the MF gestures. It is also possible that children met more difficulties to access the meaning of MF gestures, based only on photographs, and as a result, made the activation in semantic memory of a known gesture more challenging. However, the meaning of gestures was rated correctly by an independent matched sample of participants, and we also observed classical effects (accuracy and RTs) between MF and ML gestures for both groups.

In this study, we first consider hand and finger errors made during the imitation of gestures independently from their predominant configuration (i.e. predominant finger configuration or predominant hand configuration). Indeed, we reported both hand and finger errors for predominant hand configuration gestures, and we also reported hand and finger errors for predominant finger configuration gestures, instead of what is classically done in the literature (Achilles et al., 2016, 2019, 2017; Goldenberg, 1999, 2006; Tessari et al., 2021). Our results indicated that if adults produced significantly more hand errors for predominant hand configuration gestures and more finger errors for predominant finger configuration gestures, it was not the case for the children group. Indeed, we observed that if the distribution of errors was similar to adults for the predominant hand configuration gestures, there were as much as hand errors than finger errors for predominant finger configuration gestures. This may suggest that children tend to focus on the more distal part of the imitation only when the distal part includes a complex body part configuration. Further studies are indicated to better understand the distribution of errors according to the predominant configuration of the gestures.

5. Conclusion

As previously observed in younger children (3–5 years old; Sebastianutto et al., 2017), we found that children from 6 to 9 years old presented the same pattern of performance as adults, but we found distinct error profiles, that is, more hand than finger errors for MF gestures and no difference between hand and finger errors for ML gestures. Taken together, these results indicate that if the two routes are present at this age, the ability to imitate intransitive gestures may be impacted by non-specific (e.g. working memory limitation, visuo-spatial skills, etc.) and specific factors (e.g. body knowledge; Baumard & Le Gall, 2021), which are not mature from 6 to 9 years old. These results also point out the importance of reporting hand and finger errors, whatever the predominant configuration of gestures, particularly in a developmental perspective.

Further studies are now required to understand, at each step of development, the association between imitation skills and (1) general cognitive abilities (e.g. working memory); and (2) specific cognitive processes supporting imitation (e.g. body knowledge).

Data availability statement

The data that support the findings of this study are openly available in OSF at https://doi.org/10.17605/osf.io/7brks/.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

Achilles, E. I. S., Fink, G. R., Fischer, M. H., Dovern, A., Held, A., Timpert, D. C., Schroeter , C., Schuetz, K., Kloetzsch, C., & Weiss, P. H. (2016). Effect of meaning on apraxic finger imitation deficits. *Neuropsychologia*, *82*, 74–83. https://doi.org/10.1016/j.neuropsychologia.2015.12.022

Achilles, E. I. S., Ballweg, C. S., Niessen, E., Kusch, M., Ant, J. M., Fink, G. R., & Weiss, P. H. (2019). Neural correlates of differential finger gesture imitation deficits in left hemisphere stroke. *NeuroImage: Clinical*, *23*, 101915. https://doi.org/10.1016/j.nicl.2019.101915

Achilles, E. I. S., Weiss, P. H., Fink, G. R., Binder, E., Price, C. J., & Hope, T. M. H. (2017). Using multi-level Bayesian lesion-symptom mapping to probe the body-part-specificity of gesture imitation skills. *NeuroImage*, *161* (January), 94–103. https://doi.org/10.1016/j.neuroimage.2017.08.036

Assaiante, C., Barlaam, F., Cignetti, F., & Vaugoyeau, M. (2014). Body schema building during childhood and adolescence: A neurosensory approach. *Neurophysiologie Clinique*, *44*(1), 3–12. https://doi.org/10.1016/j.neucli.2013.10.125

Bartolo, A., Claisse, C., Gallo, F., Ott, L., Sampaio, A., & Nandrino, J.-L. (2019). Gestures convey different physiological responses when performed toward and away from the body. *Scientific Reports*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-49318-3

Bartolo, A., Cubelli, R., Della Sala, S., Drei, S., & Marchetti, C. (2001). Double dissociation between meaningful and meaningless gesture reproduction in apraxia. *Cortex*, *37*(5), 696–699. https://doi.org/10.1016/S0010-9452(08)70617-8

Baumard, J., & Le Gall, D. (2021). The challenge of apraxia: Toward an operational definition? *Cortex*, *141*(Ea 7475), 66–80. https://doi.org/10.1016/j.cortex.2021.04.001

Bekkering, H., Brass, M., Woschina, S., & Jacobs, A. M. (2005). Goal-directed imitation in patients with ideomotor apraxia. *Cognitive Neuropsychology*, *22*(3–4), 419–432. https://doi.org/10.1080/02643290442000275

Bekkering, H., Wohlschläger, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *The Quarterly Journal of Experimental Psychology Section A*, *53*(1), 153–164. https://doi.org/10.1080/713755872

Benjamini, Y., & Yekutieli, D. (2001). The control of the false discovery rate in multiple testing under dependency. *The Annals of Statistics*, *29*(4), 1165–1188. https://doi.org/10.1214/aos/1013699998

Buxbaum, L. J., Giovannetti, T., & Libon, D. (2000). The role of the dynamic body schema in praxis: Evidence from primary progressive apraxia. *Brain and Cognition*, *44* (2), 166–191. https://doi.org/10.1006/brcg.2000.1227

Carmo, J. C., & Rumiati, R. I. (2009). Imitation of transitive and intransitive actions in healthy individuals. *Brain and Cognition*, *69*(3), 460–464. https://doi.org/10.1016/j.bandc.2008.09.007

Caspers, S., Zilles, K., Laird, A. R., & Eickhoff, S. B. (2010). ALE meta-analysis of action observation and imitation in the human brain. *NeuroImage*, *50*(3), 1148–1167. https://doi.org/10.1016/j.neuroimage.2009.12.112

Cowan, N. (2016). Working memory maturation: Can we get at the essence of cognitive growth? *Perspectives on Psychological Science*, *11*(2), 239–264. https://doi.org/10.1177/1745691615621279

Cubelli, R., Marchetti, C., Boscolo, G., & Della Sala, S. (2000). Cognition in action: Testing a model of limb apraxia. *Brain and Cognition*, *44*(2), 144–165. https://doi.org/10.1006/brcg.2000.1226

Della Sala, S., Faglioni, P., Motto, C., & Spinnler, H. (2006). Hemisphere asymmetry for imitation of hand and finger movements, Goldenberg's hypothesis reworked⋆. *Neuropsychologia*, *44*(8), 1496–1500. https://doi.org/10.1016/j.neuropsychologia.2005.11.011

Faul, F., Erdifelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Ferguson, H. J., Brunsdon, V. E. A., & Bradford, E. E. F. (2021). The developmental trajectories of executive function from adolescence to old age. *Scientific Reports*, *11*(1), 1–17. https://doi.org/10.1038/s41598-020-80866-1

Gogtay, N., Giedd, J. N., Lusk, L., Hayashi, K. M., Greenstein, D., Vaituzis, A. C., Nugent, T. F., … Thompson, P. M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences*, *101* (21), 8174–8179. https://doi.org/10.1073/pnas.0402680101

Goldenberg, G. (1995). Imitating gestures and manipulating a mannikin—The representation of the human body in ideomotor apraxia. *Neuropsychologia*, *33*(1), 63–72. https://doi.org/10.1016/0028-3932(94)00104-W

Goldenberg, G. (1999). Matching and imitation of hand and finger postures in patients with damage in the left or right hemispheres. *Neuropsychologia*, *37*(5), 559–566. https://doi.org/10.1016/S0028-3932(98)00111-0

Goldenberg, G. (2001). Imitation and matching of hand and finger postures. *NeuroImage*, *14*(1 II), S132–S136. https://doi.org/10.1006/nimg.2001.0820

Goldenberg, G. (2013). *Apraxia: The cognitive side of motor control*. Oxford University Press.

Goldenberg, G., & Hagmann, S. (1997). The meaning of meaningless gestures: A study of visuo-imitative apraxia. *Neuropsychologia*, *35*(3), 333–341. https://doi.org/10.1016/S0028-3932(96)00085-1

Goldenberg, G., & Karnath, H.-O. (2006). The neural basis of imitation is body part specific. *Journal of Neuroscience*, *26*(23), 6282–6287. https://doi.org/10.1523/JNEUROSCI.0638-06.2006

Karmiloff-smith, A., Scerif, G., & Ansari, D. (2003). Discussion double dissociations in developmental disorders? *Theoretically Misconceived*, *39*(1), 161–163. https://doi.org/10.1016/S0010-9452(08)70091-1

Lesourd, M., Navarro, J., Baumard, J., Jarry, C., Le Gall, D., & Osiurak, F. (2017). Imitation and matching of meaningless gestures: Distinct involvement from motor and visual imagery. *Psychological Research*, *81*(3), 525–537. https://doi.org/10.1007/s00426-016-0758-1

Lesourd, M., Osiurak, F., Baumard, J., Bartolo, A., Vanbellingen, T., & Reynaud, E. (2018). Cerebral correlates of imitation of intransitive gestures: An integrative review of neuroimaging data and brain lesion studies. *Neuroscience & Biobehavioral Reviews*, *95*, 44–60. https://doi.org/10.1016/j.neubiorev.2018.07.019

Mengotti, P., Corradi-Dell'Acqua, C., Negri, G. A. L., Ukmar, M., Pesavento, V., & Rumiati, R. I. (2013). Selective imitation impairments differentially interact with language processing. *Brain*, *136*(8), 2602–2618. https://doi.org/10.1093/brain/awt194

Mostofsky, S. H., Dubey, P., Jerath, V. K., Jansiewicz, E. M., Goldberg, M. C., & Denckla, M. B. (2006). Developmental dyspraxia is not limited to imitation in children with autism spectrum disorders. *Journal of the International Neuropsychological Society*, *12*(3), 314–326. https://doi.org/10.1017/S1355617706060437

Nielsen, M., & Slaughter, V. (2007). Multiple motivations for imitation in infancy. In C. L. Nehaniv & K. Dautenhahn (Eds.), *Imitation and social learning in robots, humans and animals* (pp. 343–360). Cambridge University Press.

Peirce, J. W. (2007). Psychopy—psychophysics software in Python. *Journal of Neuroscience Methods*, *162*(1–2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Press, C., & Heyes, C. (2008). Stimulus-driven selection of routes to imitation. *Experimental Brain Research*, *188*(1), 147–152. https://doi.org/10.1007/s00221-008-1422-9

R Development Core Team. (2008). *R: A language and environment for statistical computing*. Retrieved from http://www.r-project.org

Rothi, G., Ochipa, L. J., & Heilman, K. (1991). A cognitive neuropsychological model of limb praxis. *Cognitive Neuropsychology*, *8*(6), 443–458. https://doi.org/10.1080/02643299108253382

Rumiati, R. I., Carmo, J. C., & Corradi-Dell'Acqua, C. (2009). Neuropsychological perspectives on the mechanisms of imitation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1528), 2337–2347. https://doi.org/10.1098/rstb.2009.0063

Rumiati, R. I., & Tessari, A. (2002). Imitation of novel and well-known actions. *Experimental Brain Research*, *142*(3), 425–433. https://doi.org/10.1007/s00221-001-0956-x

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*(9), 1420–1431. https://doi.org/10.1162/0898929054985374

Ruotolo, F., Iachini, T., Ruggiero, G., Scotto di Tella, G., Ott, L., & Bartolo, A. (2021). The role of mental imagery in pantomimes of actions towards and away from the body. *Psychological Research*, *85*(4), 1408–1417. https://doi.org/10.1007/s00426-020-01359-4

Schwoebel, J., & Coslett, H. B. (2005). Evidence for multiple, distinct representations of the human body. *Journal of Cognitive Neuroscience*, *17*(4), 543–553. https://doi.org/10.1162/0898929053467587

Sebastianutto, L., Mengotti, P., Spiezio, C., Rumiati, R. I., & Balaban, E. (2017). Dual-route imitation in preschool children. *Acta Psychologica*, *173*(February), 94–100. https://doi.org/10.1016/j.actpsy.2016.12.007

Tanaka, S., & Inui, T. (2002). Cortical involvement for action imitation of hand/arm postures versus finger configurations: An fMRI study. *Neuroreport*, *13*(13), 1599–1602. https://doi.org/10.1097/00001756-200209160-00005

Tessari, A., Canessa, N., Ukmar, M., & Rumiati, R. I. (2006). Neuropsychological evidence for a strategic control of multiple routes in imitation. *Brain*, *130*(4), 1111–1126. https://doi.org/10.1093/brain/awm003

Tessari, A., Mengotti, P., Faccioli, L., Tuozzi, G., Boscarato, S., Taricco, M., & Rumiati, R. I. (2021). Effect of body-part specificity and meaning in gesture imitation in left hemisphere stroke patients. *Neuropsychologia*, *151*(December 2020), 107720. https://doi.org/10.1016/j.neuropsychologia.2020.107720

Tessari, A., & Rumiati, R. I. (2004). The strategic control of multiple routes in imitation of actions. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(6), 1107–1116. https://doi.org/10.1037/0096-1523.30.6.1107

van Leeuwen, M. L., van Baaren, R. B., Martin, D., Dijksterhuis, A., & Bekkering, H. (2009). Executive functioning and imitation: Increasing working memory load facilitates behavioural imitation. *Neuropsychologia*, *47*(14), 3265–3270. https://doi.org/10.1016/j.neuropsychologia.2009.06.005

Vanvuchelen, M., Roeyers, H., & De Weerdt, W. (2007). Nature of motor imitation problems in school-aged boys with autism: A motor or a cognitive problem? *Autism*, *11*(3), 225–240. https://doi.org/10.1177/1362361307076846

Wohlschläger, A., Gattis, M., & Bekkering, H. (2003). Action generation and action perception in imitation: An instance of the ideomotor principle. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *358*(1431), 501–515. https://doi.org/10.1098/rstb.2002.1257

Appendix

List of the MF and ML gestures used in the imitation experiment. Even if we consider both hand and finger errors for each gesture, we have nevertheless indicated between brackets whether the gesture mainly involves a hand or a finger configuration.

For all the gestures, the arm is in the same vertical plane as the body of the model.

Meaningful (MF) gestures

MF01. Perfect (F).

MF02. OK (F).

MF03. Victory (F).

MF04. Bad (F).

MF05. Stop (H).

MF06. Strength (H).

MF07. Can I speak? (F).

MF08. Pointing someone (F).

MF09. Give me (H).

MF10. Hitchhiking (F).

MF11. Little (F).

MF12. Come here (F).

MF13. Shaking hands (H).

Meaningless (ML) gestures

ML01. Thumb close the middle finger (F).

ML02. Thumb close the ring finger (F).

ML03. Thumb folded and extended fingers, palm of the hand toward the observer and tilted toward the head of the model (H).

ML04. Thumb touching all fingertips and pointing outward (F).

ML05. Index folded as a hook, other fingers closed around the thumb in a fist and pointing toward the model (F).

ML06. Back of the hand toward the observer and pointing downwards (H).

ML07. Palm of the hand oriented perpendicularly to the body of the model and pointing outward (H).

ML08. Palm of the hand toward the observer, hand upright, middle finger and ring finger crossed (F).

ML09. Palm of the hand toward the observer, hand upright, all fingers folded but leaving the palm entirely visible (F).

ML10. Back of the hand toward the model, hand upside down, index and middle fingers pointing downwards, other fingers closed in a fist (F).

ML11. Back of the hand toward the observer, thumb folded, other fingers folded as a claw, hand oriented perpendicularly toward the body of the model (F).

ML12. Back of the hand toward the observer, index and middle fingers pointing upwards, other fingers closed in a fist (F).

ML13. Fist facing the observer, wrist turned 180° clockwise (from the perspective of the model) (H).