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The Relation between Infants' Manual Lateralization and Their Performance of Object Manipulation and Tool Use

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Abstract: Previous research yielded inconsistent findings regarding whether manual lateralization (e.g., a distinct and consistent hand preference) affects manual performance during infancy and early childhood. The aim of the current study was to determine whether manual lateralization, viewed as a marker of hemispheric lateralization, is associated with infants' performance in role-differentiated bimanual manipulation (RDBM) and tool use. This longitudinal study assessed 158 typically developing infants (91 males, aged 9.13 $\pm$ 0.15 months at baseline) monthly during the 9–14-month period. Developmental trajectories for manual lateralization in object acquisition were related to those for RDBM and tool use, even after accounting for potential sex differences. All statistical analyses were conducted using Hierarchical Linear Modeling software (version 6). Advanced RDBM performance was associated with a lower magnitude of manual lateralization and a higher tendency among infants to use both hands for object acquisition. No significant relation was found between the magnitude of manual lateralization and tool-use performance. Thus, the current results highlight the importance of hand coupling for enhanced RDBM performance. Moreover, across all ages, females outperformed males in sophisticated RDBMs, possibly due to their less pronounced manual lateralization and a greater inclination towards bimanual object acquisition—factors that appear to facilitate RDBM performance.

Keywords: manual lateralization; hand-use preference; object acquisition; role-differentiated bimanual manipulation; tool use; infants

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1. Introduction

Hand-use preference, or manual lateralization, refers to an individual's consistent tendency to favor one hand over the other for various manual tasks [1]. Over time, the preferred hand becomes faster, more precise, and more effective in manual performance than the non-preferred hand, which receives fewer opportunities to "practice" [2]. For decades, hand preference has been a focus of scientific inquiry as it reflects hemispheric specialization of function (hemispheric specialization, or lateralization, denotes the specialization of the two cerebral hemispheres for processing different types of information [3]). Studying manual lateralization may offer important insights into the development of other cerebral functions (e.g., motor, language, cognitive) and assist in diagnosing neurobehavioral disorders.

Specialization of functions across the two hemispheres, along with communication between the hemispheres through the corpus callosum (the corpus callosum is the major commissural tract connecting the cerebral hemispheres and allowing for the coordination and integration of sensorimotor information to optimize information processing [4,5]), ensures more effective information processing and the emergence of new skills [6–9]. The gains in the speed and quality of information processing provided by hemispheric lateralization may translate into more advanced manual performance [10]. Due to reciprocal relations between early sensorimotor experiences and hemispheric organization, infants with a distinct hand preference are likely to differ from their peers without a hand preference in their patterns of hemispheric lateralization, sensorimotor experiences, and levels of manual performance [11]. Below, we present previous research on possible associations between children's manual lateralization and manual performance.

1.1. Manual Lateralization and Motor Coordination

Early studies reported that young children (2.5–4.5 years old) with established manual dominance scored higher on gross and fine motor coordination tasks [12]. Similarly, children aged 5–13 years with a right- or left-hand preference exhibited higher finger tapping speeds than their ambidextrous peers [13]. However, other researchers found no differences in finger tapping speeds among left-handers, right-handers, and those without a distinct preference in 4–9-year-old children [14–16]. Likewise, no relation was found between manual preference for object grasping (classified as strong, moderate, or weak right- or left-handedness) and manual performance, assessed through the kinematic analysis of movements' duration, straightness, velocity, deceleration time, and the number of movement units in 5-month-old infants [17].

Infants with a stable hand-use preference for acquiring objects reportedly exhibit better coordination of their bimanual reaching when the preferred hand is obstructed by a barrier or when it is slightly weighted [18,19]. Therefore, a hand preference was linked to the development of improved bimanual control over hand movement in space. Unfortunately, in these studies, the overwhelming majority of infants with stable handedness for acquiring objects were right-handed. If hand preference itself explains the reported differences in performance, then such differences should be observed in both right- and left-handed infants, a notion that requires further investigation. By contrast, other research showed that lower manual laterality was associated with better bimanual coordination in the bimanual crank-rotation task among 3–5-year-old children [20].

The inconsistency in the results across different research groups may be due to methodological differences in assessing manual lateralization. These differences include whether lateralization is defined as a continuous measure of lateralization or a categorical variable, estimated through hand-use preference or performance level, assessed during initial reaching or object acquisition, and observed in unimanual or bimanual tasks [21–24]. Despite handedness being inherently a continuous trait, it is often presented in research as a categorical variable, which may lead to spurious findings. Previous research demonstrated more consistent and valid results when manual lateralization was represented by a continuous measure rather than a categorical outcome and when it was measured based on the subjects' grasping of objects rather than their initial reaching movements [7,22]. Importantly, it has been suggested that the degree of laterality (i.e., the absolute value of the asymmetry index) may serve as a more reliable indicator of performance in a task than the asymmetry index itself, which retains the direction of hand dominance [25].

1.2. Manual Lateralization and Object Management/Construction

Infants with stable hand-use preferences (either left or right) demonstrated more advanced object management skills (managing multiple objects by transferring objects to the other hand or placing them within reach for future use) than their peers without stable hand preferences [26]. The observed differences may have further implications for the development of other perceptual and cognitive skills, such as exploring the properties of objects, understanding the relations between objects, and the planning of actions. In agreement, Bruner considered such object management skills to be important for the development of symbolic abilities, since the ability to store objects requires the infant to "represent" the location of the object in order for it to be retrieved later [27]. Unfortunately, in the study conducted by Kotwica et al., the majority of infants with a stable handedness for acquiring objects were right-handed [26]. Thus, this issue needs further investigation in a bigger sample representing a wider range of hand preferences.

By the age of 14 months, infants with a stable right- or left-hand preference for object acquisition at 6–14 months (classified based on the latent class analysis of developmental trajectories) were able to stack (stacking objects refers to a construction skill that entails combining multiple objects into a unified structure) significantly more objects compared to infants without a distinct hand preference [28]. The researchers proposed that manual lateralization, irrespective of its direction, leads to higher manual proficiency, which translates into the advanced performance in stacking tasks. Interestingly, this early manual advantage disappeared by the age of 18–24 months: compared to no consistent hand preference for acquisition during the 6–14-month period, consistent hand preferences were not associated with more advanced stacking or more rapid development of stacking skills during toddlerhood.

1.3. Manual Lateralization and Role-Differentiated Bimanual Manipulation

Researchers suggested that the major shift in the infant's manual skills happens during the transition from unimanual reaching and the manipulation of objects to the asymmetrical bimanual manipulation [29]. Role-differentiated bimanual manipulation (RDBM) is a manual action which involves the use of both hands—one playing an active, manipulating role and the other serving in a supporting, stabilizing role [30]. RDBM requires a high level of coordination between the two hands for the execution of the spatiotemporal sequences of bimanual actions. Therefore, its development may reflect advances in hemispheric lateralization and interhemispheric transfer [19,31–34] During the first two years of a child's life, bimanual manipulation develops from non-differentiated bimanual movements through partially differentiated movements to high levels of hand-use differentiation [35–39]. Although RDBM occurs as early as at the age of 7 months, early RDBMs likely represent affordances of particular toys rather than infants' understanding of object properties and their ability to plan sequential actions [40,41]. Recognizing potential differences between early, likely accidental, and later-developing, likely more intentional and goal-directed RDBMs, previous studies categorized RDBMs as "simple" (i.e., pokes and strokes) and "difficult" (i.e., pushes, spins, pulls, and inserts [30,42]).

Previous research produced inconsistent findings while relating manual lateralization and RDBM performance. Some researchers observed a significant decrease in infants' (6–12 months) bimanual reaches just before the onset of their first successful RDBMs, proposing that the increased independence between hands facilitates the appearance of complementary movements of the two hands necessary for successful RDBM [39]. By contrast, more recent research with 9–14-month-old infants revealed that more advanced, goal-directed RDBM was associated with the coupling of the hands in bimanual reaching [42], with no significant difference in RDBM performance between those with vs. those without a distinct and stable hand preference [30,41].

It is likely that low levels of manual lateralization might not translate into optimal developmental outcomes in object exploration, whereas very strong manual lateralization might eliminate spontaneous bimanual reaching, thus negatively affecting sophisticated bimanual object manipulation. Therefore, the relation between the magnitude of manual lateralization and developmental outcomes might form an inverted U shape, with low or excessive manual lateralization producing suboptimal developmental outcomes and only moderate levels of lateralization leading to advanced global development [2].

1.4. Manual Lateralization and Tool Use

Tool use is a manual action with one object (i.e., tool) on another object to achieve a specific goal (Connolly and Dalgleish defined tool use as "a purposeful, goal-directed form of complex object manipulation that involves the manipulation of the tool to change the position, condition, or action of another object" [29] p. 895). Examples of tool use include using a spoon for eating, driving a peg down with a hammer, using a rake to acquire a distant object, and banging a mallet on a xylophone. Tool use is a highly complex behavior; it necessitates the brain extending the "self" beyond the body's boundaries, thereby treating the tool as a continuous and functional extension of the body [29,43,44].

Tool use requires the individual's ability to execute multi-step problem solving during a task, involving understanding the relation between the tool and the object, having a clear concept of the cause and effect, dynamic planning sequences of actions to achieve a specific goal (considering internal factors, such as manual preferences and dexterity, and external ones, such as object affordances and the incoming sensory information), and executing those actions [45]. Tool-use skills develop gradually during the first 2–3 years as a result of infants' extensive experience in exploring and manipulating objects [43,46,47].

Active object exploration, allowing for trial and error and proprioceptive feedback rather than passive observation allowing only for visual feedback, significantly improves not only infants' motor control but also their understanding of relations between objects, actionable goals, and causality [29,48–51]. Only by the age of 16 to 20 months do infants start intentionally demonstrating this while using the rake tool to bring the object within reach [52].

Previous research relating manual lateralization to the early performance of tool use in humans is extremely limited. Some researchers reported an increase in manual lateralization for spoon use during the second year of life and an increase in the manual control of the tool with lateral preference (manual control here was assessed based on consistency in grip patterns and an adoptive reduction to more flexible and appropriate patterns) [29]. They concluded that "preference and specialization serve to enhance an individual's ability to manipulate the tool in an action program" ([29], p. 907). However, this research did not directly evaluate the effect of the magnitude or the direction of manual preference on tool-use performance.

In a cross-sectional study, Keen observed that some children tend to use their preferred hand while grasping a spoon, even when the latter is presented in an orientation suggesting the use of the other hand [53]. These children would transfer the spoon from one hand to the other before directing it to the mouth, lay the spoon on the table to reorient it, or continue to achieve a biomechanically awkward final position (i.e., end state) of the hand and wrist. Other children in this situation show an extension of the dominant hand but then inhibit this initial response and reach for the tool with the non-preferred hand to achieve a proper radial grip rather than an ulnar one. These results suggest that a strong hand preference might impede children's effective use of tools and success in tool-use problem solving tasks.

Moreover, in a sample of toddlers (mean age 18 months), Claxton et al. observed a two-handed grasp, with the two hands simultaneously holding the handle and the action end of a tool [54]. A two-handed grasp does not require advanced planning but may provide more flexibility and result in higher rates of success during tool-use performance. It is likely that two-handed grasps would be more prevalent in less manually lateralized children, thus facilitating their success in tool-use problem solving.

Keen suggested that children under 2 years of age are more flexible in their hand use during spoon tasks, while older children, exhibiting a more developed hand preference, are less flexible [53]. By contrast, McCarty et al. reported that younger children (9-month-old) tend to reach with their preferred hand, whereas older children (19-month-old), anticipating the future problem with the end state grip, tend to acquire the spoon with the non-preferred hand [55]. The disagreement in the observed patterns of tool use between different research groups might be attributed to methodological differences. It was suggested that the relation between manual preference and tool-use learning and performance should be further explored by future *longitudinal* research [53].

1.5. Sex Differences in Manual Lateralization

Previous research identified significant sex differences in individual lateralization patterns. Sex differences in hemispheric lateralization could be attributed to the varying effects of the prenatal exposure to low vs. high levels of testosterone [56–60]. For instance, it has been proposed that prenatal exposure to testosterone may facilitate neuronal pruning in the corpus callosum, leading to a decrease in interhemispheric transfer and an increase in hemispheric lateralization in males compared to females [60]. Indeed, previous research reported that, on average, males exhibit greater hemispheric specialization than females [61–65]. Additionally, research relating callosal anatomy to manual lateralization suggested the importance of considering not only sex differences but also the interaction between sex and hand preference [66–68]. That being said, sex differences have typically been reported in research with adult populations, while the effects of sex on the early developmental trajectories of manual lateralization and performance are mostly unexplored.

1.6. Current Study

The goal of this longitudinal study was to evaluate the relation of manual lateralization in object acquisition to infants' performance of RDBM and tool use. We hypothesized that: (1) the magnitude of manual lateralization in object acquisition, irrespective of its direction (i.e., left or right), would be associated with RDBM performance (**H1**) and tool-use performance (**H2**); and (2) the relation between manual lateralization and manual performance might be moderated by the sex variable (**H3**).

2. Methods

2.1. Participants

The sample consisted of 158 typically developing infants (91 males, 67 females) coming from full-term pregnancies ($\geq$37 weeks of gestation) and uncomplicated single births. The ethnic composition of the sample was 53% White, 28% African American, 3% Asian, 3% Hispanic/Latino, and 13% mixed ethnicity. Participants' age was 9.13 $\pm$ 0.15 months at the beginning of the study and 14.24 $\pm$ 0.19 months by the end of the study. The study was conducted under the supervision of the Institutional Review Board at the University of North Carolina at Greensboro. Parents of participating infants provided their informed consent for the inclusion of their children in the study. Participants received monetary compensation ($10 gift card per each monthly visit).

2.2. Procedures and Measures

Participants were tested monthly, within +/−7 days from infants' monthly birthdays, in a laboratory setting while sitting on the parent's lap at a table. Parents were instructed to ensure their infants' stable posture by supporting them at the waist level and to not interfere with the testing procedures. All participants were tested on object acquisition and role-differentiated bimanual manipulation from 9 to 14 months (6 monthly visits). Out of the original sample, 108 infants (55 males, 53 females) were also tested for tool use from 10 to 14 months (5 monthly visits). In this longitudinal study, data attrition was 7.28% for object acquisition and RDBM testing and 1.11% for tool-use testing.

All the testing procedures were performed in the same order (1—object acquisition; 2—RDBM; 3—TU) and consisted of different, non-overlapping sets of toys. Infants' actions during all testing procedures were recorded with two (overhead and side-view) synchronized cameras that produced a split-screen video. Behavioral coding of infants' manual actions was performed by trained research assistants using the Noldus Observer XT software (version 10, Noldus Information Technology, Wageningen, the Netherlands). For object acquisition, behavioral coding was carried in frame-by-frame slow motion, whereas RDBM and TU procedures were coded in real time.

2.2.1. Manual Lateralization in Object Acquisition

We define object acquisition as a manual action revealing the infant's control of a toy, e.g., lifting a toy from the surface of the table, moving a toy on the table, or grasping a toy during an air presentation [69]. Although both object contact (the first instance when the infant's hand gets in touch with an object) and object acquisition could be used as a marker of infants' hand-use preference, we considered that object acquisition, featuring the infant's goal-directed control of the object, would allow for a more accurate evaluation of hand-use patterns.

Object acquisition testing consisted of 34 toy trials: 10 pairs of identical toys presented in alignment with the infant's shoulders (7 on the table, 3 suspended in the air) and 24 single toys presented at the infant's midline (19 on the table, 5 in the air; see [69] for more detail). The semi-random presentation order ensured alternation of double and single, as well as table and air, presentations to reduce the possibility of a response bias. Toys were medium-sized, brightly colored, and noise-producing to elicit infants' interest and engagement. All toys were presented within the infant's reach for approximately 15 s until acquisition.

In the Noldus Observer, coders identified the hand that first acquired each toy (i.e., lifted from the table surface, moved on the table, or grasped in the air). If the hands acquired a toy (or toys in the case of toy pair presentations) within a <0.25 s interval, the acquisition was coded as bimanual. This quarter-second time frame, which is "well within the ability of the nervous system to coordinate the movements of the two arms", allowed us to reliably differentiate between unimanual and bimanual object acquisitions [69] (p. 297).

Infants' hand use for object acquisition was characterized for each monthly visit through the following measures: (1) the hand-preference index (*HPI*) (the HPI is a z-score that evaluates the relative probability of the infant's hand-use preference at a time point [70]. A positive HPI indicates a right-hand preference, whereas a negative HPI suggests a dominance of the left hand, and a HPI = 0 stands for the equal use of both hands in an activity. According to previous research, z-scores are effective in classifying infants' monthly hand-use preference [71]), signifying both the magnitude and direction of the hand-use preference, calculated as $HPI = (R - L)/(R + L)^{1/2}$, where R and L represent the total number of object acquisitions performed right-handedly and left-handedly, respectively; (2) hand-preference strength (*HPS*), signifying the magnitude of the hand-use preference, calculated as an absolute value of the HPI score; and (3) propensity for unimanual hand use (*UHU*), calculated as the proportion of unimanual object acquisitions (right and left) out of the total number of acquisitions (right, left, and bimanual). Note that only the last aspect of manual lateralization considers bimanual object acquisitions.

2.2.2. Role-Differentiated Bimanual Manipulation

RDBM performance was tested in 20 toy trials; all toys had multiple parts, thus affording sophisticated manipulation (examples of RDBM toys are illustrated in Figure 1; see [30] for more detail). Toys were presented in random order, at the midline on the table, and within the infant's reach for the time duration that would allow for at least three RDBMs. Toys with separable parts were presented in the inserted position.

Figure 1. Examples of toys used during the RDBM testing that tend to elicit poke, stroke, push, spin, pull, and insert actions.

The following RDBM actions were coded in the Noldus Observer: (1) poke—when one or two fingers of an active hand touch the toy surface; (2) stroke—when more than two fingers of the active hand are moving along the surface of a toy; (3) push—when more than two fingers of the active hand are repeatedly touching the movable part of toy surface; (4) spin—when the active hand spins a movable part of a toy; (5) pull—when the active hand pulls a part of a toy; and (6) insert—when the active hand inserts one part of a toy into another part. For each RDBM action, the active hand (right or left) would get credit. Up to three first RDBM actions were coded for each toy trial. Bouts of the same behavior (e.g., repetitive pushes or spins performed with the same finger(s)) were coded as a single RDBM action, unless they were interrupted by a pause or another action. The following outcome measures were created for RDBM: (1) total number of simple RDBMs (*RDBM_SIM*), calculated as the total number of coded pokes and strokes; and (2) total number of difficult RDBMs (*RDBM_DIF*), calculated as the total number of coded pushes, spins, pulls, and inserts.

2.2.3. Tool Use

The tool-use testing procedure involved 10 toy trials; each toy featured two components—a tool and an object on which to act with a tool. The tool-use toys implemented in this testing procedure are illustrated in Figure 2. In each trial, the correct use of a tool was demonstrated to the infant before the tool was placed on the table, at the midline within the infant's reach. Infants were given sufficient time to elicit tool-use actions during each toy trial. The following tool-use actions were coded in the Noldus Observer: (1) tool-use attempts—when the infant acts with a tool on the object but does not perform the expected/demonstrated target action; and (2) tool-use solutions—when the infant's performed tool-use action closely imitates the action demonstrated by a presenter. Up to three tool-use attempts were coded; separate tool-use attempts were coded only when the previous attempt was interrupted by another action or when another action immediately followed the previous one but was performed with a considerable modification (e.g., when a tool was used on another part of the object). The *TU_A* variable was calculated as the total number of attempts per visit. Only one tool-use solution was coded per each toy trial; the total number of tool-use solutions per visit produced the *TU_S* variable. Table 1 lists the correct tool-use action for each toy trial.

Figure 2. Toys used during the tool-use testing.

Table 1. Toy trials for the tool-use testing, with a specification of the tool, the object, and the correct, expected action of the tool on the object.

Trial #	Tool	Object	Correct Tool-Use Action
1	Mallet	Xylophone	The stick hits the top of the xylophone (at least 2 hits)
2	Block	Base	The block rubs on the base (no banging)
3	Hammer	Pegs	The hammer hits the pegs (at least 2 hits)
4	Roller	Cake	The roller rolls on the top of the cake (no banging)
5	Brush	Bowl	The brush strokes inside the bowl (no banging)
6	Wooden brush	Keys	The out-of-reach keys are moved towards the child
7	Hand stick	Chicken	The hand stick is inserted in the chicken (either stick or hand side)
8	Rake	Caterpillar	The out-of-reach caterpillar is moved towards the child
9	Stick	Food box	The stick successfully catches a food piece from the box
10	Crayon	Cake	The crayon is "drawing" on the top of the cake (no banging)

Twenty percent of the randomly selected videos were re-coded by a different coder for inter-rater reliability; another 20% of videos were re-coded by the same coder for intra-rater reliability. The resulting inter- and intra-rater agreements (measured as mean Cohen's kappas) reached, respectively, 0.91 and 0.94 for object acquisition, 0.85 and 0.89 for RDBM, and 0.94 and 0.96 for tool use.

2.3. Statistical Analyses

Statistical analyses were conducted in Hierarchical Linear Modeling software (HLM, version 6; [72]) to address the issue of non-independence arising from repeated observations of the same subjects in this longitudinal study. First, we evaluated potential developmental trends and sex differences for the variables describing manual lateralization (i.e., HPI, HPS, and UHU) by entering the latter into HLM models as dependent variables (one at a time). To test the linear and quadratic trends of change across time, we entered *AGE* and AGE^2 independent variables, reflecting the actual age of each infant (in months) at each testing visit, into the Level 1 of each model. To assess potential sex differences, we included a dummy-coded *SEX* variable (0 = males; 1 = females) into the Level 2 of each model. As a result, each model also included *AGE*SEX* and AGE^2*SEX interactions, evaluating whether the effect of sex on the developmental trajectory was dependent upon participants' age. These analyses were performed to better understand the role of sex in the development of manual lateralization in order to enable the future explanation of possible moderating effects of sex in the relation between manual lateralization and manual performance.

Next, to evaluate whether RDBM and tool-use performance are significantly associated with infants' manual lateralization, variables reflecting RDBM and tool-use performance (i.e., RDBM_SIM, RDBM_DIF, TU_A, TU_S) were entered into HLM models as dependent variables (one at a time), whereas variables marking infants' hand-use preferences for object acquisition (i.e., HPI. HPS, UHU) were entered as independent variables (one at a time). These HLM models also included *AGE*, AGE^2, and *SEX* variables, as well as *AGE*SEX* and AGE^2*SEX interactions (see above).

Statistically non-significant fixed and random effects were excluded, where possible, from the final models. Statistical significance was determined according to $\alpha lpha \leq .05$. Additionally, we reported Cohen's *d* effect size (i.e., d = 0.2 small, d = 0.5 medium, d = 0.8 large, and d = 1.2 very large effects) for all important effects to mark their magnitude and meaningfulness [73,74].

3. Results

3.1. Manual Lateralization in Object Acquisition

Statistical parameters for these analyses are presented in Table 2 and significant trends are illustrated in Figure 3. The manual lateralization measures had the following statistical characteristics: (1) the HPI ranged from −4.80 to 5.39, *Mean* = 0.73, *SD* = 2.00; (2) the HPS ranged from 0 to 5.39, *Mean* = 1.77, *SD* = 1.19; and (3) the UHU ranged from 0.22 to

1.00, *Mean* = 0.69, *SD* = 0.17. Both the HPS and the UHU showed significant age and sex differences, whereas the HPI showed none. Across age, females exhibited considerably lower HPS and slightly lower UHU compared to males. Moreover, males showed quite stable HPS across age, whereas females significantly decreased their HPS with age. Both sexes slightly decreased their UHU with age.

Table 2. Statistical parameters for HLM models evaluating change across time and sex differences in manual lateralization.

Dependent Variables	Statistical Parameters
HPI	*Intercept*: $\beta = 0.71$, $SE = 0.46$, $t(156) = 1.54$, $p = .125$ *SEX*: $\beta = 0.26$, $SE = 0.23$, $t(156) = 1.15$, $p = .254$ *AGE*: $\beta = -0.004$, $SE = 0.04$, $t(157) = -0.12$, $p = .906$
HPS	*Intercept*: $\beta = 6.37$, $SE = 2.54$, $t(156) = 2.51$, $p = .013$ *SEX*: $\beta = -10.14$, $SE = 4.29$, $t(156) = -2.36$, $p = .019$ *AGE*: $\beta = -0.73$, $SE = 0.44$, $t(156) = -1.67$, $p = .097$ *AGE*SEX*: $\beta = 1.76$, $SE = 0.74$, $t(156) = 2.38$, $p = .018$ AGE^2: $\beta = 0.03$, $SE = 0.02$, $t(561) = 1.51$, $p = .132$ AGE^2*SEX: $\beta = -0.08$, $SE = 0.03$, $t(561) = -2.40$, $p = .017$
UHU	*Intercept*: $\beta = 0.94$, $SE = 0.04$, $t(156) = 23.99$, $p < .001$ *SEX*: $\beta = -0.05$, $SE = 0.02$, $t(156) = -2.53$, $p = .012$ *AGE*: $\beta = -0.02$, $SE = 0.003$, $t(157) = -6.49$, $p < .001$

Note. HPI = hand-preference index; HPS = hand-preference strength; UHU = propensity for unimanual hand use.

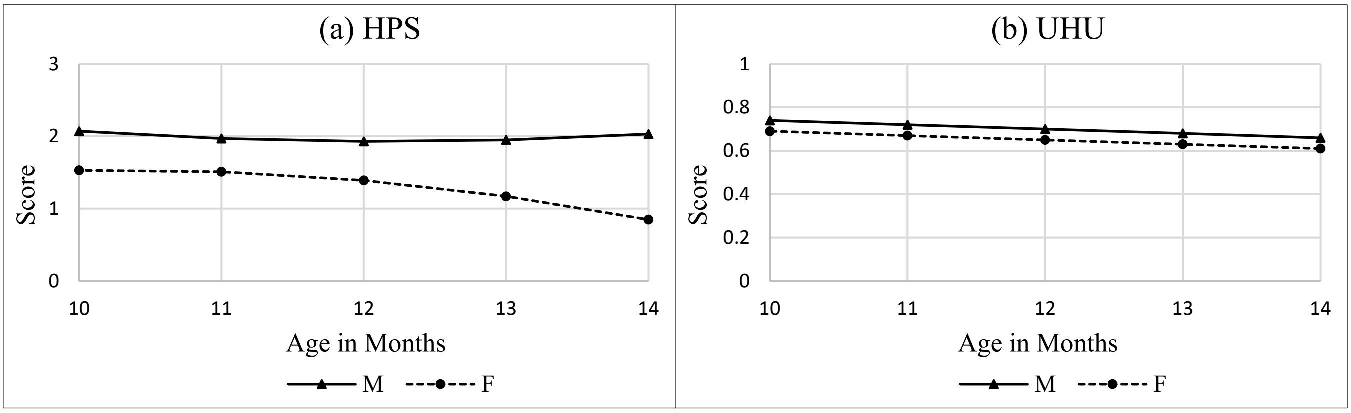

Figure 3. Estimated trajectories for the hand-preference strength (HPS) and the propensity for unimanual hand use (UHU) variables; M = males; F = females.

3.2. Manual Lateralization and RDBM Performance

Statistical parameters for these analyses are presented in Table 3 and developmental trends are illustrated in Figure 4. The number of difficult RDBMs increased with age in both males and females, whereas the number of simple RDBMs increased in males and remained quite stable in females across the entire 9–14-month period. Across ages, males on average performed consistently more simple RDBMs than females (except during the 9–10-month period), whereas females outperformed males in the number of difficult RDBMs.

Furthermore, the HPI, an index indicating both the direction and the magnitude of manual lateralization, was not associated with infants' performance of either simple or difficult RDBMs. By contrast, a significant association was detected between the HPS, an index signifying the magnitude of manual lateralization irrespective of its direction, and the performance of both simple and difficult RDBMs. Males and females with a distinct hand preference (right or left) showed significantly fewer simple and difficult RDBMs than their peers without a distinct hand-use preference. Moreover, we found that infants' propensity for unimanual hand use was associated with a lower performance of both simple and difficult RDBMs. Thus, the more infants used both hands for acquiring objects, the better RDBM performance they demonstrated across the 9–14-month period.

Table 3. Statistical parameters for HLM models evaluating the relation between reaching lateralization parameters and RDBM performance; Cohen's *d* effect size is specified for the focus variables.

Independent Variables	Dependent Variables
	Simple RDBMs
HPI	*Intercept*: $\beta = -26.70$, $SE = 10.25$, $t(156) = -2.60$, $p = .010$ *SEX*: $\beta = 42.74$, $SE = 16.49$, $t(156) = 2.59$, $p = .010$ *AGE*: $\beta = 6.47$, $SE = 1.79$, $t(716) = 3.62$, $p < .001$ *AGE*SEX*: $\beta = -7.25$, $SE = 2.87$, $t(716) = -2.53$, $p = .012$ AGE^2: $\beta = -0.26$, $SE = 0.08$, $t(716) = -3.42$, $p < .001$ AGE^2**SEX*: $\beta = 0.30$, $SE = 0.12$, $t(716) = 2.44$, $p = .015$ *HPI*: $\beta = -0.14$, $SE = 0.10$, $t(716) = -1.51$, $p = .132$, $d = 0.11$
HPS	*Intercept*: $\beta = -23.90$, $SE = 11.19$, $t(156) = -2.14$, $p = .034$ *SEX*: $\beta = 39.20$, $SE = 18.27$, $t(156) = 2.15$, $p = .033$ *AGE*: $\beta = 6.10$, $SE = 1.91$, $t(716) = 3.20$, $p = .001$ *AGE*SEX*: $\beta = -6.64$, $SE = 3.13$, $t(716) = -2.12$, $p = .034$ AGE^2: $\beta = -0.25$, $SE = 0.08$, $t(716) = -3.08$, $p = .002$ AGE^2**SEX*: $\beta = 0.27$, $SE = 0.13$, $t(716) = 2.06$, $p = .039$ *HPS*: $\beta = -0.35$, $SE = 0.15$, $t(716) = -2.37$, $p = .018$, $d = 0.18$
UHU	*Intercept*: $\beta = -23.89$, $SE = 11.07$, $t(156) = -2.16$, $p = .033$ *SEX*: $\beta = 42.32$, $SE = 18.43$, $t(156) = 2.30$, $p = .023$ *AGE*: $\beta = 6.39$, $SE = 1.89$, $t(156) = 3.38$, $p < .001$ *AGE*SEX*: $\beta = -7.22$, $SE = 3.16$, $t(156) = -2.29$, $p = .024$ AGE^2: $\beta = -0.26$, $SE = 0.08$, $t(560) = -3.28$, $p = .001$ AGE^2**SEX*: $\beta = 0.30$, $SE = 0.13$, $t(560) = 2.24$, $p = .026$ *UHU*: $\beta = -2.99$, $SE = 1.08$, $t(560) = -2.77$, $p = .006$, $d = 0.23$
	Difficult RDBMs
HPI	*Intercept*: $\beta = -17.08$, $SE = 0.99$, $t(156) = -17.35$, $p < .001$ *SEX*: $\beta = 1.93$, $SE = 0.50$, $t(156) = 3.84$, $p < .001$ *AGE*: $\beta = 2.17$, $SE = 0.09$, $t(157) = 24.00$, $p < .001$ *HPI*: $\beta = -0.05$, $SE = 0.07$, $t(562) = -0.74$, $p = .461$, $d = 0.06$
HPS	*Intercept*: $\beta = -16.10$, $SE = 1.05$, $t(156) = -15.27$, $p < .001$ *SEX*: $\beta = 1.90$, $SE = 0.50$, $t(156) = 3.84$, $p < .001$ *AGE*: $\beta = 2.14$, $SE = 0.09$, $t(157) = 23.63$, $p < .001$ *HPS*: $\beta = -0.38$, $SE = 0.11$, $t(562) = -3.37$, $p < .001$, $d = 0.28$
UHU	*Intercept*: $\beta = -14.98$, $SE = 1.32$, $t(156) = -11.34$, $p < .001$ *SEX*: $\beta = 1.81$, $SE = 0.50$, $t(156) = 3.61$, $p < .001$ *AGE*: $\beta = 2.12$, $SE = 0.09$, $t(157) = 22.79$, $p < .001$ *UHU*: $\beta = -2.27$, $SE = 0.88$, $t(562) = -2.58$, $p = .001$, $d = 0.22$

Note. HPI = hand-preference index; HPS = hand-preference strength; UHU = propensity for unimanual hand use.

3.3. Manual Lateralization and Tool-Use Performance

Statistical parameters for these analyses are presented in Table 4 and developmental trends are illustrated in Figure 5. Across ages, we observed a significant decrease in the number of tool-use attempts and a significant increase in the number of correctly performed (solved) tool-use actions. Males outperformed females in tool-use attempts during the entire 10–14-month period, whereas no sex differences were observed for tool-use solutions.

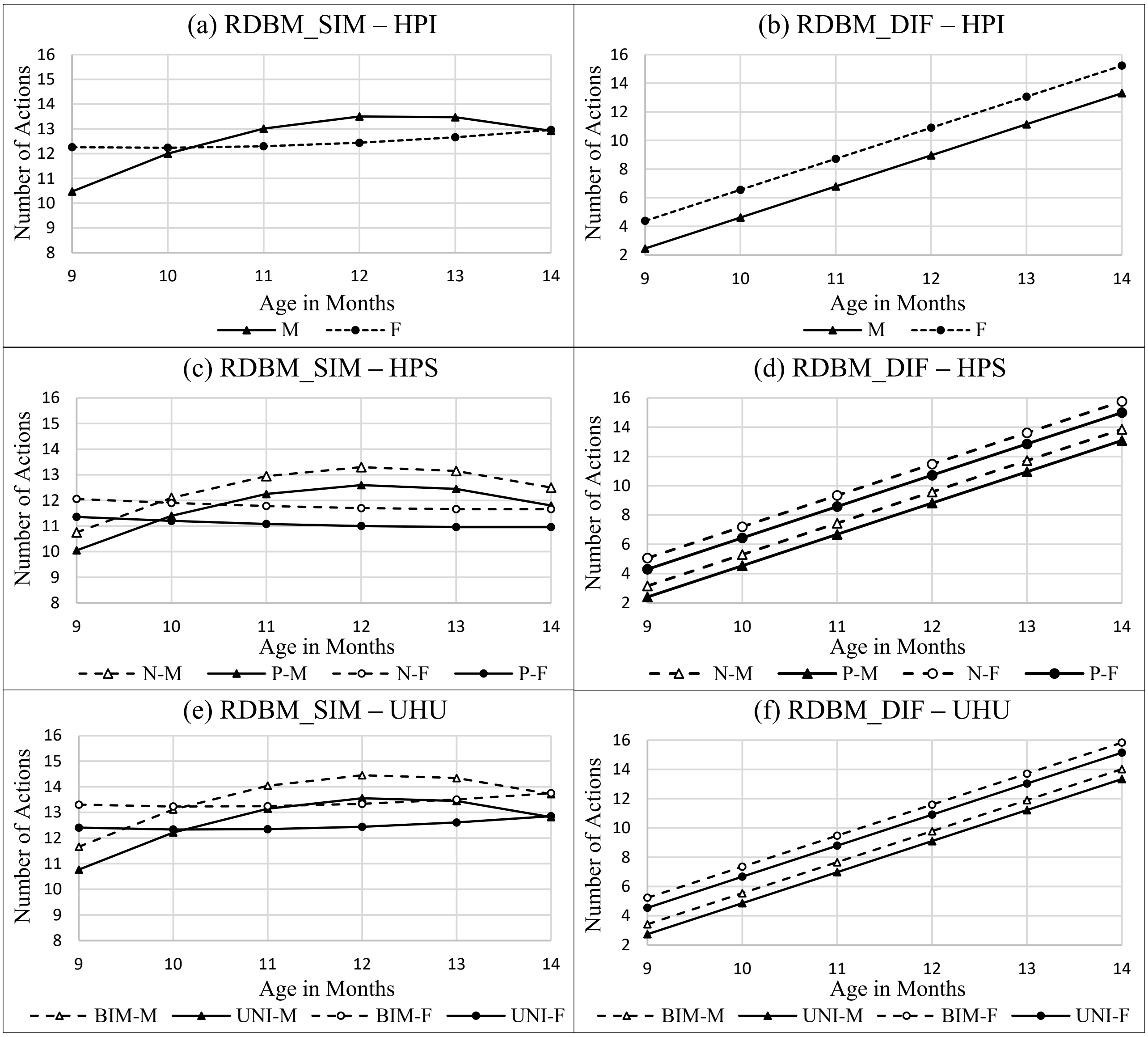

Figure 4. Estimated trajectories for RDBM performance, depending on hand-use patterns in male and female subjects; M = males; F = females; N = infants without a distinct preference for object acquisition; P = infants with the right- or left-hand preference for object acquisition; BIM = infants showing predominantly bimanual pattern of object acquisition; UNI = infants showing predominantly unimanual pattern of object acquisition.

Table 4. Statistical parameters for HLM models evaluating the relation between reaching lateralization parameters and tool-use (TU) performance; Cohen's *d* effect size is specified for the focus variables.

Independent Variables	**Dependent Variables**
	Incorrect Tool-Use Actions (TU_ATT)
HPI	*Intercept*: $\beta = 11.00$, $SE = 1.28$, $t(106) = 8.59$, $p < .001$ *SEX*: $\beta = -0.65$, $SE = 0.28$, $t(106) = -2.34$, $p = .021$ *AGE*: $\beta = -0.44$, $SE = 0.10$, $t(107) = -4.24$, $p < .001$ *HPI*: $\beta = -0.07$, $SE = 0.07$, $t(317) = -1.06$, $p = .292$, $d = 0.12$
HPS	*Intercept*: $\beta = 11.07$, $SE = 1.26$, $t(106) = 8.78$, $p < .001$ *SEX*: $\beta = -0.67$, $SE = 0.28$, $t(106) = -2.41$, $p = .018$ *AGE*: $\beta = -0.44$, $SE = 0.10$, $t(107) = -4.28$, $p < .001$ *HPS*: $\beta = -0.06$, $SE = 0.11$, $t(317) = -0.58$, $p = .562$, $d = 0.07$

Table 4. *Cont.*

Independent Variables	Dependent Variables
	Incorrect Tool-Use Actions (TU_ATT)
UHU	*Intercept*: $\beta = 10.12$, $SE = 1.38$, $t(106) = 7.31$, $p < .001$ *SEX*: $\beta = -0.63$, $SE = 0.28$, $t(106) = -2.21$, $p = .029$ *AGE*: $\beta = -0.42$, $SE = 0.10$, $t(107) = -4.14$, $p < .001$ *UHU*: $\beta = 0.88$, $SE = 0.81$, $t(317) = 1.09$, $p = .278$, $d = 0.12$
	Correct Tool-Use Actions (TU_S)
HPI	*Intercept*: $\beta = -6.38$, $SE = 0.65$, $t(107) = -9.77$, $p < .001$ *AGE*: $\beta = 0.90$, $SE = 0.05$, $t(107) = 17.32$, $p < .001$ *HPI*: $\beta = 0.08$, $SE = 0.03$, $t(317) = 2.26$, $p = .025$, $d = 0.25$
HPS	*Intercept*: $\beta = -6.36$, $SE = 0.67$, $t(107) = -9.52$, $p < .001$ *AGE*: $\beta = 0.89$, $SE = 0.05$, $t(107) = 17.20$, $p < .001$ *HPS*: $\beta = 0.04$, $SE = 0.05$, $t(317) = 0.72$, $p = .472$, $d = 0.08$
UHU	*Intercept*: $\beta = -6.75$, $SE = 0.78$, $t(107) = -8.61$, $p < .001$ *AGE*: $\beta = 0.91$, $SE = 0.05$, $t(107) = 17.10$, $p < .001$ *UHU*: $\beta = 0.55$, $SE = 0.46$, $t(317) = 1.20$, $p = .233$, $d = 0.13$

Note. HPI = hand-preference index; HPS = hand-preference strength; UHU = propensity for unimanual hand use.

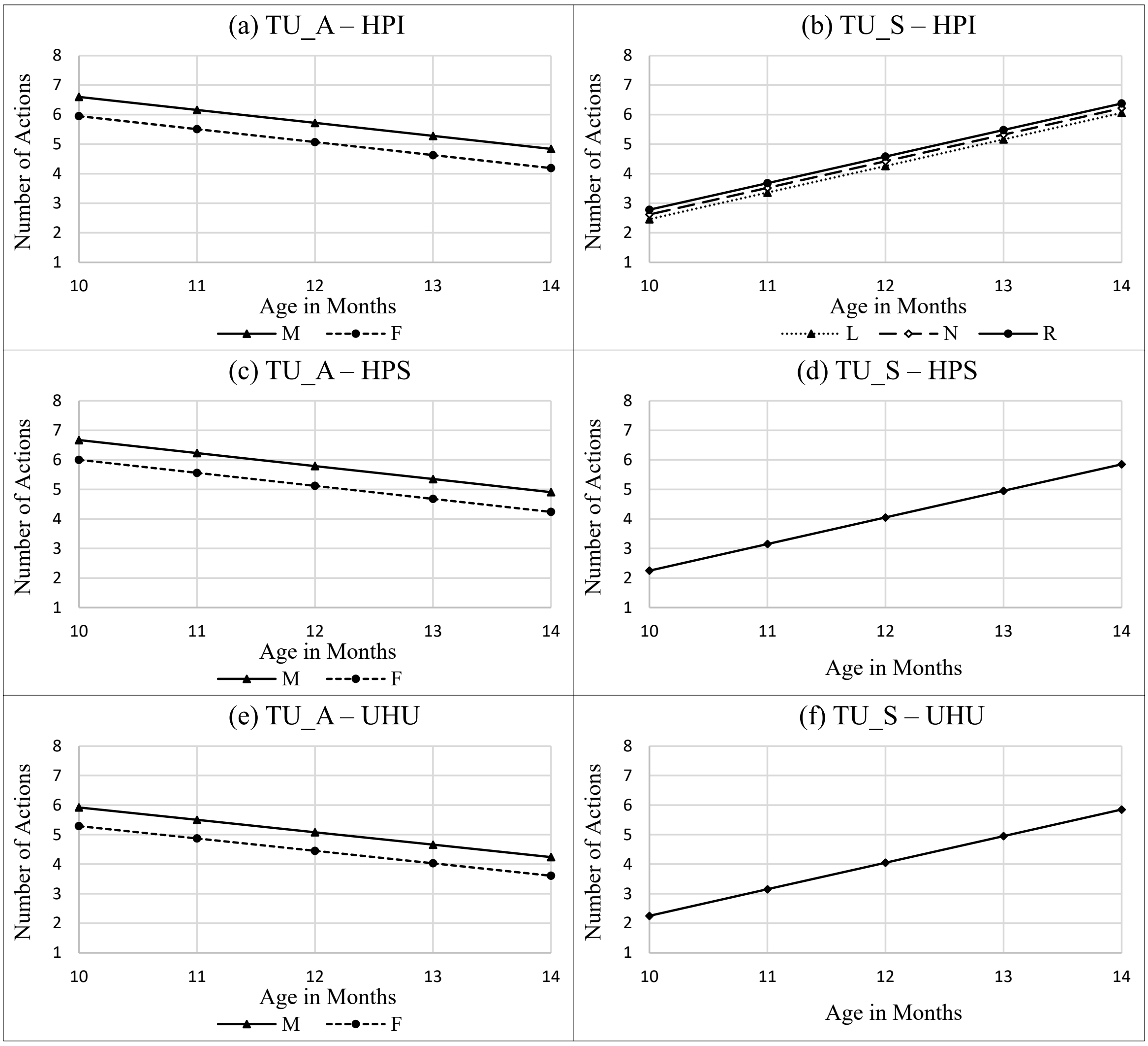

Figure 5. Estimated trajectories for tool-use performance, depending on hand-use patterns in male and female subjects; M = males; F = females; L = infants with the left-hand preference for object acquisition; N = infants without a distinct hand preference for object acquisition; R = infants with the right-hand preference for object acquisition.

We also found a significant effect of manual lateralization on the performance of the correct tool-use actions (solutions): infants with the right-hand preference for object acquisition slightly outperformed those without a distinct preference, who, in turn, outperformed infants with the left-hand preference. By contrast, there was no relation between manual lateralization and the performance of tool-use attempts.

4. Discussion

The goal of this longitudinal study was to explore manual performance in relation to manual lateralization. In specific, we evaluated the association between infants' manual lateralization in object acquisition and their performance of role-differentiated bimanual manipulation and tool use. Below, we outlined the current findings in the light of hypotheses proposed.

4.1. Manual Lateralization and RDBM Performance

In our hypothesis **H1**, we predicted that the magnitude of manual lateralization in object acquisition, irrespective of its direction (i.e., left or right), would be associated with RDBM performance. In support of this hypothesis, we observed that the direction of manual lateralization (i.e., HPI) showed no effect on the performance of RDBMs. Moreover, the magnitude of manual lateralization was found to be *negatively* associated with RDBM performance. Infants with a higher magnitude of manual lateralization (i.e., strong left- or right-hand preference for object acquisition) demonstrated an inferior RDBM performance (fewer simple and difficult RDBMs) compared to their peers with a lower magnitude of manual lateralization (no distinct hand-use preference for object acquisition). Similarly, infants' propensity for unimanual hand use—another indicator of manual lateralization—showed the negative effect on the performance of simple and difficult RDBMs. Thus, the coupling of the hands, either in bimanual object acquisition or in frequent alterations between the left- and right-handed object acquisitions, seems to be most beneficial for RDBM performance.

The current findings corroborate previous studies indicating that the *magnitude* of laterality is a more accurate predictor of performance than the *direction* of asymmetry [25]. They are also consistent with research showing that the coupling of the hands in bimanual reaching improves RDBM performance [42]. Despite the similarities in outcomes, it is important to note the methodological differences between the two studies. Babik and Michel investigated differences in RDBM performance among three hand-preference groups (left-handers, those without a preference, and right-handers), classified according to the latent classes identified in their developmental trajectories for object acquisition hand preference [42]. However, considering that infant hand preference can be variable and unstable [75–81], a more logical approach might be to examine the correspondence between the *concurrent* manual lateralization and manual performance. Therefore, the current study evaluated the relation *between longitudinal trajectories* of manual lateralization and RDBM performance. Arriving at similar conclusions while using different methods lends further credibility to these findings. Furthermore, Babik and Michel did not account for sex differences in their study, whereas the current study highlighted significant sex effects that deepen our understanding of the manual lateralization development and its association with manual performance (see below for more detail) [42].

4.2. Manual Lateralization and Tool-Use Performance

In our hypothesis **H2**, we predicted that the magnitude of manual lateralization in object acquisition, irrespective of its direction (i.e., left or right), would be associated with tool-use performance. The current results did not provide evidence in support of this hypothesis. First, we found that the magnitude of manual lateralization had no effect on tool-use performance. Second, we observed differences in tool-use performance based on the direction of manual lateralization. For example, infants with the right-hand preference for object acquisition more frequently correctly solved tool-use tasks compared to their peers with the left-hand preference, with infants exhibiting no distinct hand-use preference scoring in between the left- and right-hand preference groups. Although these differences are statistically significant, they have a small effect size (Cohen's $d = 0.25$).

The current findings can be explained by previous research suggesting that the planning and execution of manual actions during tool use are predominantly lateralized to the left hemisphere [82,83], which also oversees temporal processing during the performance of finely timed, sequential motor actions [84–86]. In this case, right-handers, having motor control of their dominant hand in the contralateral left hemisphere, might have an advantage in tool-use tasks compared to left-handers. Since the majority of infants without a distinct handedness are late-developing right-handers [30,87,88], they might also have an advantage over left-handers. Moreover, a larger corpus callosum and more efficient interhemispheric transfer in infants without a distinct hand preference [22,89,90] may further facilitate their tool-use performance compared to left-handed infants. However, it is important to note that the most recent meta-analyses conducted by the same research group showed no reliable association between handedness and the size of the corpus callosum [91,92].

In summary, contrary to some previous research, the current results do not support the notion that a distinct and stable hand preference leads to better manual performance [13,26,28,39]. On the contrary, the current findings align with other studies suggesting that a more balanced use of the two hands and improved bimanual coordination lead to enhanced manual performance [20,42]. *What factor might influence the effect of manual lateralization on manual performance during early development?* Reflecting on previous research and the current results, we propose that the nature of the manual task plays a critical role. In tasks that rely heavily on unimanual dexterity (e.g., finger tapping, object storage, peg moving, object stacking), manual lateralization may improve performance. However, in tasks requiring coordination between the two hands (e.g., RDBM, tool use), distinct manual lateralization may have no effect or could even hinder performance.

Furthermore, it is important to emphasize that an extreme degree of manual lateralization can impede the child's ability to perform sophisticated manual actions requiring bimanual coordination. It may also be indicative of a neurobehavioral disorder; therefore, moderate levels of asymmetry could be regarded as beneficial [78]. Indeed, strong hand preferences have been previously observed in clinical populations of children with cerebral palsy (cerebral palsy refers to a group of permanent, non-progressive neurological disorders of posture and movement control adversely affecting children's motor function [93,94]) and arthrogryposis multiplex congenita (arthrogryposis is a congenital, non-progressive neuromuscular condition featuring pronounced joint contractures, muscle weakness, and impaired movement in the upper and/or lower extremities [95,96]) [2,97–99]. In a study of children with arthrogryposis, an experimental increase in the use of the non-preferred hand—facilitated by the Playskin Lift™ exoskeletal garment—led to significant improvement in manual performance [2]. This improvement was demonstrated by increased bimanual object interaction and more intense, variable, and complex object exploration. Therefore, we suggest that the more balanced involvement of the two hands in object manipulation, indicating a decrease in the magnitude of manual lateralization, might improve manual performance and advance the development of manual skills.

4.3. Manual Lateralization and Performance: The Role of Sex

In our hypothesis **H3**, we predicted that the relation between manual lateralization and manual performance might be moderated by the sex variable. Although the current results suggested no such moderation effect, we observed significant sex differences in the trajectories of RDBM and tool-use performance. For example, across age, females showed a lower frequency of simple RDBMs and a higher frequency of difficult RDBMs compared to males. As simple RDBMs are often accidental and only difficult RDBMs highlight the true level of infants' object manipulation skills [30], we would suggest that females seem to outperform males in their RDBM. These results correspond to previous research showing more advanced fine motor skills in 3–4-year-old females compared to males [100]. Interestingly, compared to males, females on average exhibited a lower magnitude of manual lateralization and a higher propensity for bimanual hand use—factors that showed to facilitate the performance of RDBM. Thus, females' advantage in RDBM performance might stem from their manual lateralization patterns. However, the sex effects observed in the current study account for variance beyond that explained by the effect of manual preference. Future research should further explore the effect of sex on the relation between manual lateralization and performance.

Furthermore, although no differences were observed between males and females in correct tool-use actions, males demonstrated more incorrect tool-use actions than females. It is important to note that the main developmental trends show a decrease in incorrect tool-use actions and an increase in correct ones with age. Given this, the fact that males outperform females in incorrect tool-use actions could indicate either that males engage in more experimentation that does not result in correct problem solving, or that males have a lower understanding of how to solve tool-use tasks correctly compared to females during this developmental period.

The current results support previous research suggesting that females are less lateralized than males [61–64]. Prior studies also highlighted the importance of considering the interaction between sex and manual lateralization [66–68]. However, we found no evidence that our outcome variable, manual performance, is significantly affected by the interaction between sex and hand preference. Importantly, most previous research has focused on the impact of sex on the development of manual asymmetries in older children or adults, while this study offers valuable insights into the *early* effects of sex on manual lateralization and performance.

4.4. Conclusions, Limitations, and Future Directions

The current longitudinal study offers important insights into the development of role-differentiated bimanual manipulation and tool use in relation to infants' manual lateralization and sex. We observed that a more advanced RDBM performance was associated with a lower magnitude of lateralization and a greater tendency to acquire objects with both hands. By contrast, no significant relation was found between the magnitude of manual lateralization and tool-use performance. Thus, the current results highlight the importance of hand coupling for a more advanced performance of role-differentiated bimanual object manipulation.

The observed lack of a significant relation between manual lateralization and tool-use performance could result from the limited timeframe during which these manual patterns were observed. Although the age range of 10–14 months is a period of profound improvement in tool-use skills, tool use has an extended developmental timeline and should be studied longitudinally at least until the age of 3 years. Moreover, future research should thoroughly investigate both the *sensorimotor* and *cognitive* aspects of RDBM and tool-use development in typically developing children, as well as in children with motor and cognitive delays.

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