



Does agency matter? Neural processing of robotic movements in 4- and 8-year olds

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ABSTRACT

Despite the increase in interactions between children and robots, our understanding of children's neural processing of robotic movements is limited. The current study theorized that motor resonance hinges on the agency of an actor: its ability to perform actions volitionally. As one of the first studies with a cross-sectional sample of preschoolers and older children and with a specific focus on robotic action (rather than abstract non-human action), the current study investigated whether the perceived agency of a robot moderated children's motor resonance for robotic movements, and whether this changed with age. Motor resonance was measured using electroencephalography (EEG) by assessing mu power while 4 and 8-year-olds observed actions performed by agentic versus non-agentic robots and humans. Results show that older children resonated more strongly with non-agentic than agentic robotic or human movement, while no such differences were found for preschoolers. This outcome is discussed in terms of a predictive coding account of motor resonance. Importantly, these findings contribute to the existing set of studies on this topic by showing that, while keeping all kinematic information constant, there is a clear developmental difference in how children process robotic movement depending on the level of agency of a robot.

1. Introduction

Children born today are increasingly likely to grow up with a robotic family member. By the end of 2019, it is projected that 41.8 million robots will be part of households around the world (International Federation of Robotics, 2016). These domestic robots are used for tasks including cleaning, entertainment, and education (e.g., Fridin, 2014). Despite the increase in interactions between children and robots, our understanding of the psychological processes grounding such interactions is limited. One central issue concerns the extent to which children process robot actions in the same way as human actions, which factors influence these processes, and whether they mature across development. Therefore, the current study investigates the neural mechanisms when young children (i.e., 4- and 8-year olds) observe actions performed by robots, and whether these mechanisms are moderated by perceived agency of the robot.

When we see another human being performing an action, we process that action in such a way that it enables us to understand and predict what this person will do next, coordinate with this person accordingly, and even ascribe goals, desires, and beliefs behind his or her action

(Gallese et al., 2004; Sebanz et al., 2006a,b; Vesper et al., 2017). This ability is essential to our success and survival, as it allows us to cooperate efficiently with other individuals (Colling et al., 2013; Verschure, 2014). One of the mechanisms that has been proposed to play a role in action prediction and understanding is motor resonance: when we perceive another agent performing an action, this, in turn, activates the associated motor representation that would have generated these effects in our motor system (Bekkering et al., 2009; Hommel et al., 2001; Paulus, 2012; Sebanz et al., 2006a, 2006b). Motor resonance fits well within a predictive coding framework (Kilner et al., 2007) which posits that our brain is a prediction machine: we continuously predict incoming sensory input (e.g., when we see someone perform an action) and this prediction is compared to the actual observed sensory input. A large difference between predicted and observed kinematics will generate a large prediction error, driving the motor system to update its predictions for subsequent observations.

Empirical studies with adult samples have provided both behavioral (e.g., Brass et al., 2001) and neural (e.g., Buccino et al., 2001; Decety et al., 1997; Iacoboni et al., 1999) evidence for motor resonance. For example, participants performing simple movements (lifting or

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dropping their index finger) were found to perform that movement more slowly when they were simultaneously observing someone else performing the opposite movement (Brass et al., 2001). This increase in response latency shows that observed movement is processed in the same representational domain as executed movement (Brass et al., 2001). In an ERP study, participants in a joint action setting show similar electrophysiological responses at frontal sites (indicating action preparation) for stimuli that they should act upon, as well as stimuli that they should ignore but their interaction partner should act upon. Subsequently, the P300 amplitude is much larger for such no-go trials in a joint setting than in an individual setting, indicating greater response inhibition (Sebanz et al., 2006a, 2006b).

Moreover, studies have shown that motor resonance is already present early in development. Similar to the study performed with adult participants, action execution in 4-year olds becomes more erroneous when they are observing movements that are incompatible with their own actions (Sacheli et al., 2017). Even earlier in development, 9-month old infants are more likely to start imitating actions that were more similar to their own action capacities compared to less similar actions (e.g., Longo and Bertenthal, 2006; Paulus et al., 2011). Indeed, Lepage and Theoret (2006) showed that motor resonance occurs when children observe another human being performing a movement – a finding that has been replicated with infants as young as 6 months of age (Marshall et al., 2011; Nyström, 2008; Southgate et al., 2010). This further demonstrates that the processing of an observed action is related to the observer's own motor program, already in infancy. Yet, while much of the work on motor resonance focused on the emergence of this type of processing in infancy, motor resonance in early and later childhood has been largely overlooked by the literature (Saby et al., 2011).

Findings as to whether motor resonance is exclusively tailored towards human movement or whether it can also occur for non-human (robotic) movement are mixed. Infants as young as 2 days old discriminate between biological and non-biological movement, and looked longer at biological (human) movement in upright point-light displays (PLDs) compared to inverted PLDs (Reid et al., 2006; Simion et al., 2008). Moreover, 14-month-old infants' cortical motor system is engaged by other people's actions but not by moving geometrical shapes (Reid et al., 2011). One-year-old infants show different cortical reactivity to human versus non-human targets being touched (Müller et al., 2017). Woodward (1998) as well as Kanakogi and Itakura (2011) demonstrated that 4- to 10-month-old infants process goal-directed human action differently than an inanimate object performing the same movement. Similarly, adults have been shown to resonate with actions performed by human agents but not necessarily robots (e.g., Kilner et al., 2003; Oberman et al., 2007; Shimada, 2010; Tai et al., 2004; Urgen et al., 2013; Wilson and Knoblich, 2005).

In contrast to this series of studies, other research shows that our processing of movements is not exclusively tailored towards human-human interaction. For example, one study reported that 4-month old infants' premotor cortex resonates more strongly with robotic than with human motion (Grossmann et al., 2013). Infants from approximately 5 months of age have been shown to process movements performed by a mechanical device as goal-directed, shown by longer looking times for unexpected non-human movements compared to expected non-human movements, just as with human movement (Kuhlmeier et al., 2003; Luo and Baillargeon, 2005). Finally, robotic motion has been shown to engage the adult motor cortex more strongly than human motion (Cross et al., 2012). Yet another pattern was reported by Gazzola and colleagues (2007), who found equal engagement of the motor system for human and robot motion. Thus, some studies report motor resonance as a mechanism that is exclusive to human-human interaction while others provide evidence that it can also be engaged by non-human (robotic) movement. Importantly, Sciutti and colleagues (2012) note that this discrepancy may be due to the level of measurement: at the neurophysiological level, motor resonance has been demonstrated for robots moving with non-biological kinematics. However, at the behavioral

level, a higher level of human likeness in terms of appearance and/or kinematics appears to be required (Bisio et al., 2014; Sciutti et al., 2012).

A factor that may further help clarify these mixed findings is the perceived agency of movement. Agency is the ability to control one's actions, and through them, events in the external world (Chambon et al., 2014). Since motor resonance appears to be related to social interaction and cooperation (e.g., Novembre et al., 2014), it is reasonable to assume that our motor system is restricted to simulating movement that is agentic: movement performed by autonomous agents with whom we need to interact with for our success and survival. For the resonance with robotic movement, this would mean that we resonate more strongly with robotic action when the robot is perceived as having agency. Indeed, research with adult samples has confirmed that the agency of a non-human agent moderates the extent to which we show motor resonance for its actions (e.g., Müller et al., 2011; Müller et al., 2015; Ramsey and Hamilton, 2010; Stanley et al., 2007, 2010; Stenzel et al., 2012, 2014). It is possible that the heterogeneous pattern of results in studies with infants and children could be due to different levels of agency that the non-human agents in those studies display (cf. Johnson, 2000, for a similar argument). For example, while Reid and colleagues (2011) used geometric shapes as non-human agents, Grossman and colleagues (2012) used robots. Autonomous robotic movement is obviously different from moving geometric shapes, and it could be postulated more agentic.

An object may induce agency attributions in various ways. For example, it may have certain humanized physical features, such as a face or limbs (e.g., Johnson et al., 1998). Then, it may react contingently to its environment (Schlottmann and Surian, 1999). Lastly, an object can display self-propulsion, i.e., autonomous movement (e.g., (Heider and Simmel, 1944; Poulin-Dubois et al., 1996)). The ability to distinguish between self-propelled and remote-controlled objects has been shown from at least 12 months of age (Johnson et al., 2002; Premack and Premack, 1997; Scholl and Tremoulet, 2000; Thörmer and Sodian, 2001). When an object is self-propelled, infants interpret its movements as goal-directed. Vice versa, when an object does not move autonomously (e.g., is remote-controlled), they do not interpret it as goal-directed (Premack, 1990).

The attribution of agency as well as other human characteristics, such as emotions or subjective experience, to inanimate objects is called anthropomorphism (e.g., Epley et al., 2007). It has been theorized that preschool children anthropomorphize inanimate objects more than adults (e.g., Epley et al., 2007). Indeed, young children have much more difficulties differentiating between fantasy and reality than adults (e.g., Harris, 1991; Singer and Singer, 1990; Taylor, 2013; Taylor and Howell, 1972) and often act towards inanimate objects, such as puppets or teddy bears, as if they were alive (e.g., Fawcett and Markson, 2010).

Such anthropomorphic beliefs may originate in young children's anthropocentric world-view: reasoning that, when something moves or talks like they do, it must mean it experiences the world in exactly the same way as they do (Piaget and Inhelder, 1969). According to the model of conceptual change and in line with current predictive coding approaches (Clark, 2013; Friston, 2003), anthropomorphic beliefs decrease by accumulating experiences throughout development (i.e., with age) or explicit knowledge instruction (Carey, 1985; Springer and Keil, 1989). For example, previous work has demonstrated that preschoolers have a much more anthropomorphic understanding of robots than 7-year olds (e.g., Bernstein and Crowley, 2008). Results reported by Sommer and colleagues (2019) suggest that these age differences may be mediated by a decrease in anthropomorphic mental state attributions.

However, explicit instructions about the absence or presence of certain human-like qualities in robots (e.g., the ability to move autonomously versus being remote-controlled) have been found to matter too. For example, children aged 4 to 8 all ascribed fewer anthropomorphic qualities to a remote-controlled versus autonomous robot, regardless of age (Chernyak and Gary, 2016). Similarly, Meltzoff and colleagues (2010) demonstrated that already 18-month old children are more likely

to follow a robot's gaze after watching the robot interact and communicate with the experimenter, compared to same-aged children who did not experience the robot as a communicative agent.

Given these differences in anthropomorphic reasoning, we can expect preschoolers and older children to hold different perceptions of robotic devices and we can expect that the information children receive about a robot's abilities affects their perceptions too. Moreover, these processes might interact. Thus, when postulating that the attribution of agency plays a role in children's motor resonance for robotic movements, it seems pertinent to take developmental differences into account. Preschool children will perhaps attribute agency to robots naturally, while older children may differentiate between agentic and non-agentic machines.

1.1. The current study

In the current study we integrated theoretical claims that motor resonance is determined by the perceived agency of the actor (e.g., Müller et al., 2011; 2015) and long-standing developmental views that preschool children attribute agency to non-human agents naturally compared to older children who have the cognitive skills to understand that non-human agents do not necessarily possess agency (Piaget and Inhelder, 1969; Saylor et al., 2010). Combining these two insights, the current study will investigate the following research questions about children's motor resonance of robotic action: do children show different levels of motor resonance for agentic versus non-agentic robotic movement, and does this differ between preschool-aged and older children?

We examined these research questions by assessing mu power. Power in the mu frequency band (6–13 Hz, depending on age; cf. Marshall et al., 2002; Pineda, 2005) can be measured with electroencephalography (EEG). The mu rhythm is thought to arise out of the sensorimotor areas (Caetano et al., 2007; Pineda, 2005), where event-related desynchronization or synchronization of neurons reduces or increases the power in the mu frequency band – thus reflecting cortical activation and idling. The strength of mu power can therefore be used as an indicator for activity of the motor system. Indeed, it has been validated as a valid measurement of the underlying neural mechanisms of motor resonance, as it is associated with cortical motor activation during the perception of actions and their consequences (e.g., Nyström et al., 2011; Paulus et al., 2012; for review see Marshall and Meltzoff, 2011).

Importantly, different theoretical accounts on the psychological basis of motor resonance and the mu rhythm exist. The direct resonance account assumes that humans show the strongest motor resonance for actions that they have most experience with (e.g., Buccino et al., 2004; Calvo-Merino et al., 2004; Cross et al., 2006; Shimada, 2010). For example, expert capoeira dancers resonate more strongly with capoeira movements than with ballet movements and vice versa for ballet dancers (Calvo-Merino et al., 2005). In a related vein, an ideomotor account posits that motor resonance is based on acquired action-effect associations (Paulus, 2012). The perception of another's action leads to the activation of the motor code in one's own motor system that has been associated with it. Finally, from a predictive coding perspective, Kilner et al. (2007) suggest that motor resonance (or activity in the motor cortex during action observation) is driven by prediction error: the difference between predicted sensory input based on prior experiences and the observed sensory input. That is, when we predict something to move a certain way and that prediction is violated, this prediction error drives the motor system to update its predictions for subsequent observations – leading to greater motor resonance (Cross et al., 2011; de Lange, Spronk, Willems, Toni and Bekkering, 2008; Koelewijn et al., 2008; Saby et al., 2011). Indeed, 12-month-old infants show greater mu suppression for unusual versus ordinary daily actions (Stapel et al., 2010).

In sum, these theoretical accounts of the mu rhythm and motor resonance generate different hypotheses for the current study. Generally, we hypothesized that young preschool children would not show different levels of motor resonance for agentic versus non-agentic

robotic movement, while older children would start to differentiate between agentic and non-agentic robotic movement. However, the pattern of mu power that can be expected based on this hypothesis differs depending on the chosen interpretation of mu. According to the direct resonance interpretation of mu power, we would not expect motor resonance to be sensitive to the perceived agency of actions: agency does not affect the basic motor characteristics of the action, and the motoric characteristics of the different agents in our study were closely matched. From an ideomotor account, we would expect decreased mu power for human movements in both age groups since the perception of a human arm movement relates more to participants' own experiences. A predictive coding account of the mu rhythm would predict that motor resonance is modulated by predictability, so agency and intentionality should therefore matter. Since young preschool children show strong anthropomorphic tendencies, one would predict no differences between all types of agents. Yet, older children would show decreased mu power for non-agentic robot movement compared to agentic robot and human movement.

To test our hypothesis, we conducted an experimental study using EEG in which the agency of robotic movement was manipulated and compared to a control condition. Agency was manipulated in terms of self-propulsion: participants were presented with videos of two different robots, one which moved autonomously and one which was remote-controlled. Furthermore, to investigate developmental differences in the influence of agency on motor resonance with robotic movement, children in two age groups participated in our study: 4- and 8-year-olds. All participants were presented with animations of simple actions (e.g., grasping a cup) performed by the agentic and non-agentic robot and a human in the control condition – all of them similar in movement characteristics. Throughout the experiment, participants' neural responses during action observation were measured, focusing on the sensorimotor mu rhythm.

2. Methods

2.1. Participants

Power analysis, using G*Power 3.1 (Faul et al., 2007) with an a priori power estimate of $1-\beta = 0.80$ and an estimated effect size of $f = 0.25$ (medium effect size, see Faul et al., 2007) for an effect of the agency manipulation, revealed a minimum required sample size of $n = 28$ per age group, thus $n = 56$ in total. A total number of $n = 69$ participants was recruited, but seventeen children were excluded from the final analysis due to failing to answer correctly on the attention or manipulation check ($n = 9$, only 4-year-olds), fussiness causing too few trials to be collected ($n = 5$, only 4-year-olds) or equipment failure (4-year-olds: $n = 2$, 8-year-olds: $n = 1$). The final sample thus consisted of 52 children: twenty-two 4-year-olds ($M_{\text{age in months}} = 53.81 \pm 3.16$, 11 boys) and thirty 8-year-olds ($M_{\text{age in months}} = 101.77 \pm 3.07$, 11 boys). All participants were recruited from public birth records and were all healthy with no history of neurological or psychological problems. All parents provided informed consent prior to the child's participation. Children received a small gift for their participation, and parents were compensated for their travel costs (5€). The experimental procedure was approved by the institutional review board of the affiliated university.

2.2. Materials and procedure¹

Participants were tested in a child-friendly EEG laboratory. Upon arrival in the laboratory, children were familiarized with the environment. Children were seated inside a dimly-lit cabin, in a comfortable chair, approximately 90 cm in front of a 19" computer monitor (refresh rate = 60 Hz) on which the stimuli were presented. A speaker was

¹ Please find all materials on the [Open Science Framework](#).

located next to the screen. Children were asked whether they wanted their parent(s) to be present in the cabin during the experiment. If so, the parent(s) were seated behind the child and asked not to talk or interfere during the experiment. To motivate children to pay attention during the experiment, they were given star-shaped stickers for each experimental task. Importantly, participants' movements were recorded using a webcam to avoid decreased mu power arising from participants' own movements rather than from action observation.

Stimulus presentation was controlled using PsychoPy (Peirce, 2007). The experiment consisted of three within-subjects conditions: the Human condition, the Agentic Robot condition, and the Non-Agentic Robot condition. At the start of the experiment, all participants were presented with two priming videos (Fig. 1). Each priming video featured two agents: a robot and a human. In the Agentic condition, the robot was presented as agentic and moved autonomously, while in the Non-Agentic condition, the robot was controlled by a human being via a remote control. Both priming videos were 3D animations created in Autodesk 3ds Max, Autodesk Motionbuilder, and Adobe Premiere Pro. The human's and agentic robot's animated movements were modelled onto human kinematic trajectories using motion capture. For the non-agentic robots' animated movements, the same kinematic trajectories were used, but several frames were dropped resulting in a slightly less fluent movement. Mechanical sounds were added to the robot's movement to increase the non-agentic nature of the robot. In addition to kinematic differences, the robots differed in color: one robot was purple, the other white. The color of the robots in the agentic versus non-agentic priming video was counterbalanced as well as the order in which the videos were presented.

Beyond the kinematic and visual distinctions between the agentic and non-agentic robot, the priming videos further differed in terms of content. In the Agentic Robot condition priming video, the robot is seen introducing itself to the child and drawing a picture. In contrast, in the Non-Agentic priming video, the robot is seen as being controlled by a human being via a remote control. In the video, the human being introduces herself to the child and is then seen drawing a picture with the robot, using a remote control. To avoid potential confounds, the human being is still present in this video, but does not perform any actions: she is simply standing next to the robot while it is talking to the child and drawing.

To make sure that participants distinguished different levels of agency between the two robots and to make sure they paid attention to the videos, several control questions were asked. Directly after each priming video, participants were asked three questions (i.e., "Which color did the robot in the video have? (Purple/White)"; "Can this robot do things all by itself? (Yes/No)"; "Was this robot remote-controlled? (Yes/No)"). If participants failed to answer one of these questions correctly, the video was repeated for maximally three times. If participants still failed, they were excluded from the study. After both videos were presented, there was a short break in which the experimenter set up the remainder of the study. Subsequently, children were asked a

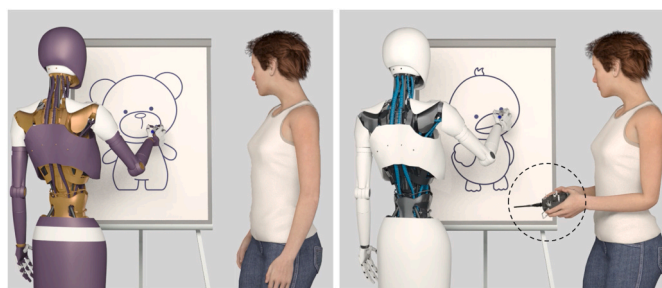


Fig. 1. Overview of the three different agents in the priming videos: the agentic robot (left), the non-agentic robot (right), and the human (both pictures). In the agentic condition, the human only accompanied the robot in the video. In the non-agentic condition, the human controlled the robot with a remote-control.

second set of control questions ("Which robot did something all by itself? (Purple/White)"; "Which robot was remote-controlled? (Purple/White)"). Again, participants had to answer these questions correctly in order to continue with the rest of the experiment.

The remainder of the experiment consisted of three blocks of 24 action observation trials. Each trial consisted of an animated video clip lasting 11.5 s, in which one of the agents (control, agentic robot, non-agentic robot) was shown grasping an object. The action clips for all three agents were created in Autodesk 3ds Max, Autodesk Motionbuilder, and Adobe Premiere Pro. The agents' animated movement was modelled onto human kinematic trajectories using motion capture. For all agents, the action videos were soundless. It should be noted that the action clips thus differed from the priming videos: in the priming videos, the kinematics of the agents differed to emphasize the differences between the robots, but in the action clips, the kinematics were matched for all three agents. This was done to ensure that any potential differences in the EEG signal between the conditions could be attributed to the agency manipulation rather than the kinematics of the agents.

For each agent condition (control, agentic robot, non-agentic robot), eight different trials were recorded: four different objects were grasped (e.g., a mug), and each grasping action was performed both from the left and right side of the screen. Per block, all 24 trials were presented in random order. In total, each trial was presented 3 times (once in each block). Each trial started with a fixation cross (500 ms) followed by a baseline still screen (2000 ms), after which the grasping action started (8000 ms) and ended with a final still screen after the action had finished (1000 ms; Fig. 2A and Fig. 2B).

In between each of the blocks, the priming videos as well as the

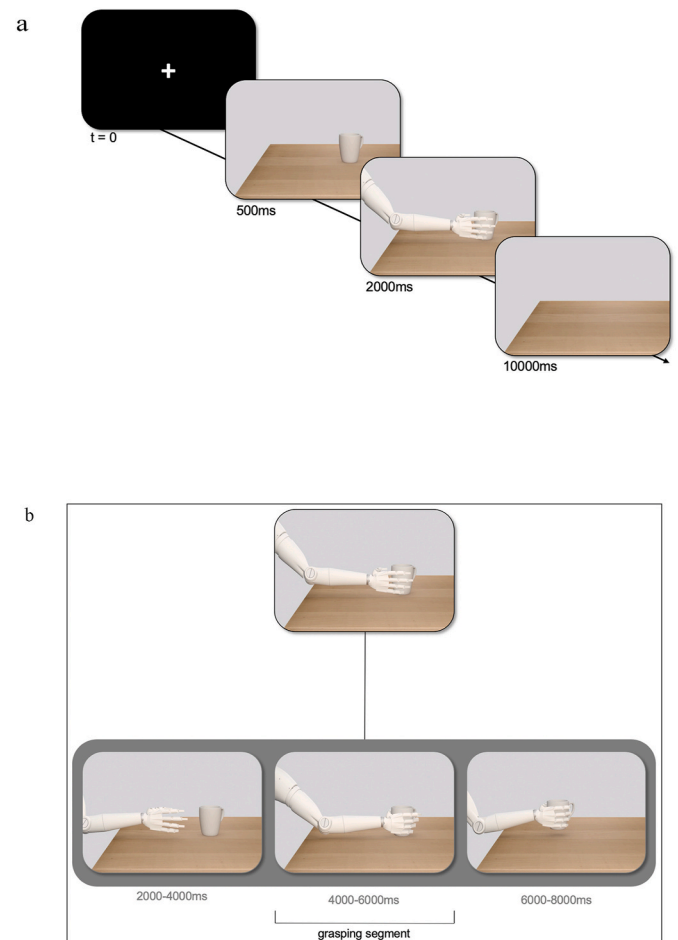


Fig. 2. (a) Overview of a trial sequence (b) with the grasping section highlighted.

manipulation check questions were repeated to ensure participants remembered which robot was agentic and which one was not. Participants who failed to answer correctly on anyone of the manipulation checks were dropped from further analysis.

2.3. EEG recording and analysis

EEG was recorded during the action observation trials, in a sound-proof, light-attenuated, and electrically shielded EEG chamber. Child-sized caps were used with 32 Ag/AgCl active electrodes (EasyCap, Germany) with a layout following the 10/20 system using a BrainAmp AC amplifier with a band-pass filter of 0.16–1000 Hz at a sampling rate of 500 Hz. All electrodes were referenced online to a central reference electrode (Cz). The ground electrode was AFz. Vertical EOG was registered by placing an electrode under the eye. Horizontal EOG was recorded with two electrodes at the outer canthi (F9 and F10). The inter-electrode impedance on all electrodes was considered acceptable at or below 25 k Ω .

EEG data were analyzed using Brain Vision Analyzer (Brain Products, Germany). Filtering was applied using a 0.1–35 Hz bandpass filter with a 50 Hz Notch and a 24 dB per octave slope. To remove eye blinks from the data, an Independent Component Analysis (ICA) was performed using restricted information maximization. Afterward, if necessary, bad channels were topographically interpolated and all data were segmented using reference markers. EEG data was re-referenced offline to the digital average of the two mastoids (T9 and T10). The data were then split into three conditions (Human, Agentic robot, and Non-agentic robot). For all trials in each condition, the 2-s segment that corresponded to the grasping motion (Fig. 2) was selected using markers. Trials with artifacts were rejected by means of the semi-automatic artifact rejection function of Brain Vision Analyzer (maximum difference of values in a segment equals 250 mV). In addition to the automatic rejection, trials in which a participant was seen to be moving or not looking at the screen were excluded from further analysis. To be included in the analysis, children needed to have at least ten valid trials per condition (the average of valid trials across conditions and participants was $n = 18$). Fast Fourier transformations (using a Hanning window) were conducted over the 2000 ms time period that corresponded to the time between the actual grasping movement. Per-participant averages of the FFTs were calculated for all three conditions. To investigate mu power during children's action perception of the three different agents, we selected the range around age-specific mu rhythm peaks (± 2 Hz) found in previous studies measuring mu power in 4-year-olds (Berchicci et al., 2011; Marshall et al., 2002) and 8-year-olds (Hasegawa et al., 2016; Lepage and Théoret, 2006). Thus, we averaged mu-frequency power over the 8–10 Hz frequency band for 4-year-olds and the 10–12 Hz frequency band for 8-year-olds. We focused on the C3, Cz, and C4 electrodes (which are located over the somatosensory cortex where an effect would be expected, cf. Oberman et al., 2008; Pfurtscheller, Brunner, Schlögel, & Lopes da Silva, 2006). In addition, mu-frequency power over the same age-specific frequency bands (8–10 Hz for 4-year-olds and 10–12 Hz for 8-year-olds) was calculated for the occipital electrodes (O1, Oz, and O2) since these can be used as a control measure to avoid confounding effects due to attentional capture with effects due to motor resonance.

3. Results

3.1. Manipulation check (behavioral)

Of the 8-year-olds, 100 percent ($n = 30$) answered the manipulation check questions correctly, while 71.0 percent ($n = 22$) of 4-year-olds managed to do so ($p = .002$, odds ratio = 25.76).

3.2. EEG data (psychophysiological)

Since the color of the robot and the order of presentation of the priming videos did not affect mu power (all p 's > 0.162), these factors were removed from models in subsequent analyses. C3, C4, and Cz were averaged and log-transformed into one central cluster. A two-way mixed ANOVA with the between-subjects factor Age (4 versus 8-year-old) and the within-subjects factor Agent (Control, Agentic robot, Non-agentic robot) was conducted to investigate the differences in mu power over the central cluster for the different agents between the two age groups (see Figs. 3 and 4 for results). While the main effect of Agent was not significant ($p = .652$), we did find a significant main effect of Age ($F(1,52) = 49.53$, $p = .000$, $\eta_p^2 = 0.49$), as well as a significant quadratic interaction between Age and Agent ($F(2,51) = 9.01$, $p = .004$, $\eta_p^2 = 0.15$). Planned follow-up repeated-measures ANOVAs showed that, while the main effect of Agent was not significant for 4-year-olds ($p = .512$), it was significant in the 8-year-old age group ($F(1,29) = 12.93$, $p = .001$, $\eta_p^2 = 0.31$). 8-year-olds on average showed significantly decreased mu power for the non-agentic robot compared to the agentic robot ($t(29) = 2.907$, $p = .007$, $d = 0.14$) and the control condition ($t(29) = 3.001$, $p = .005$, $d = 0.12$), indicating that their action processing differed for non-agentic robot movement compared to agentic robot movement or the control condition (Figs. 3 and 4).

To ensure that the Age by Agent interaction effect we reported here was not due to having used two different frequency bands, we conducted an additional analysis of the EEG data using the same frequency band (10–12 Hz) for both age groups. This showed that this main finding does not change even when considering the same frequency band for both age groups (see supplementary materials).

To exclude the possibility that potential differences in the mu rhythm

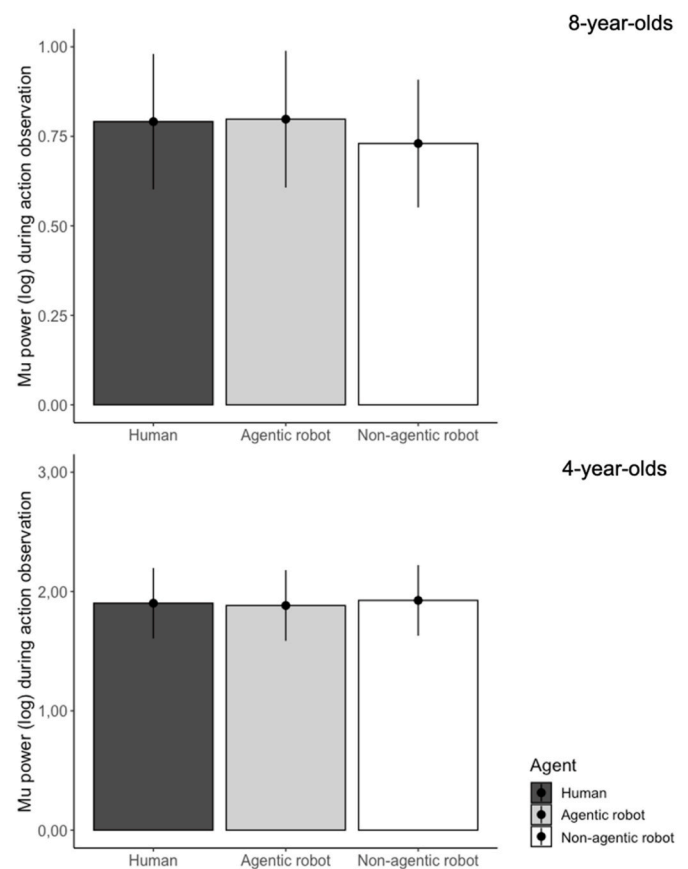


Fig. 3. Mean log-transformed mu power in microvolt (μV) for 8-year-olds (top) and 4-year-olds (bottom) during action observation of human movement (left), agentic robotic movement (middle), and non-agentic robotic movement (right).

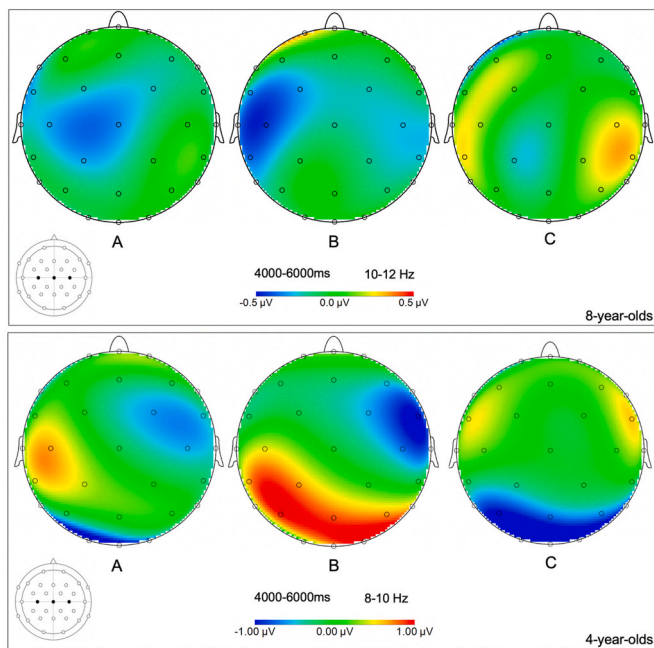


Fig. 4. The topographic maps representing power in microvolt (μV) in the mu frequency band (10–12 Hz) for 8-year olds (top) and 4-year olds (bottom), with (a) the difference between the human and non-agentic robot condition; (b) the difference between the agentic and non-agentic robot condition; and (c) the difference between the human and agentic robot condition.

could be explained by differences in attentional capture between the three conditions, a subsequent three-way repeated measures ANOVA was conducted with the between-subjects factor Age (4 versus 8-year-old) and the within-subjects factors Region (Central versus Occipital) and Agent (Control, Agentic Robot, Non-agentic robot). Results showed a significant main effect of Age ($F(1,52) = 43.19, p < .001, \eta_p^2 = 0.46$), a significant main effect of Region ($F(1,52) = 34.32, p < .001, \eta_p^2 = 0.40$), and a significant three-way interaction between Agent, Age, and Region ($F(2,51) = 9.56, p < .001, \eta_p^2 = 0.16$). This three-way interaction appeared to be driven by a differential interaction pattern between Age and Agent in the central and occipital clusters.

In the occipital region, the Agent by Age interaction was also significant ($F(2,51) = 5.63, p = .005, \eta_p^2 = 0.10$). However, in contrast to the pattern of alpha power in the central cluster, the occipital cluster contained no significant differences in alpha power between agents for the 8-year-olds (all p 's > 0.406). Yet significant differences in alpha power were found in the 4-year-old age group, between the agentic robot and the control condition ($t(22) = 2.475, p = .021, d = 0.52$), as well as between the non-agentic robot and the control condition ($t(22) = 3.211, p = .004, d = 0.73$). This pattern of alpha power in the occipital cluster was completely the opposite of the pattern found for the central cluster. Any differences in mu rhythm could thus not be explained by differences in attentional capture between the three conditions.

4. Discussion

In the current study, we investigated whether motor resonance for robotic movement is determined by the perceived agency of a robot and whether there are differences between early and middle childhood. Four- and eight-year-old participants observed movements performed by an agentic robot and a non-agentic robot while EEG was recorded. Motor resonance was operationalized by the level of suppression in the mu frequency band, with stronger suppression indicating stronger motor resonance. We hypothesized that young preschool children would not show different levels of motor resonance for agentic versus non-agentic robotic movement, while older children would start to differentiate

between agentic and non-agentic robotic movement. Results showed that, indeed, 8-year-olds resonated more strongly with the non-agentic robot than with the agentic robot and human while no such differences could be detected for 4-year-olds. This developmental difference is highly interesting, as it suggests that a child's motor cortex only becomes sensitive to the agency of a (robotic) movement later in childhood.

To fully understand the relevance and meaning of these findings, a careful examination of the different interpretations of the mu rhythm and motor resonance is required. The direct resonance interpretation of mu, which assumes that humans show the strongest motor resonance for actions that they have the most experience with, would predict that motor resonance would be the same for all agents regardless of the agency of the movement because the kinematics of the three agents were all the same. However, our findings suggest that agency does matter. Then, the ideomotor account of mu power would predict that motor resonance would be strongest for the human movement in the control condition followed by the agentic robotic movement in older children since the perception of a human and agentic robotic arm movement relates more to participants' own experiences. Yet, the findings reported here do not fully meet those predictions: while younger children indeed did not differentiate between the different agents, the older children resonated more with the non-agentic robot than the agentic robot or human.

However, a predictive coding account of the mu rhythm and motor resonance might be able to explain this pattern of findings. Predictive coding entails that motor resonance is modulated by predictions about movement patterns (Kilner et al., 2007). Based on the priming videos, 8-year-old participants may have formed certain predictions about the robots' movements. That is, the agentic robot moved seamlessly, whereas the movement of the non-agentic robot was accompanied by mechanical sounds. Yet, the kinematics of both robots and the human in the subsequent action observation trials were the same. Thus, while the kinematics in the action observation trials matched the predictions about the human and agentic robot, the expectations about the non-agentic robot were violated. The discrepancy between the predicted movement and the actual movement would have generated a prediction error, in turn driving the motor system to become more active (cf., Cross et al., 2011).

In turn, our results suggest the preschoolers do not differentiate in terms of motor resonance between agentic and non-agentic movement. Even though this younger age group was able to distinguish between the robot that moved autonomously versus the robot being remote-controlled at a behavioral level, this specific knowledge may not have translated into generalized differential predictions about their movement patterns – resulting in equal alpha rhythms for the three different agents.

In the current study, videos of the robotic and human movement were presented. The stimulus material was created in such a way that all movement characteristics were the same for all three agents. However, the visual characteristics of the agents were different: one agent was clearly a human, whereas the other two were clearly robots. By matching the movement characteristics of the three agents, we were able to control for the confounding influence of for example biological (organic) versus non-biological (mechanical) movement on the agency of movement. Moreover, since we kept the movement characteristics as well as the visual characteristic of the two robots constant across conditions, any differences we found can be attributed to the manipulation of the perceived agency of the movement, rather than differences in kinematics.

The results of this study extend upon previous research in three significant ways. First of all, previous findings on infants' and children's understanding of non-human movement provided largely inconsistent results. Some studies showed infants resonate with human movement but not with moving geometrical shapes (Reid et al., 2011). In contrast, infants' motor cortices have also been shown to respond to robotic

movement more strongly than human movement (Grossmann et al., 2013) and their processing of movement, such as of a mechanical claw, has been found to be similar to human movement (e.g., Luo and Bailargeon, 2005).

We advanced upon this mixed set of findings by introducing the concept of agency: the ability to control actions and through them, events in the external world (Chambon et al., 2014). Previous research with adults has shown that agency moderates the extent to which we resonate with movement (e.g., Müller et al., 2011; 2015). Results of the current study importantly show that the perceived agency of the actor (i.e., a robot with or without agency) does not affect pre-school children's processing of an actor's movements. However, older children's action processing begins to differentiate between agentic and non-agentic movement, and decreased mu power was found for the non-agentic robot than the agentic robot or human. An important aspect of our study is that no difference in motor resonance between the different agents could be detected for 4-year-olds, while previous research has shown that young infants process human versus non-human movement differently. This may seem paradoxical, however, the study presented here used robots as non-human agents whereas previous work mostly used mechanical claws and geometric shapes. Robots are visually similar to humans, while claws or geometric shapes clearly are not. We postulate that infants may indeed be able to distinguish between human and non-human movement when the visual contrast is big. However, when that contrast becomes smaller, such as in the current study, the differences are not so clear, and differentiation only emerges later in development.

Second, the majority of studies on the processing of non-human movement hitherto was carried out with infants (e.g., Reid et al., 2011), and the majority only assessed effects in one age group (e.g., Kuhlmeier et al., 2003) – rendering any conclusions about developmental differences impossible. In contrast, the current study investigated the neural processing of non-human movement beyond infancy: in preschoolers and 8-year-olds. To our knowledge, this is the first study to assess mu power during observation of non-human movement in this age range. Moreover, by including two age groups, we were able to draw conclusions about age-related differences between preschoolers and 8-year-olds.

Lastly, children growing up nowadays are increasingly likely to interact with robots. The majority of previous work on the processing of non-human movement included mechanical claws and geometric figures as non-human 'agents' (e.g., Müller et al., 2017). While the design of such studies allows for theoretically important questions about the origin and development of our ability to distinguish between animate and inanimate movement, it might be difficult to generalize findings to more real-life situations. In contrast, the current study used robots as non-human agents. Their movements, and the distinction between agentic and non-agentic robots, is extremely topical given the increase in household robots around the world (International Federation of Robotics, 2016). Indeed, it has been argued extensively that the research area of child-robot interaction requires more studies investigating specifically to what extent robotic movement is processed in similar terms as human movement (e.g., Cross et al., 2019; Schellen and Wykowska, 2018). Importantly, the current findings can naturally be generalized to the movements of robots that children will encounter in real life.

While the current study has theoretical and societal significance, it is also the first empirical study about children's neural processing of agentic and non-agentic robotic actions, and replications are therefore required to confirm the reliability of the results reported here. One could argue that the differences observed in this study between the agentic and non-agentic conditions are due to differences in kinematics between priming videos and observation trials, and thus unrelated to the agency of the robot. However, if that was the case, one should find similar EEG responses in both 4-year-olds and 8-year-olds. Nevertheless, to diminish the influence of kinematic differences, a replication study with an added control condition in which the physiological properties of the agentic-

and non-agentic robot in the priming videos are matched would be worthwhile. Furthermore, based on a large set of previous literature (e.g., Caetano et al., 2007; Marshall and Meltzoff, 2011; Nyström et al., 2011; Paulus et al., 2012; Pineda, 2005) one central assumption in this study was that mu rhythm is a proxy of motor resonance. Yet, it should be noted that more recently the functionality of mu power has been debated in the field (Fox et al., 2016; Hobson and Bishop, 2016; Bowman et al., 2017). Moreover, the alpha signal (originating in occipital regions) and mu signal (originating in sensorimotor areas) are known to mutually obscure processes related to action processing, perception, and attention (Hobson and Bishop, 2017; Perry and Bentin, 2010). The current study found opposite mu and alpha patterns between the different conditions, and hence it is unlikely that the mu pattern observed in 8-year-old participants can be explained by mere attention processes. However, it is still possible that the 4-year-old alpha suppression due to mental effort and/or attention confounded the observation of mu. Future research should target the precise source of the patterns in mu rhythm reported here, as well as the temporal dynamics of such patterns. For example, methods allowing for source localization such as MEG, fMRI, or fNIRS would help to further explore children's processing of human-robot interactions.

Moreover, given that the study was carried out with young children, many trials had to be excluded due to inattention or general fussiness. Because children moved a lot in between trials, the part of the trial that was intended to be used as a baseline could not be used as such – simply because many participants were moving and the mu power from their own movement interfered with the measurement of our dependent variable (decrease in mu power due to movement observation). The lack of a baseline limited our statistical inferences about the level of motor resonance. Therefore, we cannot say whether, in the 4-year-old age group, children had no motor resonance for neither agent or motor resonance for all agents. Future research should consider using a different type of baseline (e.g., longer trials) to allow for such baseline-to-observation comparisons. Lastly, to be able to closely match kinematic characteristics, the current study used stimuli of movement on a computer screen. However, Cuevas et al. (2014) suggested that live action observation is more effective than video observation for measuring mu power. Therefore, it would be valuable if future studies would include real-life observations of robotic movement.

Given the fact that children are increasingly likely to grow up around robots, questions about children's neural processing of robotic movements are becoming more and more pertinent. This study was the first of its kind in assessing motor resonance for agentic versus non-agentic robotic and human movement in preschool-aged and 8-year-old children. Our results indicate that the ability to distinguish between agentic and non-agentic robotic movement emerges later in childhood. Together with a series of similar findings in this domain (e.g., Cross et al., 2011; Saby et al., 2011; Stapel et al., 2010), our results show that the motor system of older children becomes more engaged when an observed action clashes with the prior predictions and knowledge one holds about the agent performing the action. With the frequency of child-robot interactions only increasing in years to come, this research thus forms a valuable next step towards understanding how children process robotic movement.

Author contribution

Sari R.R. Nijssen, Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. Carolina Plettim Software, Validation, Formal analysis, Investigation, Resources, Writing – review & editing, Supervision. Markus Paulus: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. Barbara C. N. Müller, Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. BM

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Appendix A. Supplementary data

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