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▶ **To cite this version:**

Charlotte Hym, Marie-victorine Dumuids, David Anderson, Vincent Forma, Joëlle Provasi, et al.. Newborns modulate their crawling in response to their native language but not another language. Developmental Science, In press, 10.1111/desc.13248 . hal-03801002

HAL Id: hal-03801002
https://hal.science/hal-03801002

Submitted on 3 Nov 2022

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Newborns modulate their crawling in response to their native language but not another language

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

Highlights

Newborns' crawling is enhanced when they hear their native language

Newborn crawling appears to be modulated by supra spinal mechanisms

The findings add one more ability to newborns' rich repertoire of actions

The findings shed new light on the early origins of locomotion and its control

Abstract

Human newborns can propel themselves to their mother's breast when positioned skin to skin on her abdomen just after birth. For decades, researchers have considered this primitive crawling behavior a spinal reflex, immune to supra spinal control. However recent research suggest that neonatal crawling is already responsive to visual and olfactory stimuli processed at a supra spinal level. Here we report that a few hours post birth, French newborns can also modulate their crawling in response to their native language – a source of information that is processed supra-spinally. The crawling patterns of 23 French-born newborns were recorded on video and via an infra-red motion capture system during two randomly ordered 2-minute trials. The newborns were secured on a mini skateboard to facilitate arm and leg movements during their crawling propulsion. They heard a repetitive sequence of the same sentences either in French, their native language, or in English, a rhythmically different and hence discriminable unfamiliar language, on each trial. In French, compared to English, crawling was enhanced, with significantly more arm and leg steps and significantly more and larger trunk rotations in the cephalo-caudal axis. Moreover, newborns rotated their head and trunk toward the appropriate loud speaker when hearing French but not English. These preliminary findings suggest that newborn crawling is not a simple stereotyped reflex under spinal control, but a complex pattern that can be modulated in response to higher-order, supra-spinally-processed stimuli. The findings open fascinating questions about the range of stimuli to which newborn crawling is responsive.

Keywords: crawliskate, locomotion, neonatal, actions

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Researchers and clinicians traditionally described the behaviors of newborn human infants as reflexive reactions to stimuli from the external environment. Increasing evidence suggests, however, that newborn behaviors are prospective and flexible goal-directed actions (von Hofsten, 2004). This evidence has important implications for the study and understanding of motor development. For example, it forces a reexamination of the competencies newborns possess at birth, particularly with respect to their ability to plan, predict and modify their movements on the basis of information about environmental events and properties and their own internal states. In addition, the evidence raises important questions about the extent to which motivational factors govern newborns' behavior and the emergence and development of control over new patterns of coordination. The current exploratory study builds on previous research suggesting that newborns might be capable of modulating their crawling patterns based on information that has hedonic value and/or is processed supra-spinally (Forma et al., 2018; Hym et al., 2020).

The traditional view of newborn crawling

Humans are born with the remarkable capacity to crawl toward their mother's breast, even though their caregivers' nurturing provides no need for self-propulsion at birth (e.g., Widström et al., 1987, 2011; Righard & Alade, 1990; Varendi et al., 1994). This remarkable capacity for self-propulsion is accompanied by head rooting (nipple-finding) movements (Hym et al., 2020). For decades, researchers have considered this primitive crawling behavior a spinal reflex which is immune to supra spinal modulation, controlled principally by tactile/proprioceptive feedback coming from the body/limbs touching a surface, and characterized by bipedal activation of the legs rather than quadrupedal coordination among the arms and legs. Many researchers believe the crawling pattern disappears rapidly after birth

and has no link with mature locomotion (Widström et al., 2011). This belief may explain why newborn crawling has attracted limited scientific scrutiny until recently (see Varendi & Porter, 2001 and Varendi et al., 1994 for exceptions). The recent scrutiny suggests that neonatal crawling is more than a disorganized bipedal reflex and it can be modified by stimuli processed supra-spinally (e.g., Forma et al., 2019; Hym et al., 2020). We must acknowledge, however, that no research to date has established a link between what has been referred to as newborn crawling and later appearing crawling during the first months of life, as has been done for newborn stepping and later walking (André-Thomas & Autgaerden, 1966; Zelazo et al., 1972). Consequently, some researchers might not accept that the "crawling" movements documented in newborns in the prone position represent "true crawling." Unfortunately, there is no consensus in the research literature on the definition of "crawling." Researchers have used the term to refer to a range of propulsive behaviors in the prone position, even when the displacement is minimal or occurs over a long duration, such as in the breastcrawl.

Newborn crawling is a complex quadrupedal behavior

The combination of a relatively large and heavy head and relatively weak arms and legs makes it difficult for newborns to express the crawling pattern. Without any support for their head and trunk, newborns cannot move their bodies effectively across a mattress. The weight of the head blocks arm movements and hinders propulsion (Forma et al., 2018). However, 80 years ago, McGraw (1939, 1941) demonstrated that newborns could perform occasional quadrupedal arm and leg movements if supported in a prone position in the water or on a mattress with their head and trunk raised by an experimenter (McGraw, 1939, 1941; see also Katona, 1988, 1989). Moreover, if an experimenter provided the appropriate support, this quadrupedal swimming/crawling pattern did not disappear. Rather, it persisted for several months after birth, even though the quadrupedal movements became more disorganized. Motivated by these findings, Barbu-Roth and colleagues developed a mini skateboard, the

Crawliskate®, to analyze newborn crawling in more detail (Forma et al., 2019). The Crawliskate conforms to the newborn's unique morphology in a way that supports the head in a slightly flexed position and encourages a natural lengthening of the spine while simultaneously raising the head and the trunk off the ground and freeing the arms. When comfortably secured to the device, the newborn can not only actively move its arms, head, trunk, and limbs, but also propel itself in any direction thanks to small ball-bearing-style wheels secured to the underside of the skateboard deck. Most importantly, the device allows the newborn to express active locomotion free from any disruption or facilitation that might occur when an experimenter provides support.

Forma et al. (2019) showed that newborns were able to propel themselves when secured to the Crawliskate, without any assistance from an experimenter. In addition, they performed leg and arm movements with occasional ipsilateral and contralateral patterns of coordination between the limbs that were representative of mature hands-and-knees crawling. These results suggest that even though newborns do not have the strength, balance, and morphology to express mature forms of crawling (e.g., Adolph et al. 1998; Freedland & Bertenthal, 1994), their crawling patterns appear to be controlled by quadrupedally organized spinal networks that, despite being primitive, were likely functional prior to birth. However, the question remains as to whether this primitive quadrupedal crawling pattern is controlled exclusively at a spinal level or whether it can be modulated by supra-spinal factors. The crawling behavior observed on the Crawkiskate by Forma et al. (2019) could be controlled at the spinal level because the newborns were exposed to the tactile stimulation that has traditionally been considered the primary elicitor of stepping and crawling in newborns (e.g., Barbu-Roth et al., 2009).

Neonatal crawling in response to stimuli processed supra-spinally

As noted above, Forma et al. (2019) did not establish whether the crawling patterns observed on the Crawliskate were responsive to stimuli processed supra-spinally. In fact, very few studies have investigated whether newborns can modulate their crawling in response to stimuli processed supra-spinally. In a recent paper, Hym et al. (2020) investigated newborns' crawling and rooting behavior (nipple-finding movements of the head) in response to the odor of their mother's breast. Twenty eight 2-day-old newborns were wrapped prone on a Crawliskate, their head positioned directly on top of a pad infused with either their mother's breast odor or the odor of water. Video and 3D kinematic analyses of the number and types of arm and leg stepping movements and quantification of displacement across the surface revealed that newborns are significantly more efficient crawlers when they smell the maternal odor, moving greater distances although performing fewer stepping movements. Varendi and Porter (2001) had shown previously that newborns would travel further in response to the smell of their mother's breast odor compared to a neutral odor, however, they did not analyze the limb movements the newborns used to propel themselves. In addition, the newborns in the Hym et al. (2020) study made significantly more head rooting movements in the presence of the maternal odor. These findings suggest that the circuitry underlying quadrupedal locomotion and exploratory movements of the head is already responsive to supra-spinal factors because olfactory stimuli are known to be processed at the cortical level (e.g., Bartocci et al., 2000; Ayoama et al., 2010; Adam-Darque et al., 2018; Frie et al., 2018). Moreover, the coupling between olfaction and the two action systems, locomotion and rooting, is already differentiated because maternal odor increased rooting movements but reduced stepping movements and the correlation between the two behaviors was weak and non-significant.

Hym et al.'s (2020) results raise an interesting question. As crawling enables the newborn to move toward the mother's breast immediately after birth, crawling is generally interpreted as having a feeding function. However, crawling could also have a more general

nurturing function, that is, to move toward the mother's face and arms or those of a conspecific for the purpose of soothing or increasing comfort. If so, it is biologically plausible that one important function of efficient crawling is to facilitate early mother-infant or caregiver-infant interaction through active skin-to-skin contact, which benefits the mother/caregiver and the newborn (Brimdyr et al., 2020). The results of the Hym et al. (2020) study highlight the potential value of using maternal odors to stimulate crawling at birth. However, maternal odor is only one stimulus that has hedonic value or motivational valence for the newborn and only one of many stimuli available during mother and caregiver interaction with the newborn. If crawling facilitates early mother-infant interaction or early caregiver-infant interaction, then other maternal/caregiver stimuli known to be discriminated early in development, like the mother's native language, might also stimulate it.

Newborn speech processing

At birth, infants possess a wide range of speech perception and language processing abilities. Some of these abilities are language-general and universal, allowing infants to start acquiring any language, others are already shaped by speech experienced prenatally. Newborns' universal abilities include, for instance, a preference for speech over sine wave analogues (Vouloumanos & Werker, 2004). Newborns can also discriminate languages from one another, even if those are unfamiliar to them, on the basis of their different rhythms (Mehler et al. 1988; Nazzi, Bertoncini & Mehler, 1998; Ramus et al., 2000). Furthermore, they readily detect the acoustic cues correlated with word boundaries (Christophe et al., 1994). They are also sensitive to different lexical stress patterns (Sansavini, Bertoncini & Giovanelli, 1997). Young infants can also discriminate many of the phonemes appearing in the world's languages (Dehaene-Lambertz & Pena, 2001; Cheour et al., 2002; Cabrera & Gervain, 2020). This universal discrimination repertoire is one of the hallmarks of young infants' broad-based abilities, allowing infants to learn any language they are exposed to.

Newborns are not only sensitive to the sound patterns of language, but also show abilities that allow them to begin learning about language structure. They can discriminate the two universal lexical categories of functors, i.e., words that mark morphosyntactic structure (e.g. *the, she, in, up* etc.), and content words, words that carry lexical meaning (e.g. *door, rainbow, run, beautiful*, etc.), on the basis of the different phonological properties of the two categories (Shi, Werker & Morgan, 1999). They are also sensitive to word order, and can detect the violation of the serial order in sequences of words (Benavides-Varela & Gervain, 2017). They can also detect more abstract patterns, such as repetition-based regularities like ABB (e.g., "mu ba ba", "pe na na" etc.) or AAB (e.g., "ba ba mu", "na na pe" etc.), and discriminate them from otherwise similar random sequences such as ABC (e.g., "mu ba ge", "pe na ku" etc.), or from one another, e.g., ABB vs. AAB (Gervain, Berent & Werker, 2012; Gervain et al., 2008). In sum, newborns exhibit a broad range of universal speech perception abilities.

An increasing body of research now suggests that newborns' speech perception abilities are also shaped by the speech they hear prenatally (for a review, see Gervain, 2015). Newborns show preferences for sounds and speech stimuli they heard in utero. For instance, they prefer their mother's voice over an unknown female voice (DeCasper & Fifer, 1980; Moon, 2017). Similarly, newborns show a preference for a melody they heard repeatedly during the last trimester of gestation over an unfamiliar one (Panneton & DeCasper, 1986; Granier-Deferre, Bassereau, Ribeiro, Jacquet & DeCasper, 2011) as well as for a story that the mother had read aloud during pregnancy (DeCasper & Spence, 1986). Newborn infants can also discriminate their native language, i.e., the language spoken by the mother during pregnancy, from a rhythmically different unfamiliar language and prefer listening to it over unfamiliar languages (Mehler et al., 1988; Moon et al., 1993; Byers-Heinlein et al., 2010). Furthermore, several studies provide evidence that newborns learn about the distinctive

prosodic features of the language(s) they heard prenatally. For instance, they are able to discriminate well-formed prosodic sequences from ill-formed ones only when the patterns can be found in the language(s) heard prenatally (Abboub et al., 2016). Similarly, newborns can discriminate sentences according to their emotional valence (sadness, happiness, anger or neutral) only when the sentences are pronounced in their native language (Mastropieri & Turkewitz, 1999). Even more excitingly, the impact of prenatal learning may be so strong as to influence production. Newborns' communicative, i.e., non-pain related, cries have been found to follow the dominant prosodic contours of their native language (Mampe et al., 2009).

A growing body of brain imaging literature with newborns (for a review, see Nallet & Gervain, 2021) shows that these speech perception abilities are processed in cortical brain regions similar to the ones used in adults. When 3-month-old infants listen to sentences in their native language they show brain activity in similar left hemispheric regions as adults, including the inferior frontal areas, superior temporal gyrus and the angular gyrus (Dehaene-Lambertz et al., 2002). This left cortical lateralization for language discrimination was confirmed at birth (Peña et al., 2003). Newborns show significantly greater activation in the left temporal areas in response to speech than in response to speech played backward (time-reversed) and silence, suggesting an early dominance of left regions for the processing of speech (Peña et al., 2003). Prenatal experience shapes this cortical specialization, in particular the left hemispheric lateralization, as several studies have found lateralization and/or an increased activation for the native language as compared to unfamiliar languages (May et al., 2017; Bartha-Doering et al., 2019). A left hemispheric dominance was also observed for speech when compared with music (Kotilahti et al., 2010). Recent studies also show adult-like electrophysiological activity in newborns' cortical language areas in response to speech, e.g., speech envelope tracking (Ortiz Barajas, Guevara Erra & Gervain, 2021; Cabrera & Gervain, 2020).

It should be noted that in addition to cortical speech processing, adult humans also process sounds at the brainstem level. For example, Zhao and Kuhl (2018) provide evidence of complex auditory brainstem responses in human adults when exposed to Spanish and English speech sounds. However, the adult responses observed at the brainstem level are strictly related to the physical form of the sounds included in speech. In previous studies on newborns, the sentences expressed in the two languages had complex acoustical properties and so it is difficult to imagine the two languages could be discriminated at the brainstem level of auditory processing.

Taken together, the aforementioned results reveal that typically-developing newborns possess cortical networks ready to recognize their native language. Consequently, the native language preference is one of several factors that helps the newborn construct a pattern of interaction with its mother and caregivers who share the same native language. As noted before, the newborn's capacity to crawl could have many functions in addition to a feeding function, by generating multiple reciprocal effects on the mother (primarily, though also a caregiver) and the infants, facilitating mother/caregiver bonding (Brymdir et al., 2020). Would native language alone be able to modify newborn crawling? A positive answer to this question would shed new light on the importance of native language in the stimulation of newborn mobility. To answer this question, it is necessary to design a study that isolates the native language from other maternal stimuli, such as odor and facial expressions, and provide the newborn with a context in which to express fully-fledged crawling behavior without help from an experimenter and without having to place the infant on the mother's abdomen.

Purpose and significance of the study

The current study sought to determine whether French newborns, when secured on the Crawliskate, would modify their quadrupedal locomotion in response to their native language compared to a rhythmically different unfamiliar language. Potential crawling modifications

include: travelled distance and orientation relative to the loudspeakers from which the native language was broadcast, number of leg and arm steps, stepping kinematics, stepping coordination, and trunk orientation. We also sought to determine whether newborns would modify their head orientation toward the loudspeaker broadcasting the native language. Finally, we determined whether the newborns would increase their head rooting movements in the presence of their native language, similar to what has been observed relative to the breast odor. The latter purpose was to investigate the specificity of the effect of language, relative to the effect of olfaction shown by Hym et al. (2020), on the newborn's behavior and investigate if the recognition of its native language could elicit a feeding behavior in the newborn.

We chose French as the native language because it is the mother's language and the predominant language heard by the newborns tested in our study. We chose English as the comparison language because it is rhythmically different (stress-based language, whereas French is a syllable-based language) and there is evidence that newborns are able to differentiate languages with different rhythms (Nazzi et al., 1998; Ramus et al., 2000). However, as far as we are aware, this is the first study comparing newborns' responsiveness to French versus English.

Given prior evidence of rhythm-based language discrimination, we predicted that newborns would show different crawling and head orientation behavior in response to their native compared to the non-native language, though we were uncertain which aspects of the crawling pattern would be modified. In contrast, we did not expect any differences in rooting behavior in the two conditions because rooting is functionally directed toward searching for the breast whereas language could be geared toward a more general nurturing function.

Methods

This study was approved by the French human subjects committee CPP 2017-A02596-47. Newborns were recruited and tested at the Maternity Port Royal in Paris. All caregivers provided written informed consent for their child to participate in the study.

Participants

To be included in the experiment, newborns had to be born at least at 38 weeks gestational age, with a minimum weight of 2,700 g, with uncomplicated deliveries, a minimum Apgar score of 8 at 5 min after birth, no pathologies, a positive Oto Acoustic Emissions Test (OAE) and their mothers had to live in France and speak French more than 80% of time during the last 3 months of pregnancy. In total, 48 newborns were tested in the experiment. However, as the goal of this study was to compare their locomotor crawling movements in response to French or English sentences, 6 newborns were excluded because they didn't move in one of the conditions (3 in the French condition and 3 in English condition) and 4 because they didn't move in both conditions. Thirteen additional infants were excluded for falling asleep during the experiment and two for technical problems with the recording equipment. The final analyzed sample consisted of twenty-three 2 day-old newborns (12 girls, 11 boys; mean age = 2.06 days, *SD = 0.50* and mean weight of 3,410 g (*SD = 0.29*) at birth, mean term of 39.93 weeks (*SD = 0.71*), mean birth size of 50.35 cm (*SD = 1.43*), mean birth head circumference (HC) of 34.93 cm (*SD = 0.98*). The infants were not weighed at test but only newborns who had lost less than 10% of their birth weight by the test day were permitted by the medical staff to participate in our study. The participants were predominantly middle class and 21 (92%) were Caucasian. The other 2 (8%) were of North or Central African descent. All infants were breast-fed and were tested when they woke up just before feeding. The mean delay between feeding and testing was 143 min (*SD = 59)*. All infants were in stage 3 (eyes open, no movements) on Prechtl's (1974) arousal scale just prior to testing.

Apparatus and Stimuli

The primary piece of the apparatus was an 8-cm high x 1-m wide x 1.6-m long pediatric mattress placed on a 1-m high x 1-m wide x 2-m long table surrounded by three 5-cm high x 5-cm wide barriers, except on the experimenter's side. The table was surrounded by 8 Qualisys (Göteborg, Sweden) Oqus 100-motion capture cameras that were fixed to the walls and pointed toward the center of the mattress. The capture volume was larger than the size of the pediatric mattress. Two Sony (Sony Corporation, Tokyo) Handicam hdr-cx 160 HD video cameras were positioned on either side of the mattress at a height of 1.6 m so that they captured the left and right sides of the infant. The video cameras were synchronized with the motion capture cameras through the use of Qualisys Track Manager (QTM) software. Two Kinyo PS-31 loudspeakers were used for the auditory stimulus. Each was located 1.2 m away from the start position of the newborn on the left or right side.

To allow the newborns to propel themselves with arms and legs in a prone position, the infants were secured onto a mini skateboard, the Crawliskate®. The Crawliskate® has an aluminum base that is 29 cm long and 10 cm wide and shaped like a skateboard. Inverted-V-shaped outrigger wings are attached to a plate at the front of the Crawliskate® that supports the newborn's head. The wings project 20 cm away from the plate and are designed to prevent the Crawliskate® from tipping over, while providing space for the arms to move freely. The surface that supports the newborn's trunk is inclined at 20 degrees to ensure the newborn's head is raised and the legs are in contact with the surface. The surface underneath the trunk is constructed of a layer of high-density foam and a layer of low-density foam. Ten sets of low-friction, ball bearing coasters under the base and the wings permit the Crawliskate® to move easily in any direction. The newborn is secured snuggly to the Crawliskate® via a harness system with Velcro straps (Barbu-Roth et al., 2016; see also the Video in Supplementary Information).

The stimuli were 11 sentences that a caregiver might use to encourage an older child to move to him/her. They were created in French (76 words) and translated in English (82 words). In French, as in English, the complete stimulus (2 minutes in total) consisted of four repetitions of the 11 sentences (30 seconds) by four different females. Four different female native speakers of each language were recorded to ensure that infants discriminated between languages rather than between speakers' voices or ways of speaking (Nazzi et al., 1998). Speakers were asked to use infant directed speech. The recordings took place in a sound-attenuated room.

The 44 sentences (11 sentences x 4 voices) were matched across languages on number of words (French: 304 / English: 328), syllables (F: 396 / E: 370) and phonemes (F: 876 / E: 956). A statistical analysis using student's t tests between the 44 sentences for each language (11 sentences for each of the 4 voices) did not show any statistical differences between the French and the English stimuli. The stimuli were broadcast at 68 dB.

French sentences

Coucou, tu viens me voir ? Oui, c'est bien ! Avance encore un peu, allez viens que je te fasse un gros câlin. Oui, super, tu es en forme aujourd'hui ! Olalala, avec toute cette activité tu vas avoir faim. C'est bientôt l'heure de manger, tu vas être content. Viens minou, allez, viens par ici, tu vas y arriver je suis sûre. Encore un petit effort. Tu y es presque. Oui, c'est bien, continue à avancer. Bravo!

English sentences

Hi there, you're coming to see me? Yes, very good! Come a little closer, come on I'll give you a big hug. Yes, great, you're feeling good today! Ooooo, after all of this moving around you'll be hungry. It's almost time to eat, you'll be happy. Come here sweetheart, come on, come over here, you can do it, I'm sure. Just a little more. You're almost here. Yes, very good, keep coming closer. Good job!

Procedure and Conditions

Upon arrival at the laboratory, the infants were undressed down to an undergarment and a diaper. Different-sized elastic bands were used to place 8 spherical light reflective markers on the newborn's legs and arms. Two were placed on the lateral malleoli of the ankles, two were placed on the lateral epicondyles of the femurs to mark the knees, two on the lateral epicondyles of the humerus to mark the elbow, and two to the styloid processes of the ulna to mark the wrist. Five additional trunk markers were placed on the wrapping system of the Crawliskate® directly above anatomical landmarks. One marker was placed dorsal to the acromion process of each shoulder, one dorsal to each acetabulum of the pelvis, and one on the upper part of the back (closest to C7 vertebrae). The infants also wore a cap with 3 head markers; two were placed laterally, slightly above the ears, and one centrally, at the top of the forehead (see Figure 1. A1 in the main text and video in supplementary information).

The newborns were tested when crawling on the Crawliskate® in two randomly-ordered 2-min conditions (with a 5-min break between conditions): (1) during the broadcast of the French stimulus (French condition: F), and (2) during the broadcast of the English stimulus (English condition: E). The loudspeaker allowing the broadcast of the stimulus was randomly assigned either on the left side or on the right side of the newborn but on the same side for both trials for each newborn. The start of the trial and of the recording of the movements was synchronized with the start of the auditory stimulus. A Matlab script was written to generate random numbers for the randomization processes used to assign the order of conditions and the side from which the stimuli would be broadcast.

At the beginning of each trial, the lead experimenter placed the infant on the CrawliSkate® and stood behind him/her during the entire trial to ensure security (without touch). The second experimenter operated a computer used to manage the data collection process and was positioned 1.5 m behind the experimental table. The mother sat

approximately 1 m behind the table out of sight of her infant and was asked not to speak during the trial. The overhead lights were switched off to minimize brightness. The room temperature was maintained between 24 and 25°C.

Data Capture, Conditioning and Coding

The 16 light-reflective markers were sampled at 60 Hz. The data were filtered with a 3-Hz Butterworth filter and gap filling was done for all gaps smaller than 15 frames using a linear interpolation. If at least one limb marker or trunk or head marker was tracked less than 50% of the trial before gap filling, we excluded the participant from all kinematic analyses. Consequently, one participant was removed from the analyses of movement amplitudes, velocities, displacement, trunk and head movements (22 infants were included in the analysis).

We used the method described by Forma et al. (2018) to code arm and leg locomotor movements (Forma et al. 2018). We coded two types of locomotor movements: leg and arm steps (see Figure 1. A2). We counted flexion and extension movements separately, regardless of whether they were or were not part of a full cycle of successive flexion- extension. The arm steps were considered as locomotor movements characterized by a flexion or extension of the shoulder associated with hand displacement forward along the newborn's longitudinal axis (flexion) or backward (extension). The leg steps were considered as locomotor movements with hip flexion or extension associated with knee displacement forward along the newborn's longitudinal axis (flexion) or backward (extension). Note, to count as a flexion movement, the limb did not have to start in a fully extended position and to count as an extension movement, the limb did not have to start in a fully flexed position. We acknowledge that our definition of a step is not consistent with the way others have defined a step in infant upright stepping and adult walking (e.g., Forssberg, 1985). However, Forma et al. (2018) noted that classifying the leg and arm steps as including a full flexion and extension cycle was inappropriate for the

newborn crawling pattern. First, because the extension phase in upright stepping can occur passively and rapidly under the effects of gravity in upright stepping whereas extension must be initiated actively and against friction in crawling, the pauses within and between flexion and extension cycles was highly variable. The pauses between flexion and extension could be quite long, making it difficult to determine what constituted a cycle and what did not. Second, unlike stepping and walking, which are initiated from an upright position with the knees and hips extended, the clear cycles we observed in the prone position often started with an extension followed by a flexion.

The crying duration was calculated from the video recording to measure the arousal of the infant during the two trials. Siekerman et al. (2015) showed that crying duration is strongly correlated ($r = .093$, $p = .0001$) with the excitation state of the infant as measured according to Thelen's arousal scale (Siekerman et al., 2015; Thelen et al. 1982, 1984). This coding was done to ensure that the infant was not overly aroused in one of the two conditions[1].

A primary coder coded all of the trials using a two-stage process. First, the primary coder coded 26% of the trials. Second, the primary coder re-coded the same 26% of the trials to establish within-coder reliability. At the same time, a secondary (experienced) coder coded the same 26% of trials to establish between-coder reliability (the trials were re-coded on 6 of the 23 infants, i.e., 26% of the infants). We calculated the proportion of agreement for each movement identified to determine reliability between the two sets of coding performed by the

[1] We have generally looked at three arousal states in our research relative to Thelen's (Thelen et al., 1982) six-point scale adaptation of Prechtl's (1974) behavioral states. The first state is one in which the newborn is awake and alert. The second is the state of crying. The third is one in which the newborn is drowsy/sleepy. Over the course of our experiments, newborns either stay awake and alert, become drowsy/sleepy, or begin to cry. As all of our infants have to remain awake and alert to remain in the experiment (from an analysis perspective), crying provides a reasonable (far from perfect) measure of whether some infants are more aroused than others. Thelen et al. (1982) identified two crying states (state 5 and 6). However, we have not been able to differentiate these two states reliably using video coding but can differentiate crying and non-crying states reliably (e.g., Siekerman et al., 2015).

primary coder and between the primary and secondary coders. We used the following formula: Proportion of agreements between two coders = 1- (number of disagreements / total number of movements). For this formula, we considered that there was a movement when it was detected by at least one coder. We considered that there was a disagreement when a movement was validated by only one coder or when there was a difference of more than 12 frames for the beginning or the end of the movement that was coded, whatever its category. Both coders were blind to the nature of the stimulus condition. To avoid the possibility of the coders comparing the crawling pattern across conditions, each trial for each infant was assigned a randomly generated code. The coding was then performed randomly across trials and infants to minimize the potential bias associated with knowing how an infant had performed in the other condition. The between-coder proportion of agreements were all high, ranging from 0.81 to 0.87 across all movement variables coded for the trial. The within-coder proportions of agreement were equally high, ranging from 0.91 to 0.97. For the crying duration, the between-coder correlation coefficients was 0.96 and intra-coder correlation coefficients was 0.98. The data from the primary coder were subjected to analysis.

Several kinematic variables were calculated, including: 1) rotation of the trunk, 2) rotation of the head, 3) duration, amplitude and velocity of the flexion and extension of the step movements, 4) displacement during crawling, 5) coactivation of the flexion and extension of the arm and leg movements, 6) head rooting movements, and 7) the sum of the three dimensional (3D) movements of the legs and arms performed outside of the stepping movements.

The trunk movements were characterized relative to the mattress in order to evaluate how the trunk of the newborn moved during the newborn's crawling. We extracted the roll of the trunk (rotation around the cephalo-caudal axis) from the motion capture data during each trial as the roll of the trunk increases during locomotion. We calculated two variables: absolute

roll and amplitude of the roll. The absolute roll was the sum of each rotation movement at each frame during the trial and the amplitude roll was characterized by the maximum angle of rotation during the trial. We also calculated the relative position of the trunk in each condition separately to evaluate how the trunk was oriented relative to the position of the loudspeaker. In this case, we calculated the effective rotation of the trunk by subtracting the angle of rotation from the start of the test from the angle of rotation at the end of the test. A positive value corresponded to an orientation to the right and a negative value to an orientation to the left.

The head movements were characterized relative to the trunk in both conditions to evaluate how the head was oriented relative to the position of the loudspeaker. We extracted the roll of the head from the motion capture data to calculate the effective rotation of the head. As previously done for the effective rotation of the trunk, the head variable was calculated by subtracting the angle of rotation from the start of the test from the angle of rotation at the end of the test. A positive value corresponded to an orientation to the right and a negative value to an orientation to the left (see Fig 1B2 for an example of the head rotation).

For each extension or flexion of the leg or arm step movement, we were able to calculate their duration from the video coding and their amplitudes and maximum velocities (Vmax) using both the video coding and the motion capture data. The durations of flexion and extension corresponded to the time between the start and the end of the coded movement. The amplitudes corresponded to the mean displacements of the two markers of the concerned limb between the start and the end of the movement. Velocities represented the mean of the peak velocities (Vmax) of the two markers attached to each limb during the movement.

The effective displacement (Dxy) during crawling was determined by measuring the distance traveled by the center of mass of the newborn in the XY horizontal plane of the mattress between the first frame and the last frame of the trial. The value was positive if the newborn moved forward or negative if s/he moved backward. We also measured the

displacement in the y plane (Dy: lateral displacement) because the stimulus was positioned laterally relative to the newborn.

In order to analyze how the four limbs were moving together and how flexions and extensions were coactivated, we calculated a coactivation ratio (CR) for each of the 6 possible pairs of limbs: leg pairs, arm pairs, ipsilateral pairs (left arm-left leg and right arm-right leg), and diagonal pairs (left arm-right leg and right arm-left leg). Those coefficients were based on whether two limbs were in motion at the same time, regardless of the duration of the coactivation (e.g., two limbs could be coactivated for as little as a single frame). In this calculation, the limbs were in-phase if they moved in the same direction at the same time (both in flexion or both in extension) and anti-phase if they moved in opposite directions at the same time (one in flexion and the other in extension). The CR value could range from –1 for a perfect in-phase coactivation to +1 for a perfect anti-phase coactivation and 0 for a 50/50 split.

$$CR = percentage\ of\ antiphase\ Coactivation - percentage\ of\ in\ phase\ Coactivation$$

We were especially interested to see if the newborn crawling pattern shows evidence of a diagonal gait, that is, diagonal contralateral limb pairs moving in phase (negative value of the CR) and ipsilateral limb pairs moving anti-phase (positive value of the CR) (see Table 1).

The goal of the head rooting analysis was to measure the small cephalic movements of the newborn specific to searching for the nipple to see if s/he would make more such movements when listening to the native language. To quantify the small lateral displacements of the head characteristic of the rooting movements, we extracted the roll of the head (rotation around the cephalo-caudal axis) from the motion capture data during each trial. The head movements were characterized relative to the trunk. We calculated the number of head rooting movements. A rooting movement was counted each time the head crossed a virtual line (designated as 0 degrees) characterized by the newborn's nose aligned with the body axis

midline (cephalo-caudal axis). We also integrated two thresholds to count a rooting movement. The minimum threshold was a movement greater than 3 degrees to remove all small random rotations associated with noise in the data signal. The maximum threshold was 50 degrees to be sure not to include any head movement if the face of the subject was turned completely to the left or right. These thresholds led to the detection of bursts of rooting movements that corresponded almost perfectly with bursts of rooting that were identified from qualitative analyses of the video data.

To investigate if English or French would increase overall limb movements unrelated to crawling steps, we extracted the leg and arm movements performed outside of the steps. The 3D score we calculated corresponded to the sum of all the displacements of each limb joint (ankle and knee for the leg; wrist and elbow for the arm) in X, Y and Z directions during each trial except during the frames where steps occurred. We also excluded the 60 frames before and after the occurrence of each step in this calculation to discard any noise coming from the preparation and ending of each step. These 60 frames were determined using the motion capture data.

Data Analysis

The statistical analysis was conducted with Statistica® software (version 6.1). According to the Kolmogorov-Smirnov test, all the data were normally distributed. The number of crawling steps and their amplitudes, max velocities and durations were analyzed with a 2 Condition (French or English) x 2 Limb (Leg or Arm) repeated-measures analysis of variance (ANOVA). The trunk rotations, the orientation of the head, the distances, the rooting movements, 3D scores of non-stepping movements and the crying duration were analyzed using Student's t-tests. The in-phase vs. anti-phase coactivations of the limb pairs were analyzed with a 2 Condition x 6 Limb Pair (Ipsilateral: left arm/left leg and right arm/right leg, Diagonal: left arm/right leg and right arm/left leg, Leg: left leg/right leg and Arm: left

arm/right arm) repeated-measures ANOVA. A Tukey HSD post hoc test was used to follow up significant effects. The threshold for statistical significance was set at $p < .05$.

Results

Only 22 infants were used in all kinematic analyses because one infant's data were corrupted during processing. Of these 22 infants, 9 infants had the loudspeaker on their left and 13 on their right. Of the 23 infants used for the other analyses based on video coding, the corresponding numbers were 10 and 13 in terms of loudspeaker position. All results are summarized in Table 1.

Effect of language conditions on crawling

Newborns were able to differentially adapt their crawling in response to the French and English infant-directed sentences. In French, their native language, compared to English, their crawling was enhanced, with significantly more arm and leg steps (Figure 1. B1) ($F_{(1,22)} = 9.3$, $p = .006$, $\eta^2_{partial} = 0.30$) and significantly more and larger trunk rotations in the cephalo-caudal axis ($t_{(22)} = 2.2$ and 2.5, $p = .038$, Cohen's $d = 0.44$ and $p = .023$, Cohen's $d = 0.50$, respectively). Importantly, the pattern of crawling was not a disorganized succession of limb movements, but demonstrated several characteristics of a quadrupedally organized pattern of propulsion (see the coactivation ratios in Table 1 and a newborn propelling himself forward in the Video in supplementary information). Despite a larger number of crawling steps in French, the traveled distances calculated in XY axes together or in the Y axis alone were not significantly higher in French compared to English ($t_{(22)} = .25$, $p = .805$, Cohen's $d = 0.042$ and $t_{(22)} = -.21$, $p = .833$, Cohen's $d = -0.048$, respectively). The Dxy distance traveled in the French condition ranged from -3.46 cm to 59.66 cm and in the English condition from -4.1 to 72.18 cm. No significant differences were found between French and English for the amplitude ($F_{(1,22)} = 2.90$, $p = .103$, $\eta^2_{partial} = 0.12$), velocity ($F_{(1,22)} = 3.45$, $p = .077$, $\eta^2_{partial} =$

0.14), duration ($F_{(1,22)} = 0.080$, $p = .780$, $\eta^2_{partial} = 0.03$) or coactivation of the steps ($F_{(1,22)} = 0.091$, $p = .254$, $\eta^2_{partial} = 0.01$).

Effect of language conditions on non-crawling behaviors

To test for the possibility that in addition to crawling, French elicits a non-specific increase in the newborn's movements, we investigated the newborn's head rooting movements during the entire trial and all the leg and arm movements (in three dimensions) recorded outside of the crawling step periods. The number of rooting movements did not differ in the French and English conditions ($t_{(21)} = 1.31$ $p = .204$, Cohen's $d = 0.33$). The number of non-crawling leg and arm movements outside of the stepping periods did not differ in the French and English conditions ($t_{(21)} = .578$ $p = .570$, Cohen's $d = 0.12$). Finally, no difference in crying duration was observed between conditions ($t_{(22)} = .971$ $p = .342$, Cohen's $d = 0.21$).

Orientation and displacement toward the loudspeaker in French or English

The analyses in this section were performed separately for the French condition and the English condition. Newborns oriented their head toward the appropriate loud speaker ($t_{(20)} = 2.4$, $p = .029$, Cohen's $d = 0.93$) when hearing French but not English (Figure1. B2 &Table1) ($t_{(20)} = -0.82$, $p = .410$, Cohen's $d = -0.35$). A similar result was observed for the trunk, with newborns orienting their trunk toward the appropriate loud speaker when hearing French ($t_{(20)} = -1.95$, $p = .042$, Cohen's $d = 0.79$) but not English ($t_{(20)} = -0.78$, $p = .447$, Cohen's $d = 0.34$) (Table 1). However, no significant lateral displacements toward the loudspeaker (Dy) were observed in either the French ($t_{(20)} = -1.13$, $p = .273$, Cohen's $d = 0.49$) or English condition ($t_{(20)} = -0.33$, $p = .738$, Cohen's $d = -0.15$).

Discussion

The purpose of this experiment was to determine if newborns could differentially adapt their crawling in response to French, their native language, or English. In French compared to English, their crawling was enhanced, with significantly more arm and leg steps and significantly more and larger trunk rotations in the cephalo-caudal axis. Moreover, newborns rotated their head and their trunk toward the appropriate loud speaker when hearing French but not English.

Effect of native language on newborns' head and trunk orientation and displacement toward the loud speaker

One impact hearing its native language had on the newborn was on its head and trunk turn toward the speaker from which the native language was broadcast. The same response was not observed in English. This response alone is sufficient to confirm that newborns are able to discriminate between their native language and an unfamiliar rhythmically different language. However, to our knowledge, this is the first study to show such discrimination between French and English at birth and to show a head and trunk motor response. These results cohere with other behavioral studies showing that newborns discriminate between languages by modifying their non-nutritive sucking (Nazzi et al. 1998). The capacity of the newborn to turn its head toward the appropriate loud speaker in French is a remarkable behavior by itself, knowing that head turning is difficult to perform in the prone position (due to the weight of head and the newborn's weak neck muscles) compared to when sitting upright with the head supported, as has been done in previous studies where newborn head turning was explored in response to visual or olfactory stimuli presented in front of the infant (see Marlier & Schaal, 2005 or Von Hofsten, 1982 for examples). Interestingly, the head turning observed in the French condition was accompanied by trunk turning. This orientation of the trunk toward the loudspeaker in French but not English could reflect a postural orientation behavior similar to that of the head and/or be a part of an attempt to crawl toward

the loudspeaker. However, a greater lateral displacement (Dy) of the infant toward the loudspeaker was not observed in either language condition and crawling in the y axis was very limited (see Table1). This result is perhaps not surprising given that crawling laterally is likely more difficult than crawling straight ahead and the newborn had a very limited time (2 min) to learn how to organize lateral crawling. Interestingly, the traveled distance Dx,y reported by Forma et al. (2019) and Hym et al. (2020), was mainly the result of newborns crawling in the x axis; crawling laterally in the y axis was negligible in both studies.

Effect of native language on the crawling movements of the newborn

The results revealed quite clearly that newborns moved differently on the Crawliskate when exposed to their native language compared to another language. The differences were apparent in the number of arm and leg stepping movements and the number and amplitude of trunk rotations, both of which were significantly higher in response to French compared to English. Interestingly, the higher number of movements known to be specific to crawling did not result in either a greater displacement of the newborn toward the loud speaker in the French condition, or a modification of the amplitude, velocity, duration or coordination of the arm and leg steps. What accounts for these effects? As noted above, one probable explanation is linked to the newborn's difficulty coordinating its crawling steps on the Crawliskate to orient and propel its body toward a loud speaker that is on its left or right. In contrast to the Hym et al. (2020) study, where the stimulus was positioned under the nose of the infant who thus had no need to orient itself other than straight forward, here the newborn had to be a proficient Crawliskate user to manage steering and propulsion in the appropriate direction, for example by applying more force with the right limbs to orient the Crawliskate toward the left. It is plausible that with no previous experience using the Crawliskate, the newborn was unable to master steering and propulsion in only two trials of two minutes each. It is also plausible that the increase in stepping seen in the French condition represented the newborns'

unsuccessful attempts to reorient and move the crawliskate in the y axis toward the loudspeaker, which in turn could have negatively impacted the steps directed toward propelling the body forward and accounted for the lack of difference between the two conditions in the travelled distance (Dx,y). Another factor impacting the efficiency of the propulsion toward the appropriate loud speaker was the newborns' head position. As discussed earlier, the newborns oriented their head toward the appropriate loud speaker in French but not in English. However, head turning could have interfered with propulsion by: 1) putting the behaviors of head turning and crawling in competition, and/or 2) modifying the tonus of the limbs ipsilateral or contralateral to the side to which the head was turned. It is relevant to note here that infants have a difficult time moving their head freely during crawling until they are approximately three years of age (Touwen et al., 1992). The alternative explanation for the null findings on lateral displacement is that the newborns were not attempting to crawl toward the loudspeaker.

As in the Hym et al. (2020) study with maternal odor, we did not find an effect of the native language on the characteristics of the steps or on the interlimb coordination, with the exception of a difference in the coactivation ratio of the arm pair (Table 1). We believe the same explanations could be offered in the current study as in the previous odor study. In fact, crawling effectiveness and efficiency at this early age may not be managed through modifications of the amplitude, velocity, duration and coordination of the steps, as all factors are highly variable and difficult to control, especially at birth and when positioned on a Crawliskate for the first time. In contrast, a change in the position of the foot and/or hand onto the surface of support may be a more effective and efficient way for the newborn to push against the surface to propel itself. Unfortunately, we did not have a reliable way of quantifying these movements in the current study. It is difficult to compare our interlimb coordination findings with those reported previously in the literature because researchers had

not quantified interlimb coordination in newborn crawling prior to Forma et al. (2018, 2019). Moreover, the interlimb coordination values reported by researchers who have studied crawling in older infants and adults are influenced by factors like crawling velocity, anthropometric characteristics, whether the crawling is performed on the belly or on hands and knees or hands and feet, and the method used to derive the coordination value (e.g., Patrick et al., 2009; Shapiro et al., 2014). Nevertheless, the coactivation ratios for the diagonal arm and leg couplets for the two language conditions are negative and therefore reveal a tendency for the two limbs to move in phase as is the case for the common diagonal gait infants adopt when they begin to crawl on hands and knees (Adolph et al., 1998; Freedland & Bertenthal, 1994; Patrick et al., 2009). Notably, Adolph et al. (1998) reported that infants do not show consistent coupling values between diagonal limb pairs when they crawl on their bellies.

Is the effect of native language on newborn crawling movements specific to crawling?

Because the native language increased the number of steps and the number and amplitude of trunk rotations, but not the traveled distance or the kinematic characteristics of the steps, one could argue that the effect of native language reported here could be the result of a non-specific arousal effect increasing all infant movements. Several results argue against this idea. First, the coding of the step movements of the legs and arms performed by the newborns on the Crawliskate is specific to crawling, as described by Forma et al. (2019). Second, when we analyzed all of the arm and leg movements performed outside of the stepping periods (via the summed scores of all non-locomotor limb movements in three planes of motion) there was no difference between conditions, so there is at least some degree of specificity in the effect of native language on the newborns' crawling movements. Third, arousal, as measured through crying duration (a variable showing a strong positive correlation with commonly used arousal scales – see the footnote in the methods section), was similar

during the French and English trials. Moreover, a previous study using a familiarity/novelty paradigm showed that fetuses increase their heart rate in response to a *non-native language*, but not to their native language (Kisilevsky et al., 2009), suggesting the *unfamiliar* language is more arousing. Fourth, there was no effect of native language on rooting movements of the head. These results further argue against a simple non specific role of arousal on crawling steps in the native language condition since arousal should have increased rooting as well.

The head rooting result is interesting in its own right because it suggests that the crawling response to native language is not driven by the newborns' motivation to search for the breast. If it were, the feeding-elicited rooting behavior should have increased. Moreover, the head rooting result highlights, as argued by Hym et al. (2020), that crawling and rooting are the expression of different perception-action couplings, with native language eliciting an increase in the number of crawling movements but not in the number and amplitude of rooting movements in the current study. These results suggest that motoric behaviors like crawling and rooting are quite complex and are unlikely to be reducible to automatic reflex behaviors triggered by arousal.

If not arousal, what other mechanism could explain our results?

Is linguistic familiarity an example of a supra spinal factor capable of modifying crawling?

It is difficult to record cortical activity when newborns are performing limb and body movements while crawling across a surface. However, prior evidence already shows that the newborn crawling pattern is adaptable to stimuli that are processed supra-spinally. For example, Forma et al. (2018) showed that newborns flexed and extended their legs significantly more when placed on a pediatric mattress and exposed to optic flows specifying forward or backward translation than when exposed to a static checkerboard pattern. As mentioned earlier, Hym et al. (2020) and Varendi and Porter (2001) showed that newborns

crawled further when exposed to their mother's breast odor compared to a neutral odor. These findings are particularly important because odors are known to be processed cortically. From the first days post-birth, artificial odorants elicit hemodynamic brain responses at all levels of the human olfactory tract up to piriform, insular, cingular and orbitofrontal cortices, following the same neural network noted in adults (Adam-Darque et al., 2017; Frie et al., 2017). Our results are also in line with studies showing that human newborns can perform intentional arm movements (Van der Meer et al., 1995). Even fetuses demonstrate a surprisingly advanced level of motor planning with one study showing different fetal hand movement kinematics when the fetus touched its own body versus the external environment (Zoia et al., 2007). These findings suggest that a wide repertoire of newborn movement patterns, including crawling, might be under supra-spinal control.

We believe neonatal crawling is a complex quadrupedal behavior which, though potentially activated by arousal, can also be modified by supra spinal factors that could operate at a brainstem or cortical level even if the cortico-spinal channels are not yet mature and recruit intermediate circuits. Previous research has shown that newborn leg movements and even premature newborn kicking movements in a supine position are already linked to the activation of the premotor cortex (Kanasawa et al., 2014). Even if kicking is not crawling, both behaviors have neuromuscular profiles in common (Thelen & Fischer, 1982; Barbu-Roth et al., 2014; Sylos-Labini et al., 2020).

What are the potential implications of the current findings?

The results of this study confirm that newborns can discriminate their native language from another language and provide further evidence that newborn crawling can be modulated by multiple stimuli, some of which are known to be processed at the brainstem or cortical level. We hypothesize that newborns are not only capable of recognizing the maternal and conspecific caregivers' signals via visual, olfactory, and auditory channels, but they are able

to respond with appropriate motor movements to these signals. Orientation towards native speech and hence towards potential conspecific caregivers is in line with findings highlighting newborns' rich repertoire of capacities to discriminate meaningful stimuli, e.g., preference for human faces (Johnson et al., 1991), believed to be an adaptation crucial for survival. Other motor responses of the newborn have been studied, such as sucking, eye and hand movements, supine movements of the limbs performed in response to different stimuli from con specifics. However, crawling is probably the most spectacular response in terms of its visibility to the caregiver if the newborn is placed in a position that allows the expression of crawling, such as when a clinician induces the breast crawl by placing the baby on the mother's belly immediately after birth. Our hypothesis is that this behavior allows the infant to actively express itself at (and after) birth, by moving toward the familiar signals emitted by its mother or con specifics and this behavior could be important not only for nurturing, but to build mother/caregiver-infant bonding as soon as birth.

The final implication is specific to the study of newborn language discrimination. Our findings reveal that language discrimination can be evidenced by motor responses other than sucking, thus offering the language community a new tool for studying language discrimination. Whether head and body rotations and increases in the movements associated with crawling are more or less sensitive to language than sucking remains to be seen.

Limitations

We must reiterate at the outset of the discussion that our study was exploratory and because we did not account for type I errors in our statistical analyses our findings and our interpretations of those findings must be accepted cautiously. We also acknowledge that our definition of crawling might not be universally accepted because neonatal crawling looks very different from mature crawling. This is also the case when one examines the characteristics of the earliest independent walking steps and later mature walking. However, crawling is more

difficult to define and examine than walking, because there are so many combinations of limb movement that can be used to propel the baby forward in the prone position. Other limitations included the trial duration, which limited to distance travelled by the newborns, and the sample size, which was reduced because some newborns did not crawl at all in one or both of the conditions.

Conclusion

The finding that crawling could be modified by native language sheds new light on the early origins of locomotion and its control. However, future studies are needed to go further in our understanding of the mechanisms underlying the effect of native language on crawling. As we could not replicate the same study on English newborns listening to French or English, it would be interesting to replicate our study on French newborns with a similar protocol to Pena et al. (2003), but analyzing their crawling response to hearing: (i) infant-directed speech in French, (ii) the same speech played backwards, thus suppressing the linguistic nature of the stimuli while preserving its acoustic properties, and (iii) silence. It would be interesting also to look at the newborns' crawling behavior in response to its mother's voice compared to the voice of another mother who speaks the same native language, or silence. The context of future studies could be changed also to facilitate the propulsion of the newborn toward a loud speaker positioned in front of the infant and not on the right or left side.

Acknowledgments

This work was supported by the grant ANR-11-BSH2-007 01 from the Agence Nationale de la Recherche, grant from Région Ile-de-France and the Fondation de France. We would like to thank Professor Goffinet, chief of the Maternity Port Royal in Paris and all infants and parents who participated in the study.

Author Contributions

Conceptualization, M.B.R., C.H., J.G. and T.N.; Methodology, C.H., M.B.R.; Investigation, C.H., M.V.D., J.P. and C.D.; Software, C.H., V.F. and L.G.; Analysis, C.H. and D.A.I.; Writing, C.H. MBR and D.I.A.; Funding Acquisition, M.B.R.; Ressources, C.H., C.D. and M.B.R.; Supervision, M.B.R.

Declaration of Interest

The authors declare no conflict of interest in the conduct of the study or in the publication of the manuscript.

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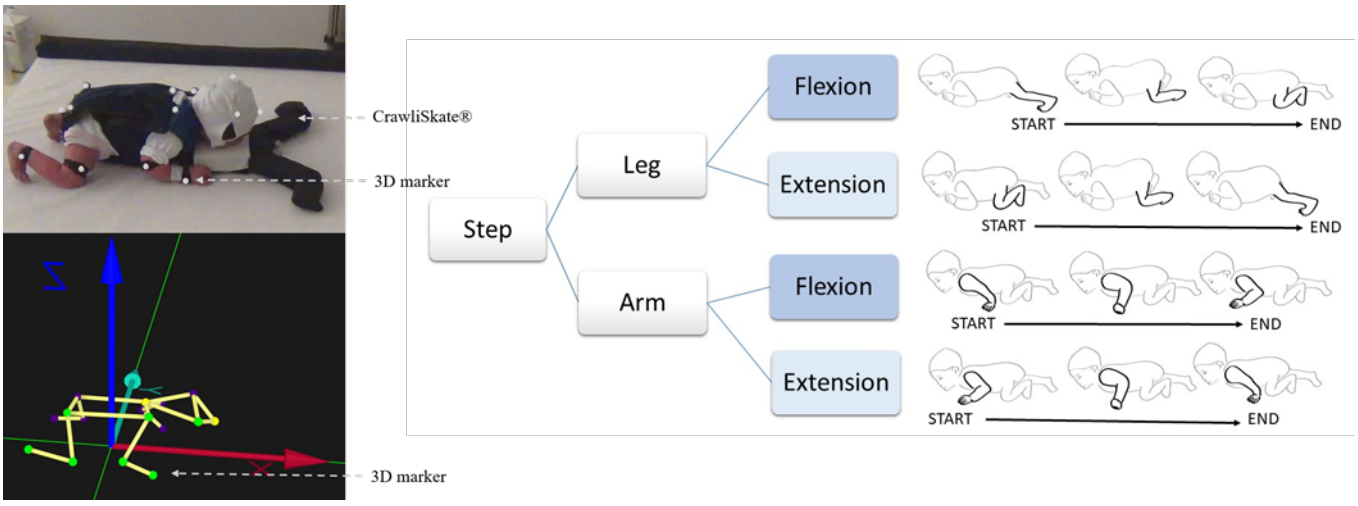
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Figure 1. Experimental set up, coding and primary results.

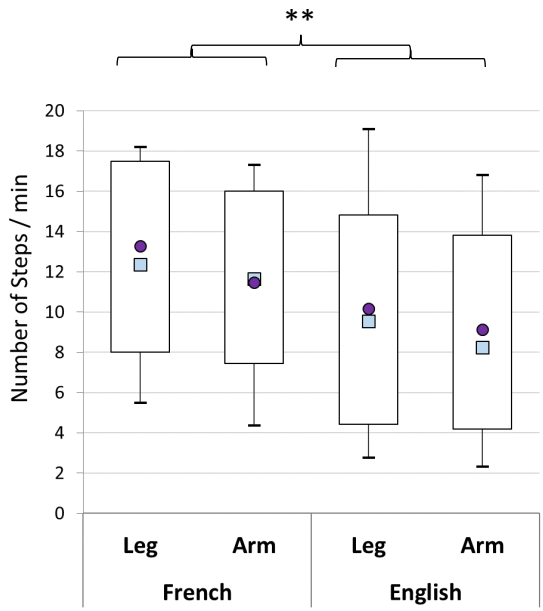
Legend: Panel A1 shows the Crawliskate® used to promote crawling in the newborns and a stick figure representation of the newborn on the device generated by the Qualysis Track Manager software. Panel A2 is a cartoon depicting how the flexion and extension movements of the arm and leg steps were defined and identified during crawling. Panel B1 shows the number of arm and leg steps taken in the two conditions. Significantly more leg and arm steps were observed in the French condition than in the English condition. Panel B2 shows the orientation of the head toward the loud speaker from which the auditory stimuli were broadcast in the French condition. When the stimuli came from the left speaker the newborns were more likely to rotate their head to the left and when the stimuli came from the right speaker the newborns were more likely to rotate their head to the right. The orientation of the head to the left and right was significantly different in the French condition. There were no differences in head orientation to the left or right speakers in the English condition.



Step coding

Figure 1 A1

Figure 1 A2



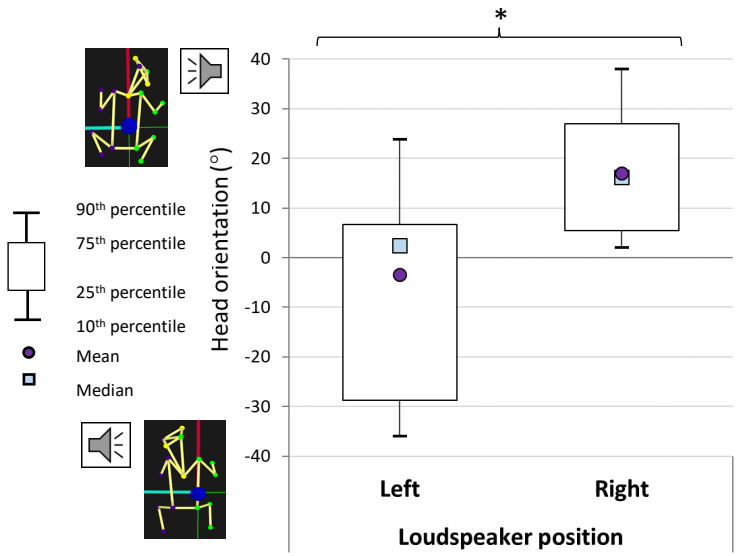


Figure 1 B1

Figure 1 B2

Table 1. Dependent measures analyzed in the study

N.S.: not significant, * = <.05, ** = <.01. See the Methods for details on the statistical analyses. N: number of participants or number of sentences for auditory stimuli

	Conditions						
	French		English				
Variables	Mean	*(SD)*	Mean	*(SD)*	N	p	sig.
CRAWLING							
Number of Steps (Leg and Arm) *(/min)*	**12.36**	*(5.4)*	**9.65**	*(6.0)*	23	**.006**	**
Amplitude of Step Movements *(mm)*	40.01	*(11.1)*	37.43	*(13.9)*	22	.103	N.S.
MaxVelocity of Step Movements *(mm/s)*	152.81	*(30.3)*	138.77	*(41.6)*	22	.077	N.S.
Duration of Step Movements *(s)*	0.80	*(0.2)*	0.79	*(0.2)*	23	.600	N.S.
Traveled distance Dxy *(cm/min)*	7.23	*(8.6)*	6.82	*(10.5)*	22	.805	N.S.
Trunk rotations *(°)*							
Absolute roll	**253.45**	*(102.3)*	**209.15**	*(98.5)*	22	**.038**	*
Amplitude roll	**12.08**	*(4.1)*	**10.23**	*(3.1)*	22	**.023**	*
Coactivation ratio (CR)							
Legs CR	-0.11	*(0.3)*	-0.10	*(0.4)*	23	.822	N.S.
Arms CR	0.23	*(0.2)*	0.09	*(0.4)*	23	.043	*
AL-LL pair CR	0.27	*(0.3)*	0.26	*(0.4)*	23	.883	N.S.
AR-LR pair CR	0.15	*(0.2)*	0.25	*(0.3)*	23	.173	N.S.
AL-LR pair CR	-0.26	*(0.4)*	-0.11	*(0.4)*	23	.155	N.S.
AR-LL pair CR	-0.13	*(0.3)*	-0.03	*(0.4)*	23	.354	N.S.
ORIENTATION TOWARD LOUDSPEAKER							
Head orientation in French *(°)*							
Left loudspeaker effective roll	**-3.40**	*(11.6)*			9	**.029**	*
Right loudspeaker effective roll	**16.98**	*(15.0)*			13		
Head orientation in English *(°)*							
Left loudspeaker effective roll			-7.13	*(11.0)*	9	.994	N.S.
Right loudspeaker effective roll			-7.06	*(18.5)*	13		
Trunk orientation in French *(°)*							
Left loudspeaker effective roll	**-0.20**	*(2.5)*			9	**.042**	*
Right loudspeaker effective roll	**3.42**	*(5.1)*			13		
Trunk orientation in English *(°)*							
Left loudspeaker effective roll			-1.07	*(3.4)*	9	.447	N.S.

Right loudspeaker effective roll			0.14	*(3.7)*	13		
Traveled distance in French DY *(cm/min)*							
Left loudspeaker			-0.29	*(1.6)*	9	.273	N.S.
Right loudspeaker			1.18	*(3.7)*	13		
Traveled distance in English DY *(cm/min)*							
Left loudspeaker			0.40	*(1.6)*	9	.738	N.S.
Right loudspeaker			0.98	*(4.9)*	13		
OTHER VARIABLES							
3D scores (outside step coded)	8.27	*(2.8)*	7.88	*(3.9)*	22	.570	N.S.
Crying duration *(s/min)*	45.92	*(17.3)*	41.84	*(21.6)*	23	.342	N.S.
Number of Rooting Movements *(/min)*	24.52	*(16.3)*	19.16	*(16.1)*	22	.204	N.S.
AUDITORY STIMULI							
Number of words *(/sentence)*	6.91	*(4.0)*	7.46	*(4.2)*	44	.759	N.S.
Number of syllables *(/sentence)*	9.09	*(5.4)*	8.41	*(4.5)*	44	.782	N.S.
Number of phonemes *(/sentence)*	19.91	*(11.1)*	21.73	*(11.5)*	44	.710	N.S.
Mean frequency *(Hz) (/sentence)*	254.77	*(28.9)*	244.83	*(22.9)*	44	.382	N.S.
Max-Min frequency *(Hz) (/sentence)*	237.92	*(52.2)*	269.02	*(49.8)*	44	.169	N.S.

Video in supplementary information.

2-day-old French newborn crawling on the Crawliskate® with motion capture markers in 3D and 2D. The newborn is hearing encouragements to move in French.