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NEONATAL MANUAL SPECIALIZATION IN LANGUAGE AND MUSIC CONDITIONS: CONSISTENCY WITH THE HEMISPHERIC SPECIALIZATION ADULT MODEL

F. MORANGE-MAJOUX^{1,2} & E. DEVOUCHE¹

Université de Paris, LPPS, F-92100 Boulogne-Billancourt, France

Address for correspondence

F. Morange-Majoux
Université de Paris
Laboratoire de Psychopathologie et Processus de Santé (URP 4057)

¹ 71 avenue Edouard Vaillant
92100 Boulogne-Billancourt
France
+33 1 76 53 29 43
francoise.morange-majoux@parisdescartes.fr; francoise.morange-majoux@u-paris.fr

² Laboratoire Paragraphe EA 349, Paris 8 University, 2 Rue de la Liberté, 93200,
Saint-Denis, France

Conflict of interest

The authors declare no conflicts of interest. They also declare that the research was conducted in accordance with APA ethical standards.

ABSTRACT

The main purpose of this study was to test in neonates the influence of the sound environment, *i.e.*, language versus music, on asymmetric hand movement activity in the presence of a target object. Based on hemispheric specialization, our hypothesis was that infants would use their right hand more in the speech context (left hemisphere) and their left hand more in the music context (right hemisphere). The study involved 19 full-term 3-day-old neonates. An object was presented successively in the two sound environments in counterbalance order for 120 s each. Left and right movements and mouth activity were scored during the target object presentation. Results show that neonates moved their left hand twice as much as their right hand in the music condition than in the language condition, and they moved their right hand a longer time in the language condition than in the music condition. The average number of sucking bursts was significantly higher in the language condition than in the music condition. We discuss the results in terms of manual specialization in relation to the development of hemispheric specialization.

Keywords: handedness, manual specialization, development, hand movement, hemispheric specialization, newborns

INTRODUCTION

Hemispheric specialization and handedness are the two major asymmetries of the human brain and behavior [1]. Functional hemispheric specialization is described as a left hemisphere advantage for speech production, planning of sequential acts [2], and temporal organization of perceptual and/or motor information and information processing during ongoing movement [3]. Conversely, a right hemisphere advantage has been described for processing music, such as rhythm, pitch, melody, and harmony [4]; decoding emotional content and spatial planning of a task and allocating attention in space [5]. Handedness is described as a strong right-hand use preference for unimanual activities. In bimanual activities, handedness appears in the differentiated and complementary use of both hands: typically, the left-hand supports the fine motor manipulation actions of the right-hand [6]. These bimanual actions require sophisticated bimanual coordination and intense inter-hemispheric information transfer [7]. Even if this right-handedness is not associated with the left-brain specialization for the language [8], some researchers have proposed that language and right handedness could be linked phylogenetically: evolutionarily, primitive language, gestures and movements, such as pointing and/or symbolic gestures, were the primary form of communication. These communicative gestures could have played a key role in the evolution of right-handedness and cerebral asymmetries, yielding the same original brain mechanisms for nonverbal and verbal communication, praxis, and language. In this approach, right-handedness would have evolved because communicative activities involve a certain level of complexity in terms of organization, planning, and production that is specialized in the left hemisphere [9]. Thus, we need to explore this link not only from the functional but also from developmental perspectives, in order to evaluate hand-use preference in specific situations and at different ages, using cognitive or perceptive functions known to be lateralized in one hemisphere, i.e., in visuospatial, language, or musical situations.

The goal of this study was to test in neonates the influence of a speech environment, as compared to a music environment, on asymmetric hand/arm movement activity in the presence of a target object. A recent study showed that an asymmetric hand activity could occur according to the sound environment during a short period in the first year of life : 5–7-month-old infants used their left hand more to reach for an object when they listened to a piece of classical music as compared to adult speech; From 8 months, a lateral right bias for reaching for an object occurred and increased strongly until 12 months whatever the sound context [10]. Such a manual asymmetry has been interpreted as the expression of hemispheric specialization: leftward hemispheric asymmetries develop gradually for high order language areas during childhood [11,12] and already, at birth, the perisylvian region of the left hemisphere is activated when neonates listen to speech in their native language, similar to that found in human adults [13,14]. Moreover, the onset of babbling around 6 months is associated with intrahemispheric connectivity in the left hemisphere instead of initial interhemispheric connectivity, favoring the left hemisphere specialization for language [15], and is associated with increased right hand activity [16]. The progressive increase of right hand use between 5 and 12 months (from 38% to 66%) could be associated with language specialization in the left hemisphere [10]. On the contrary, rightward hemispheric asymmetries are present as soon as the first hours of life for music processing [17] with an activation in the right primary auditory cortex [18]. The advantage of left-hand use between 5 and 7 months could reflect the right specialization for rhythmic and music [10]. From this perspective, hemispheric specialization for language and music would develop independently.

Few studies have investigated the patterns of a *manual specialization* in infants whereas there is evidence of an early hemispheric specialization [19]. However, in adults, such a manual specialization exists and is revealed in tasks requiring specific skills. Thus, the left hand usually has a reaction time advantage in goal-directed aiming [20]. In a repetitive target pointing task, right-handed adults perform more rapid and complex hand

movements with their left hand than left-handed adults with their right-hand and exhibited more transfer of training from the left hand to the right hand than *visa versa* [21]. This left-hand advantage is associated with preparing the spatial aspects of the movement and directing visual attention to a specific location in space through the right hemisphere. Conversely, the right hand is superior at movement execution [22] and in a fine building task, left-handers use their right hand 50% of the time [23] and increase their right-hand use to pick up small *versus* big pieces [24]. This *manual specialization* task-dependence reflects the underlying functionality associated with the hemispheric specialization, and is observed independently of handedness [25–27]. In children, the major interest on this question concerns the asymmetric development of gestures during the second year of life. Indeed, deictic gestures (e.g., pointing) are more often produced by the right hand during the second year of life [28,29] and the lexical spurt is accompanied by an increase of the right hand for pointing but not for manipulation [30], supporting the idea that right-hand preference could be associated with advanced language skills, developed in the left hemisphere [31].

In neonates, except for the study of Morange-Majoux et al. (2019), a similar one by Young and Gagnon (1990), and the recent research of Somogyi et al. (2021), such a *manual specialization* has not been investigated in these terms during the first weeks of life, and *a fortiori*, at birth. Young and Gagnon (1990) conducted the first study in this area. They examined 46 seated, healthy male and female 2-day-olds. The seat was equipped with a white bar, positioned above the subject's waist area and at the shoulder level. The experimenter stood behind the subject and symmetrically placed his or her hands on a bar, and recorded head and manual activity during 20 varying low-intensity, 60 db, 2-sec musical stimuli or matched consonant-vowel speech stimuli (10 each) in order to determine their lateralized search response backwards to the left or the right. In the data analysis, the authors used a laterality index, which allowed for determining the ratio of left and right sided behavior to both the stimuli conditions. The results indicated that the newborns manifested a marked preference to turn more to the left to musical stimuli (and more to the right to speech

stimuli (relative to their initial baseline head position). The nature of the results for the neonates' manual behavior was analogous to that of the turning data. For one finding, up to 76% of the participants expressed this pattern. The authors concluded that the results indicate that the right brain is specialized even from birth for musical functions and the left side for speech [19]. Somogyi et al. (2021) have studied the self-touch movements of 2-weeks- and 3-month- olds infants in verbal communicative (mother/stranger talked to the infant) and noncommunicative contexts (mother/stranger presented a rattle). At 2 weeks, results showed that infants moved more their hands in a communicative than a noncommunicative situation. Moreover, they moved more their right hand than their left hand when their mother shook a rattle and more their left hand than their right hand when a stranger talked to them [32]. These results suggested that, as early as 2 weeks, manual asymmetries are context-dependent, *i.e.* communicative nature of the situation, emotional level (stranger/mother), intrinsic properties (sound of the rattle). This *manual specialization* task-dependence could reflect the onset of the underlying functionalities associated with the hemispheric specialization. One possible explanation of these results is that, at 2 weeks, mother rattle shaking is a positive emotional experience, thereby tapping left hemisphere's specialization emotionally (and thus right-hand activity, [33]), whereas a stranger talking is stressful thereby eliciting a right hemisphere emotional activity (and consequent left hand activity).

Others studies reported interesting hand differences : the majority of neonates make reflexes and spontaneous movements that were stronger and more coordinated on the right than the left side of the body [34]. In the presence of the target, they used their right hand more to execute movements toward the midline (target directed movements), whereas without a target, the spontaneous movements showed no side preference [35]. Young et al. (1983) found a similar pattern, although in that study, as well, 1-month-olds used the left hand in non-directed movements, which were posited to reflect the right hemisphere's early spatial function specialization [27]. The palmar grasp, a reflex observed during infant routine

neurological testing from birth to 5 months, displays discreet but real asymmetric palmar grasp strength in favor of the left hand at 12 h of life but not at 72 h [36]. In research without lateralized differences, 2–6-day-old infants can perform different movement configurations with their arms, hands, and fingers according to the environmental situation: neonates made more finger movements and hand flexions towards people and more thumb–index finger activity and extension of the arms and hands with objects [37]. In addition, very young infants (3 weeks) performed more reaches and wider exploratory arm movements in the mother's voice and music conditions as compared with the silence condition [38]. Moreover, neonates can purposefully control their arm movements in the face of external forces, attesting to a certain graduated motor control [39]. *In utero*, fetus can perform specific actions according to the goal of the movement with their upper members, suggesting a primitive form of intentional action [40]. All these studies suggest that neonates can display a variety of arm movements and a manual use asymmetry according to contrasted task conditions (mother's voice/music, objects / people, objects/ no objects), giving evidence that manual movements are not stereotyped but adapted, which is a requirement for manual specialization. Also, a right-sided preference for head turning in healthy full-term human neonates has been found [41]. Domellöf and collaborators have shown that neonates performed smoother trajectories with their right leg, and found a significant side difference for the onset in terms of a shorter latency for the left foot [42].

Thus, the question of the origins of handedness, its relationship with hemispheric specialization, and the conditions under which manual specialization might emerge is becoming clarified in the research, but further work is required for progress. Indeed, because genetic studies have revealed asymmetrical gene expression in the left perisylvian regions with consequent cerebral asymmetries, specific to human lineage and language [43], early experiences may contribute to developing the hemispheric specialization. Moreover, before birth, the neonate has, *in utero*, first heard the heart rhythm, and then their mother's language. Moreover, intrauterine position contributes to the organization of postnatal posture

and reflexes, including asymmetrically; as a consequence, an asymmetry results in prenatal vestibular and auditory experience and developmental organization [44]. The right ear is more exposed to speech sounds and the left vestibular system is more exposed to mother's locomotion movements [45]. This vestibular asymmetry leads to bias in neonatal head orientation preference, with a preference for the infants to lie with their head turned on the right [46]. It is noteworthy that lateral bias in head orientation predicts future right-hand-use preference [47]. Nevertheless, the onset of manual specialization and its link with neurobiological asymmetries remains unclear: if additional left–right hand/arm movement differences exist, they could be attributed to further neurodevelopment and extrinsic factors rather than solely to initial organic factors such as genetics. In order to investigate this question, the main purpose of the present study was to test the influence of a music environment as compared to a speech environment on possible asymmetric hand activity in an object-target task in neonates, while presuming the results will reflect an early hemispheric specialization already present at birth. Given that hand movements may be infrequent at this age, we also observed the infant's lip activity according to the sound contexts. To our knowledge there is no research on this subject.

Based on previous findings and reviewed studies, the following hypotheses were addressed:

- 1- Our first hypothesis was that neonate hand movements manifest side differences as measured by frequency and duration of arm/hand used during the presence of an object
- 2- The second one was that these side differences were related to the sound context; specifically, there would be lateralized right side activity to speech and left side activity to music
- 3- The last one was that specific neonate's mouth movements (sucking movement) differed in terms of frequency and structure according to the sound context. We

predicted that there would be more mouth movements in the language compared to music condition

Note that our hypotheses and the study based on them go farther than those of Young and Gagnon (1990). The latter investigated head turning to musical and speech stimuli in newborns. In our case, we looked at directed hand movements, as well as mouth movements. In both cases, the author anticipated that the pattern of newborn hemispheric specialization would reflect an early specialization along adult lines.

METHODS

Participants. Nineteen healthy, full-term newborn Caucasian infants, aged 3 days (nine girls, mean age = 52 h 25 min; range = 41 h 52 min to 62 h 8 min) successfully completed the study (mothers were recruited before the baby's birth). Their birth weights ranged from 2,880 g to 4,700 g (Mean = 3.543). The following inclusion criteria were adopted: gestational age between 37 and 41 weeks (Mean = 39.6) with absence of clinical complications; vaginal delivery; 1-min Apgar score of ≥ 8 (Mean = 9.2) and Apgar score of 10 after 5 min. The infant's parents must have signed the informed consent form, completed the Edinburgh handedness questionnaire, and provided information about their musical skills and the type and frequency of music listened to during the pregnancy. Both parents were right-handed on the Edinburgh test. They were observed at home in the presence of the mother and/or father. The procedure was approved by the medical ethical committee at the University of Paris (IRB #00012017-01) and was conducted in accordance with the Declaration of Helsinki. All observations were made in state 3 (quiet wakefulness) or 4 (active wakefulness excluding crying) according to the scale of Prechtl and O'Brien [48].

Material. Hand movement preference was tested with a 3-cm yellow wooden cube, adapted to infant hands, and fixed to a 20-cm iron rod. The experimenter was positioned in front of the baby, slightly on the opposite side of the parent. The experimenter held the iron

rod in such a way that the wooden cube appeared in the middle of the child's field of view, within reaching distance of the child and at the eye level. This task was carried out in two different sound environments [10] : a language environment and a musical environment. The language environment consisted of the recording of a man's voice during a meeting about the evolution of economics over 20 years. The selected extract lasted 3 minutes. The musical environment consisted of the recording of Tatiana Nikolayeva's playing of Prokofiev's Peter and the Wolf (1936) for piano, which lasted 3 minutes. The economics speech was chosen for its technical words, spoken with a monotonous voice. The recordings were matched in intensity and volume, and they were played back at the same intensity level on a cell phone. Each subject heard successively the music and the language environment during the manual task (6 min). The order of the two sound environments was counter-balanced over participants. All hand movements were captured by two cameras (Canon EOS 650D) placed in front and above the infant.

Procedure. The infants were observed in the morning, from 9:30 am to 11:30 am, in a quiet room. To enhance hand movements, the infants were placed on a baby-changing table, in a seated position (60° inclination), with the neck and trunk firmly supported by one hand of the parent, the other one keeping in position the pelvis and legs. Before each session, a video of the "good" position was presented to the parent, then the experimenter showed to the parent the position required and tested it with her. The parent was randomly positioned on the left or right of the infant. The experimenter was positioned in front of the baby, slightly on the opposite side of the parent. One digital video camera was placed in front of the baby at the midline 100 cm away from the baby and recorded the experiment (Figure 1). Another digital video camera was placed directly above the infant. The caregiver and experimenter did not speak throughout the experiment. The experimenter randomly chose the first sound environment (music or speech) and started to play the speech or the music selected on her cell phone (Samsung, S8). The phone was positioned on the baby-changing table about 30-40 cm in front of the infant. After 1 min, the experimenter held the iron rod on

which the target object was fixed so that the yellow wooden cube was placed in front of the baby at the midline and at the level of their eyes and at a reachable distance (about 12/15 cm). The distance between the infant and the object was individually adjusted to enable the baby to reach the object by extending their arm. The object was presented for 120s in each sound condition. Given that the object was fixed to the iron rod, the wooden cube could move slightly and could stimulate the infant and enhance hand movements. After 120 s of the first sound environment, the object was removed and the phone was stopped. The state of the baby and their body position were checked. After this short break, the experimenter started to play the second sound environment, on her phone, waited for 1 min and presented the object again in front of the infant during 120 s. At the end of the experiment, the experimenter stopped her phone and the cameras and the parent took the baby in their arms.



Figure 1. Experimental setting. The infant is watching the yellow target object and is moving his right hand

Video analysis. Each session was videotaped using two synchronized video cameras. The videos (120-s of each sound condition) were analyzed frame by frame with Elan®, and the following variables were scored: when the hand/arm started and the duration as it moved towards the object, and with which hand; the number of sucking bursts. After the

introduction of the target-object in the baby's visual field, all movements -small as well as large movements- extending more than 40 mm in length towards the object were considered. The beginning of the movement was coded on consecutive frames, when distance from the hand to the object reduced from one frame to the following one. The end of a preceding movement and the start of the next movement were defined by unmoving hand/arm for five successive frames or by a reversal movement > 15 mm. Because infants could move their hands freely, some movements could be performed simultaneously. A hand/arm movement was bimanual when the second hand started to move (extending more than 40 mm in length) towards the object 80 ms or less before the initial movement towards the object of the first hand/arm as defined by Fagard et al. (2009) [49]. According to this criterion, only one bimanual movement was performed and removed from further analyses. In the others words, it was extremely rare that neonates moved and extended more than 40 mm in length both their hand / arms synchronously towards the object.

Two independent observers coded twenty percent of the data set and were blind to the conditions and the hypotheses. The beginning and the stop time had an error tolerance up to 2 frames. The inter-rater reliability of the two coders was 96% for movement duration coding, 100% for hand movements and 99% for mouth coding. Contentious trials were re-examined a second time by the both experimenters and re-coded together until a 100% inter-rater agreement was reached.

Dependent variables. The analyses of handedness were carried out on 278 movements in total over the 19 neonates. 1. We scored *Number of movements*: The total number of each hand/arm movements produced during 120 s in each sound condition. Handedness was defined with a handedness index (HI; formula: $[\text{Right}-\text{Left}]/[\text{Right}+\text{Left}]$). Of the multiple ratios used in the literature, we chose this classical formula which is easy to interpret and read : the negative scores signify more left- than right-hand use and positive scores more right- than left-hand use [50]; 2. We also scored *Total duration of hand/arm movements*: The total time the infants moved each hand/arm during each condition. This

duration, reported on the total time for the behavior in each session (120 s), yielded a proportion of time. 3. *Mean duration of one hand/arm movement* was scored: The average duration of one hand/arm movement. 4. At last, we scored the *number of sucking bursts per minute*. These sucking movements, included tongue protrusion and small lip movements.

Statistics. Analyses were performed with Stata for Windows (version 14). Multiple logistic regression was used to estimate odds ratio (OR) and 95% confidence intervals (CIs), with an adjustment on gender, birthweight, and age at testing. Proportions and durations associated with hand/arm movements were submitted to a two-way repeated measures ANOVA. A paired samples T-test was used to analyze sucking bursts.

RESULTS

Hand movements

In all, 278 manual movements were analyzed with a higher proportion in the language condition (n=159 (57.2%, 95%CI = 51.3%-62.9%)). Moreover, more right arm movements were manifested by newborns (n=167 (60.4%, 95%CI = 54.6%-66.0%)). Following analyses were thus focused on the comparison right hand/left hand.

The left hand/right hand comparison

We computed the HI (right minus left) in each condition. The mean HI was >0 in the language condition (0.36) and was almost zero in the music condition (0.01). Figure 2 shows that the distribution of the infants according to their HI in both conditions followed an ascending scatterplot: a higher HI in the language condition indicated a higher HI in the music condition ($r = 0.73$, 95% CI = 0.41–0.89, $t(17) = 4.41$, $p < 0.0005$).

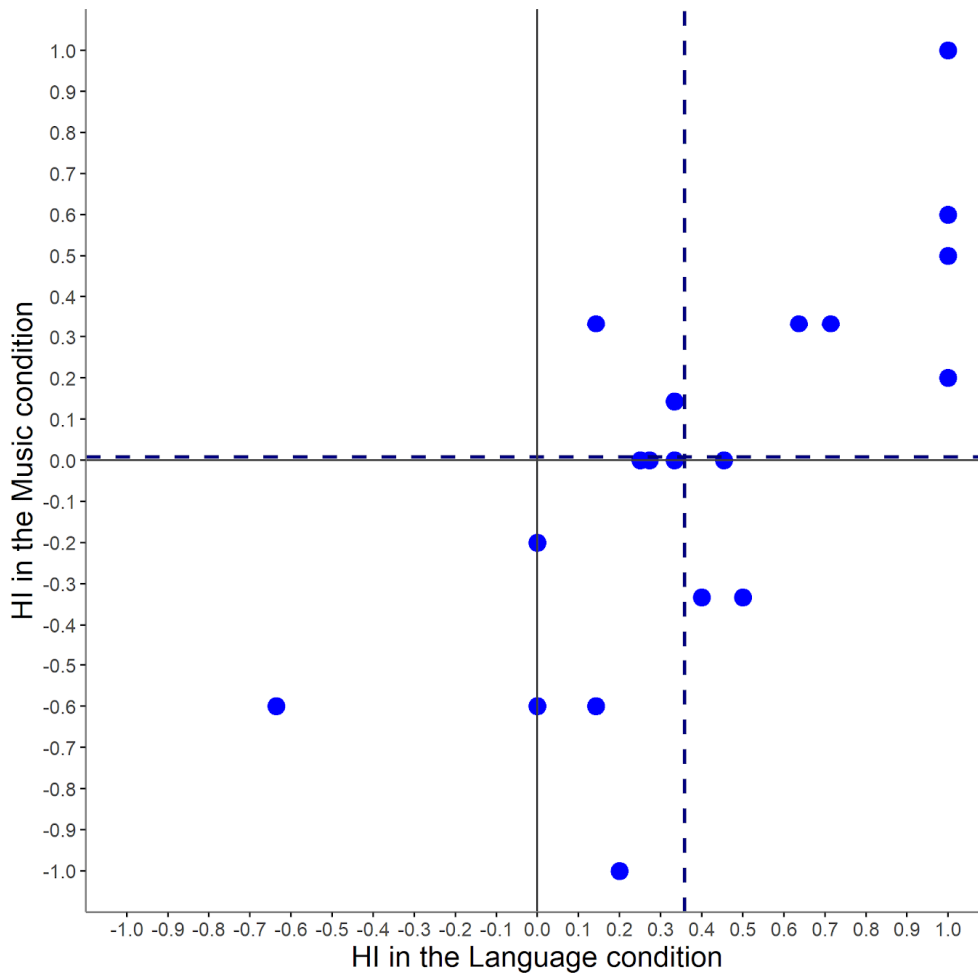


Figure 2. Scatterplot of HI according to condition. A value < 0 indicates higher use of the left hand than the right hand. The dotted line represents the mean HI (0.36 in the language condition; 0.01 in the music condition).

In the music condition newborns used overall equally the left hand (n=59) and the right hand (n=60, $odd=59/60=0.98$), whereas in the language condition, they used less the left hand (n=51) than the right hand (n=108, $odd=51/108=0.47$). Thus, newborns moved 2.08 more their left hand than their right hand in the music condition than in the language condition (unadjusted: $OR = 0.98/0.47 = 2.08$, $p=.004$, $95\%CI = 1.28-3.40$; adjusted on gender, birthweight, and age at testing: $OR = 1.96$, $p=.008$, $95\%CI = 1.20-3.22$).

Total duration of hand/arm movements

The total time the infants moved each hand during each condition was reported as the proportion of time of the condition (i.e., 120 s), leading to four proportions of time. Shapiro-Wilk tests computed for each of the four measures were all non-significant ($p = 0.10-0.78$). The condition \times hand repeated measures analysis of variance (ANOVA) conducted on the *proportion of time during which the hand moved* revealed that the infants moved their right hand for significantly longer (Mean_{right} = 16.4% \pm 8.3 (range 2.0-31.2) vs. Mean_{left} = 8.0% \pm 4.9 (range 0-16.8); $F(1,18) = 12.04$; $p = 0.0027$; $\eta^2_p = 0.40$) and more during the language condition (Mean_{language} = 14.6% \pm 6.4 (range 4.4-27.0) vs. Mean_{music} = 9.8% \pm 3.2 (range 5.5-19.9); $F(1,18) = 16.09$; $p = 0.0008$; $\eta^2_p = 0.47$). We also observed a significant condition \times hand interaction ($F(1,18) = 50.02$; $p < 0.0001$; $\eta^2_p = 0.74$); simple main effects computation revealed a significant difference between both hands in the language condition ($p < 0.0001$) but not in the music condition ($p = 0.44$). Indeed, in the language condition, the newborns moved their right hand more times than the left hand (respectively, 23.8% \pm 12.7 (range 2.9-48.1) and 5.4% \pm 4.5 (range 0-16.8)), whereas proportions were quite close in the music condition (9.1% \pm 5.9 (range 0-19.8) for the right-hand vs 10.5% \pm 6.0 (range 0-22.3) for the left hand; see Figure 3).

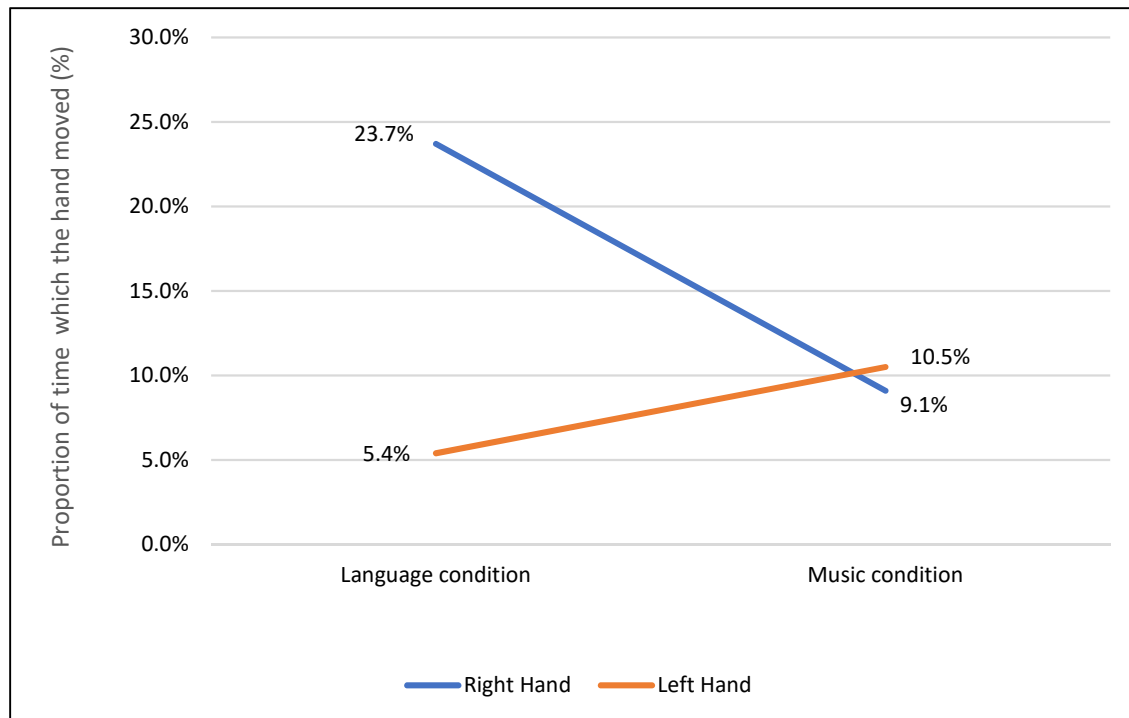


Figure 3. Proportion of time during which each hand moved according to the sound condition (language / music).

Mean duration of one hand/arm movement

We also conducted a two-way repeated measures ANOVA on the mean duration of neonate hand movements. Shapiro-Wilk tests computed for each of the four measures were all non-significant ($p = 0.155\text{--}0.200$). The condition \times hand repeated measures ANOVA revealed that a movement with the right hand lasted significantly longer ($\text{Mean}_{\text{right}} = 4.1 \text{ sec} \pm 1.5$ (range 1.5-7.0) vs. $\text{Mean}_{\text{left}} = 2.9 \text{ sec} \pm 1.4$ (range 0-5.4); $F(1,18) = 6.18$; $p = 0.023$; $\eta^2_p = 0.26$), but did not reveal a significant difference between the conditions ($\text{Mean}_{\text{language}} = 3.4 \text{ sec} \pm 1.1$ (range 1.3-5.4) vs. $\text{Mean}_{\text{music}} = 3.6 \text{ sec} \pm 1.4$ (range 1.6-7.8); $F(1,18) < 1$; $p = 0.67$; $\eta^2_p < 0.001$). The ANOVA also showed a significant interaction ($F(1,18) = 65.51$; $p < 0.0001$; $\eta^2_p = 0.78$). The infants performed right arm movements that lasted longer in the language condition than in the music condition (respectively $5.0 \text{ sec} \pm 1.8$ (range 1.8-7.5) and $3.2 \text{ sec} \pm 1.8$ (range 0-8.1)), whereas their left arm movements lasted longer in the music condition

than in the language condition (respectively, 3.9 sec \pm 2.0 (range 0-8.3) and 1.9 sec \pm 1.1 (range 0-3.4), see Figure 4).

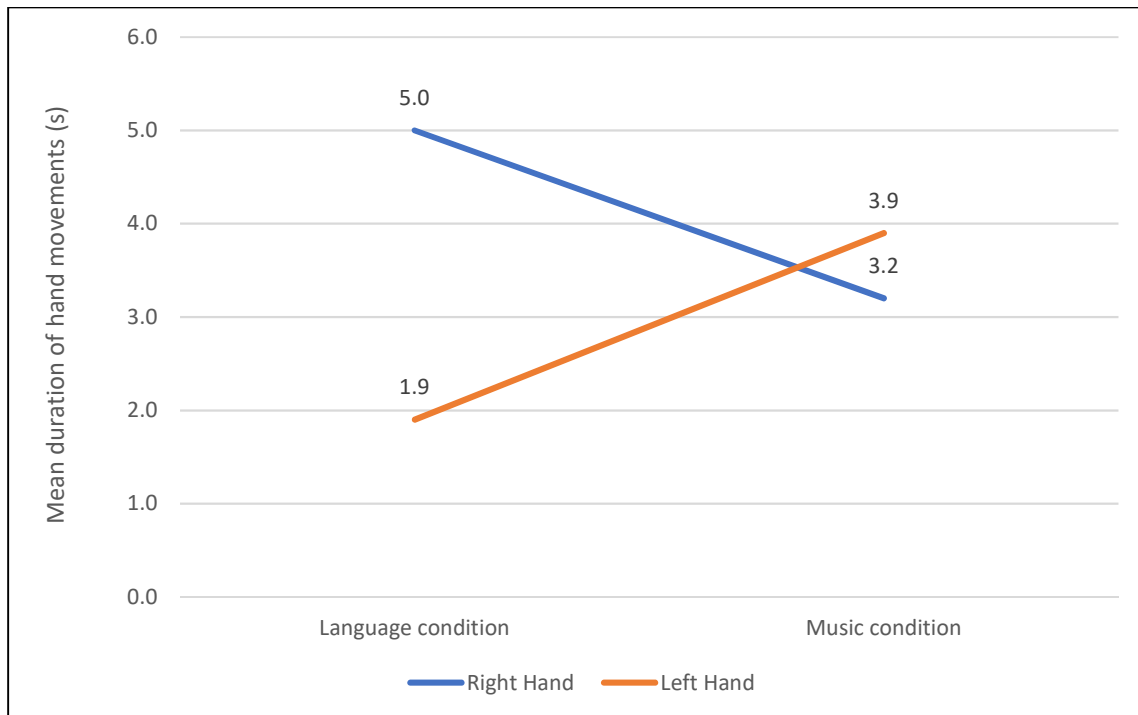


Figure 4. Mean duration of hand movements according to hand (right / left) and sound condition (language / music).

Number of sucking bursts per minute

Number of sucking bursts collected in the two sound conditions were converted in rate per minute. Both rates per minute thus obtained for each newborn were analyzed with a paired samples T-test. The average number of sucking bursts was significantly higher in the language condition (2.4 \pm 0.8 (range 0.5-3.5) than in the music condition (1.7 \pm 1.2 (range 0-4.0); $t(18)=2.41$, $p=.027$, $\eta^2 = 0.25$).

DISCUSSION

The primary goal of the present study was to test in neonates the influence of a music environment, compared to a speech environment, on differential left/right target-directed

hand/arm movement activation in the presence of a target object. We hypothesized that, by stimulating each hemisphere with stimuli typically associated with it, each sound could favor the contralateral hand activity with respect to the hemisphere typically associated with it. Specifically, we predicted that the music condition would favor left-hand activity and that the language condition would favor right-hand activation even in the young neonates tested. Regarding the number of movements, our results confirmed that the music condition favored left-hand activity relative to the language condition, which favored right-hand activity. Regarding the total duration of hand/arm movements, our results confirm that the same pattern. As for mouth movements, there were more of them in the language compared to the music condition.

Assessment of manual specialization

A strong asymmetry was present in favor of right hand/arm activation in the language condition, as much in the total duration of movements as in the mean duration of one movement. On the contrary, the infants moved their left hand two times more than their right hand in the music condition than in the language condition. In other words, listening to speech just after birth could lead to the emergence of greater right-hand activation than listening to music. A few researchers have reported such asymmetric hand activation in neonates in very specific task conditions, especially in presence of a target object. Ottaviano and collaborators have shown that neonates use their right hand more to execute movements toward the midline (target-directed movements) in the presence of the target whereas spontaneous movements showed no side preference in the absence of a target [35]. In the same vein, Lynch et al. have shown that a right-hand preference emerged with the onset of reaching around 19/20 weeks, whereas there was no right–left difference in pre-reaching arm movement use from 8 weeks to the onset of reaching [51]. These authors suggest that hand asymmetry could develop between the start of reach onset and the end of the first year. Hand asymmetry for reaching could emerge because of infants' exploration of their new skills of reaching and grasping, and these motor movements are difficult at this

age, leading to left hemisphere activation. As Young postulates, the left hemisphere becomes dominant when a target is present [52]. This dominance could operate by promoting exploratory movements of the contralateral limb (i.e., the right) more inclined to exploration. Our results argue that the presence of a target is not the only factor that favors the right-hand asymmetry. Indeed, if it was the case, we would have found right-hand asymmetry in the music condition. Therefore, we may conclude that the sound environment, either speech or music, is another factor that can affect hand-use asymmetry. Only an early hemispheric specialization, with a left hemisphere dedicated to the language process and a right hemisphere dedicated to the music process, could explain these results. Several studies have shown that anatomical and functional hemispheric asymmetries are present from the first postnatal hours of life for language and music processing [17,53], and activation induced by language is lateralized more strongly in the left hemisphere than music in the right hemisphere [17]. The production, as well as the reception of language, predominantly increase the cortical excitability of the hand representation in the language-dominant (i.e., left) hemisphere, suggesting a closer relationship between cortical networks mediating language processing, and planning and execution of hand movements [54,55]. Morange-Majoux and Devouche found that infants used their left hand more when they listened to a piece of classical music rather than adult speech at 5–7 months, and right-hand asymmetric use emerged only from 8 months regardless of the sound environment [10].

This pool of results on right-handedness in the language condition has been interpreted as slower development of the left hemisphere, supported by neuroimaging showing that leftward asymmetries seem to develop gradually for high-order language areas during childhood [11,12]. The onset of reaching and babbling around 6 months would stimulate the left hemisphere specialization for language and manual skills, as explained above.

However, our results do not confirm this proposed developmental trajectory, as do the results of Young and Gagnon (1990). In both studies, the language condition promotes right hand activation in neonates. From the same perspective, the strength of the grasp reflex is

significantly greater for the right hand than the left at birth [56]. However, between birth and 5 months of age, many sensorimotor, cognitive and socio-emotional components develop and interact with the physical and social environment. For example, head and trunk postural control changes rapidly and is linked to arm and hand control before and after reach onset [57]. Moreover, as Lynch et al. pointed out, physical and socioemotional interactions between the caregiver and the baby change significantly during this period [51,58]. By providing objects, play activities, and deploying socioemotional communication, cradling, touching and seeing the baby, the adult partner of the baby may influence asymmetrical infant behaviors [59,60]. During this period, infant-directed speech is specific: highly intonated and with positive emotional valence; this “motherese” is wholly different from the speech stimuli heard in the present experiment. We may hypothesize that, at birth, language, without emotions, is relatively new for the baby and would stimulate the left hemisphere. However, the study of Somogyi et al. (2021) showed that infants produced more left-hand than right-hand movements in a communicative situation with a stranger. They suggested that infants in this case could react to the novelty of the situation more than to the language (vs mother) [32]. Others have suggested that left-hand activity could be related to self-regulatory response to stress, likely to elicit more right hemisphere (and consequent left hand activity) [61]. These results show that hand activity and duration of movements are influenced by several interrelated factors, such as emotions, communicative (mother, stranger, language) or noncommunicative situations (object, music) and stress. Numerous reports have provided evidence that environmental factors can modulate human handedness. The amniotic environment [62], body position during gestation [63,64], body self-contact [65], head position at the birth [41], visual field explored [66], trunk position [67][68], emergence of reaching [35], and auditory feedback [38] all contribute to the development of handedness. All these factors influence each other and require further studies, especially to determine how extrinsic stimulation could be involved in hemispheric specialization development.

Assessment of orofacial activity in relation to language condition

Our results reveal that the average number of sucking movements (tongue protrusion and small lip movements) was significantly higher in the language condition than in the music condition. Nonnutritive sucking (NNS) is traditionally considered a stereotypical burst-pause pattern characterized by the absence of nutrient delivery. This behavior begins *in utero*, at around 15 weeks' gestational age and it can be modified by sensory inputs, such as tactile, olfactory, auditory, and visual stimulation, from birth. A recent study has shown that social sensory input also modulate NNS: infants increase their suck response when looking at faces compared to cars [69]. In conclusion, NNS increases infant attention and improves behavioral responsiveness, and increased attention enhances visual preferences. It is well known that during speech, infants look at the mouth movements of the speaker in front of them [70,71], especially from the approximate onset of babbling. Several researchers have found that early attention to the mouth predicts later expressive language development [72]. In the present study, mouth movements could be interpreted as specific mouth movements linked to the infant's attention to the language context, even as prespeech, a manifestation or motivation to communicate. Thus, babies reduce mouth movements when they see their parents in a non-contingent versus identical contingent face-to-face interaction [73,74]. It is interesting to note that parents respond positively to these early mouth movements, imitating and affirming them, and according them communicative and playful significance. These movements generate social interaction and verbal communication. Other reflexes, such as backward postural reactions to an optic flow [75] or grasping, can be modulated according to the situation, i.e., an object's texture property [76] or object shape perception [77]. Presently, these reflexes are considered precursors of more elaborate movements, with common sophisticated subcortical neural networks. From this perspective, these mouth movements could be precursors of speech movements. This possibility could help explain their early laterality in the direction that one would expect for an early hemisphere specialization for language-related activity.

CONCLUSION

The present study provides evidence that the sound context, i.e., speech or music, influences neonatal use of differential left/right directed hand/arm activity in presence of a target object. The study adds to research that manual specialization is important to consider in addressing hemispheric specialization and such manual specialization could serve as markers of hemispheric specialization development (Young et al., 1983; Young and Gagnon (1990).

Current theories on the development of hand dominance postulate the interaction of intrinsic and extrinsic factors [2,78]: genetics, hormonal rate, head position, onset of babbling and onset of reaching. Our results demonstrate that the sound environment can be added to the list of extrinsic factors. Each hand is used according to the specific skills of the contralateral hemisphere. The production, as well as the reception of language, predominantly increase the cortical excitability of the hand representation in the language-dominant (i.e., left) hemisphere, suggesting a closer relationship between cortical networks mediating language processing, and planning and execution of hand movements [54,55]. From an ontogenetic perspective, we may hypothesize that the right hemisphere is responsive to nonverbal stimuli, *e.g.*, it can be stimulated by the heart rate from fetal life, and develop a specialization for rhythm and music, expressed via left hand use in a music context. Right-handedness can be heightened by the linguistic environment, in particular, from birth via left hemisphere specialization. Humans would be right-handed not only by the genetic programming of hemispheric specialization, but also because the specific linguistic human environment reinforces this brain specialization. As Forrester et al. (2014) have underlined, handedness can be considered a marker of cerebral lateralization. We clarify that more specific manual specialization can serve this function. Further studies, especially those between 1 and 5 months, are required to better understand the developmental course of handedness and the influence of speech and music environment on it.

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