Detection of sensorimotor contingencies in infants before the age of one year: a comprehensive review

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Abstract

In order to benefit from the exploration of their body and their physical and social environment, infants need to detect sensorimotor contingencies linking their actions to sensory feedback. This ability, which seems to be present in babies from birth and even *in utero*, has been widely used by researchers in their study of early development. However, a careful look at the literature, particularly recent literature, suggests that babies may not be uniformly sensitive to all sensorimotor contingencies. This literature review examines in detail the mechanism of sensorimotor contingency detection in infants before the age of one year. Four aspects of sensorimotor contingency detection are considered: characteristics of action and feedback, contingency parameters, exposure conditions, and inter-individual differences. For each topic we highlight what favours and what hinders the detection of sensorimotor contingencies in infants. Our review also demonstrates the limitations of our knowledge about sensorimotor contingency detection. We advocate the importance of making progress in this field at a time when sensorimotor contingency detection is of major interest in developmental robotics and artificial intelligence.

1. Introduction

Exploring the body and the environment is obviously essential for infant development: it helps the infant understand the causal structure of the world and to engage socially with other agents; it enables the infant to develop awareness of its body, a sense of agency, and self-consciousness. Roboticists have recently also become interested in how infants explore their body and the world around them, since mimicking how babies learn may be a way to develop autonomous agents capable of open-ended learning (see for ex. Cangelosi and Schlesinger, 2015). This paper focuses on an underlying ability needed for this exploration to be effective, namely the ability to detect when an action is associated with an outcome — in other words the ability to detect "sensorimotor contingencies".

That babies should be able to detect sensorimotor contingencies is generally taken for granted by developmental psychologists, presumably because this ability is at the basis of operant conditioning, which was used very successfully in the 70's and 80's as a tool for studying cognitive functions in infants. The best example is the "mobile paradigm" which has been extensively used in the study of infant memory (see for ex. Rovee-Collier, 1999 for a review), and where one of the baby's limbs is attached to a mobile above it in such a way that the baby's movements activate the mobile. Given this and a plethora of other work based on infants' ability to detect contingencies (for ex. DeCasper and Fifer, 1980; Dunham and Dunham, 1990; Rochat and Striano, 1999; Watson, 1972), developmental psychologists have good reason to consider that babies are highly sensitive to sensorimotor contingencies.

However, does this mean that infants are able to detect any contingency? Looking at recent work using operant conditioning and reconsidering earlier work more closely, it seems that infants' sensitivity to sensorimotor contingencies might be more complex than appears at first sight in the literature. Indeed, in some studies, only a fraction of the observed babies seem to be sensitive to the contingency used by the experimenters. Consider for example the famous

"mobile paradigm" developed by Carolyn Rovee-Collier (Rovee and Rovee, 1969), in which one of the baby's limbs is connected to a mobile so that the baby's movements induce "conjugate" movements of the mobile. This paradigm has been used extensively to characterize early development, particularly memory development, with more than fifty studies from Rovee-Collier's team alone. However, even within these, it appears that some babies did not learn the contingency between their movements and the mobile: e.g., 8% in Hayne, Greco, Earley, Griesler, & Rovee-Collier, 1986 (2-month-old infants), 9% (experiment 1) and 11% (experiment 2) in Rovee-Collier, Griesler, & Earley, 1985 (3 month-old-infants), or 18% in Fagen, Morrongiello, Rovee-Collier, & Gekoski, 1984 (experiment 2, 3 month-old-infants). The failure of some babies to learn is also (and more clearly) reflected in studies from other teams (using the mobile paradigm or other operant conditioning procedures). This is the case, for example, in Watanabe and Taga (2009) in which only 45% of the 120 babies in the study learned the contingency, or also in the study of Tiernan and Angulo-Barroso (2008) in which only between 30% and 60% of the 8 to 12 infants (depending on the experimental condition) were able to learn the contingency, or even in Angulo-Barroso et al. (2017) in which only 45% of the 38 infants were sensitive to the contingency. Moreover, it also appears that under certain experimental conditions, babies do not even show any contingency learning at the group level. For example, Tiernan and Angulo-Barroso (2008) obtained no statistical difference between infants tested in contingent situations and infants in a non-contingent control group, or the study of Floccia, Christophe, & Bertoncini (1997) in which the authors found that newborns were not sensitive to operant conditioning under certain conditions. Also, it is worth noting that these examples illustrating infants' difficulty to learn sensorimotor contingencies correspond only to published papers. Our personal communication with numerous investigators who have attempted to study sensorimotor contingencies with infants suggest that there have actually

been many failures to obtain reliable learning effects, rendering publication of the results impossible.

What then accounts for these rejection rates and these difficulties in obtaining reliable results? Are there very significant individual differences between infants? Or are there special characteristics that a contingency must have in order to match the properties of a baby's contingency detection mechanism? Despite an abundance of published studies using operant conditioning, there is to our knowledge no paper systematically reviewing the characteristics of baby's sensitivity to non-social sensorimotor contingencies (i.e. contingencies involving the body itself or the external physical world but not the social partners). To investigate this question the present paper will provide an overview of available data about the properties of babies' responsiveness to contingencies in different circumstances. More precisely, we will review the following aspects of the contingency detection mechanism: (1) characteristics of action and feedback, (2) contingency parameters: temporal, relational, spatial, (3) exposure conditions: amount of exposure, time window between two repetitions of the contingency, probability of occurrence, prior exposure, and (4) inter-individual differences: motivation, inter-individual differences. We hope this will help experimenters in future to find contingencies that match infants' sensitivity, thereby increasing the chance of successful experiments.

2. Characteristics of action and feedback

2.1. Action

In order to detect a sensorimotor contingency, an infant needs to isolate the action involved in this contingency. Two features of the contingent action might influence contingency detection: (i) the saliency of the contingent action, and (ii) the infant's proficiency in executing the contingent action.

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2.1.1. Saliency of the contingent action

It has been hypothesized that contingencies involving salient actions, i.e. actions that an infant can easily isolate and identify relative to other actions, should be more easily detected by infants (Zwicker, Moore, & Povinelli, 2012). The saliency of an action, and therefore the infant's ability to identify it as involved in a contingency, depends on several aspects such as its amplitude, its suddenness or its goal-directedness. For example, with respect to the action's suddenness, Zwicker et al. (2012) argued that "*movements that involved a sudden onset and offset would facilitate the participant's ability to detect [the associated contingency], whereas movements that were of a continuous nature with no sudden start or stop would diminish their ability to detect [the associated contingency]*" (p. 30). To our knowledge only Watson (1979) has tested the influence of an action's saliency on the detection of sensorimotor contingencies. In his experiment, 2-month-old infants' foot pressure on a pillow triggered movements of a mobile above their heads. Infants were divided into two groups depending on the sensitivity of the pillow: one group had a very sensitive pillow (a low foot pressure was sufficient to trigger the feedback) and one group had a pillow that was half as sensitive (a high foot pressure was needed to trigger the feedback). Watson (1979) found that infants exposed to the less sensitive pillow learnt more rapidly compared to infants exposed to the more sensitive pillow. A plausible interpretation of the result is that the observed enhancement of learning is due to the saliency of the contingent action. However, it is worth noting that, as actually suggested by Watson in his article, the explanation could be that infants prefer "less-than-perfect" contingencies to "perfect" contingencies. We will come back to this issue in the section "Probability of occurrence". Though it would seem natural to expect that increased action saliency should improve detectability of contingencies, the literature generally only provides anecdotal evidence. For example, Millar and Watson (1979) reported having ensured "*that relatively extensive arm movement was required to operate the [contingent feedback]*" (p. 748).

Finkelstein and Ramey (1977) explained that they preferred to use a panel-pressing action rather than an arm-pulling action because "*it was less susceptible to unintentional responding*" (p. 810). Our personal communication with workers in the field also confirms that they deliberately choose salient contingent actions in order to increase the detectability of the contingencies in their experiments, for example by using an action with a well marked start or end - (e. g. pressing a button). Nevertheless, it seems that diminished saliency of actions does not completely prevent contingency detection: Maister, Tang, & Tsakiris (2017) found that 5-month-old infants were able to detect a contingency between their heartbeats (a non-salient and non-intentional action) and movements of a character on a screen.

2.1.2. *Proficiency in executing the contingent action*

Another feature of an action that might improve its identification among other motor commands, and so enhance the detection of the associated contingency, is the infant's proficiency in executing this action. One might argue that infants might be more apt to identify actions that they have already mastered, as claimed for instance by Rochat and Striano (2000) who noticed that operant conditioning was feasible in newborns only when an "*already well organized and preadapted action*" (p. 527) was reinforced (here non-nutritive sucking). Thus, probably based on this statement, developmental psychologists seem to have carefully chosen the contingent actions used in their experiments so as to consider the motor abilities of the infants at the tested age. For example, the most frequently used paradigm with newborns is non-nutritive sucking because at this age sucking is one of the only actions that infants have already mastered. This paradigm is then generally abandoned by researchers working with older infants as older infants do not tend to suck anymore and prefer to interact manually with objects or to interact socially with agents. Another example is given by the extensive use of the mobile paradigm in 3-month-old babies, where the contingent action involved is babies' kicking when lying on their backs. Why choose this action over another one? This choice seems to be

justified by the good kicking control possessed by babies of this age, while their control of arm movements is much more limited. In older babies — who no longer tend to kick so much in a supine position — the mobile paradigm is abandoned: see for example Hartshorn and Rovee-Collier, 1997 in which the authors explicitly explain that they had to switch to another task with babies older than 6 months of age; or see Watanabe and Taga, 2006, in which the authors adapted to the current skills of older babies by using reinforcement of arm movements, saying that "*as infants grow, it becomes apparent that the arms are more frequently used for manipulatory behaviors while the legs are involved with posture and locomotion*" (p. 403). Nevertheless, it is worth noting that no experiment has come to our attention that directly compares contingency detection between more or less proficient actions.

2.1.3 Conclusion

Contingency detection seems to be enhanced by salient actions such as high amplitude sucking or very sudden arm movements. Hence, actions that are noticeable among other motor commands, as actions with a clear beginning and end (e.g. when pressing a button), seem beneficial for contingency detection as they ensure that the infant can easily determine which action is the one causing the effect.

In addition, for contingent situations to be easily detected by an infant, the contingent action must be adapted to the infant's motor abilities. The degree to which it is adapted will depend strongly on the infant's age: on the one hand, the action should preferably be in the infant's motor repertoire (e.g. non-nutritive sucking in newborns) and, on the other hand, it must correspond to the infant's spontaneous motor behaviour at its particular period of development (e.g. object manipulation between 6 and 9 months).

2.2. Feedback

A second factor that obviously influences the baby's ability to detect a contingency is the accompanying contingent feedback. In this section we explore how babies' sensitivity to contingencies is affected by the sensory modalities of the feedback and its attractiveness to the baby.

2.2.1. Sensory modalities

One might ask to what extent the sensory modality of the contingent feedback influences contingency detection in infants. To our knowledge, three studies have investigated this question (McKirdy and Rovee, 1978; Kraebel et al. 2004; Tiernan and Angulo-Barroso, 2008). In these studies, 3-month-old infants were assigned to three groups, each exposed to a contingency involving their leg movements, but with feedback from different sensory modalities: visual feedback (a silent and visible mobile), auditory feedback (a noisy but out of sight mobile), or audiovisual feedback (a noisy and visible mobile). Babies in each group were exposed to the same procedure: first, a baseline during which the baby's movements are measured in the absence of contingency, then a phase of exposure to the contingency (*acquisition phase*), immediately followed by stopping of the contingency (*extinction phase*) and followed, 24 hours later, by a re-exposure to the contingency (*retention phase*). In the three studies, the authors found that all groups were able to learn the contingency regardless of the feedback they were exposed to (visual, auditory and audiovisual) — the "learning criterion" consisting in a higher kicking rate during the *acquisition phase* than the one observed in the baseline. However, the authors found slightly diverging results between the visual, auditory and audiovisual groups. McKirdy and Rovee (1978) found that all feedback groups showed similar kicking rates in the *acquisition phase*, but that in the *extinction phase* (when the contingent feedback was removed) the infants exposed to the auditory feedback reacted

differently compared to the other groups (visual and audiovisual feedback). Infants in the auditory group diminished their kicking rate while infants in the visual and audiovisual groups maintained their kicking rate at a level similar to the rate in the *acquisition phase*. The difference in behaviour in the *extinction phase* might be explained by the difference in stimulation during this phase: infants in the visual and audiovisual groups were exposed to a non-moving mobile while the infants in the auditory groups received no stimulation at all (since during the *extinction phase* the mobile was not visible in this group and no sound was displayed). Kraebel, Fable, & Gerhardstein (2004) found that all the groups (visual, auditory or audiovisual) showed similar kicking rates in the *acquisition phase,* but that infants in the audiovisual group had a higher kicking rate in the *retention phase* compared to infants in the unimodal groups (visual or auditory). Tiernan and Angulo-Barroso (2008) found that infants exposed to audiovisual feedback showed a higher kicking rate compared to infants exposed to unimodal feedback (visual or auditory). They found no difference in kicking rates between the two types of unimodal feedback (visual and auditory). It is worth noting that this enhancement of learning using audiovisual feedback was also noticed by McKirdy and Rovee (1978): in their experiment, infants exposed to the audiovisual feedback had higher kicking rate in the *acquisition phase* than infants in the unimodal groups (visual and auditory) but these differences did not reach statistical significance. Altogether the results of these three studies suggest that the sensory richness of feedback might improve contingency learning in infants since the use of combined audiovisual stimulation as compared to visual or auditory stimulation seems to facilitate the detection of a contingency and to enhance its long-term retention.

2.2.2. *Attractiveness of the feedback*

A second feature of the feedback that might influence contingency detection is the attractiveness of the feedback for the infant. First of all, it is worth noting that the simple fact of producing an effect, whatever it is, is attractive to babies (we will come back to this notion

in the "Intrinsic Motivation" section). In addition, it seems obvious that an infant should be more likely to detect a contingency if the infant is highly attracted by the feedback involved in this contingency. The attractiveness of the feedback can be defined along two dimensions, (i) the baby's interest in the stimulus itself, and (ii) the baby's interest in the way the stimulus is presented (i.e. with or without variation). To our knowledge, developmental psychologists have not attempted to assess babies' ability to detect contingencies according to the first dimension — experimenters have simply used stimuli that are known to be of high interest for infants: their own mother's voice (e.g. in van der Meer and van der Weel, 2011), happy infant faces (e.g. in Lewis, Sullivan, & Brooks-Gunn, 1985), infant toys (e.g. mobile, train in Hartshorn et al., 1998), social interactions with the experimenter (e.g. in Ramey and Ourth, 1971), infant movies (e.g. Kenward, 2010), infant songs (e.g. in Kraebel et al., 2004), colored lights (e.g. in Millar and Schaffer, 1972), animal pictures (e.g. in Wang et al., 2012), etc. Concerning the second dimension of stimulus attractiveness (i.e. the way the stimulus is presented), Siqueland and DeLucia (1969) found a positive influence of variation in feedback on infants' contingency learning. They exposed 12-month-old infants to a contingency between their sucking and the appearance of visual stimuli and found that infants exposed to redundant stimuli responded to the contingent situation for a shorter time compared to infants tested with non-redundant stimuli. This finding can be compared with the effects observed in studies using the habituation paradigm (see for ex. Aslin, 2007 for a recent review on visual habituation). Even though developmental psychologists do not generally explicitly justify their choice of contingent feedback, the observations above suggest that the attractiveness of the feedback plays a role in the propensity of an infant to detect a sensorimotor contingency.

2.2.3. Conclusion

With regard to feedback, richer stimuli seem to favour contingency detection, i.e. those involving several sensory modalities and that vary during the experiment. Stimuli that are

pleasant and of high interest for the baby given its age (e.g. the mother's voice or heartbeats in newborns) may also enhance contingency detection.

3. Contingency parameters

3.1. Temporal parameters

From the very first months of life, infants are able to distinguish small differences in temporal duration and temporal sequences (see for ex. Lewkowicz, 1989 for a review). The time interval between an action and a subsequent perceptual change can therefore presumably be used by the infant's brain as an indication of a contingent link between two events. Following this hypothesis, developmental psychologists have studied how infants' sensitivity to contingencies depends on temporal delays. They have done this for contingencies involving the physical environment, the social environment and feedback of the baby's own movements. In a first paragraph, we will attempt to determine what delay separates situations considered by infants as contingent from those considered as non-contingent.

3.1.1. *Contingent or Non-contingent?*

Infants are able to differentiate between contingent and non-contingent situations, both in terms of interaction with the physical environment (e.g., Wang et al., 2012) and with the social environment (e.g. Murray and Trevarthen, 1985; Nadel, Carchon, Kervella, Marcelli, & Reserbat-Plantey, 1999). This raises the question of when babies consider a situation to be non-contingent, or more precisely for what delay between the action and feedback? It seems that when delays are longer than 3 seconds, infants are no longer able to detect sensorimotor contingencies. Ramey and Ourth (1971) exposed 3-, 6- and 9-month-old infants to a sensorimotor contingency between their vocalizations and a multisensory response of the experimenter. At each age infants were exposed to time intervals of either 0, 3 or 6 seconds.

They found that all age groups behave similarly: infants exposed to the non-delayed sensorimotor contingency increased the frequency of their vocalizations but infants exposed to both 3-second and 6-second time intervals did not. Millar (1972) and Millar and Watson (1979) replicated this result in 6- to 8-month old infants exposed to a sensorimotor contingency between arm pulling and an auditory and visual stimulation. Finally, coherent with the above results, Bahrick and Watson (1985) and Zmyj, Hauf, & Striano (2009) showed that infants discriminate a 3-second delayed view of their limbs from a real-time view. Nevertheless, this ability emerges at different ages depending on the experimental set-up. Curiously, there is no study to our knowledge that has determined from what delay between an infant's action and the partner's response, a social contingency is no longer detected by the infant - indeed, in social contingency studies, non-contingent conditions are either replays of a previous interaction between mother and baby (e.g. Nadel et al., 1999), or the mother's observance of the timing of another mother's responses, i.e. a "yoked' condition (e.g. Goldstein and Schwade, 2008). Hence, we have no way of concluding whether babies are more tolerant with regard to social contingencies — as social contingencies are intrinsically delayed — and whether they can detect social contingencies with a delay of more than 3 seconds.

3.1.2. *Infants' sensitivity to delayed contingencies*

In the previous section, we saw that contingencies with a delay of more than 3 seconds seem to be not detected by babies. But what about contingencies with a delay of less than 3 seconds?

Contingencies involving the physical environment

A first way to answer this question has been to test infants' sensitivity to contingencies involving the physical environment and having delays ranging from 0 to 3 seconds. Millar (1972) exposed 6- to 7-month old infants to sensorimotor contingencies with no delay, or 1 or 2 seconds of delay. He showed that infants are able to detect both non-delayed and delayed

contingencies but that they need more time to detect the delayed ones. In another experiment of the same article, he changed the delay and found that infants notice when the delays changed going from no delay to 1 or 2 seconds of delay.

Contingencies involving the social environment

A second way to investigate how babies' sensitivity to contingencies varies with delay is to study the interactions between babies and their social partners, since from birth and even before, infants are frequently exposed to delayed contingencies through social interactions. From 3 months onwards, infants seem to be sensitive to these delayed contingencies and use them to engage in "protoconversations" with their caregivers (Trevarthen, 1979). Infant-caregiver protoconversations have been extensively studied during the last decades. What we can take away from this literature is in particular the fact that these protoconversations are organized in a turn-taking fashion: both the infant and the caregiver respect minimal *gaps* and minimal *overlaps* between their mutual communicative signals (e.g., Gratier et al., 2015). Moreover, these protoconversations between young (4-month-old) infants and their caregivers seem to be organized into approximately 3-second windows (Van Egeren, Barratt, & Roach, 2001). And more precisely, mothers seem to respond to their young (3-month-old) infants within a time interval of less than 1 second (Keller, Lohaus, Volker, Cappenberg, & Chasiotis, 1999). Note that the precise time interval respected by the infant and the mother depends on the dyad itself and on the socio-cultural context (see section "Inter-individual differences" for more details). Interestingly, in the case of social contingencies, babies seem to react differently to contingencies with a delay of less than 1 second and to contingencies with a delay ranging from 1 to 3 seconds. Striano, Henning, & Vaish (2006), for example, observed that 12-month-old infants preferred to interact with a contingent partner rather than with a partner responding with a delay ranging from 1 to 3 seconds. However, there is no study to our knowledge that precisely compares babies' ability to detect delayed and non-delayed social contingencies.

Hence, we cannot conclude whether babies remain more tolerant in their ability to detect delayed contingencies as compared to non-social contingencies.

Contingencies involving feedback of the infant's own movements

A final way to study babies' sensitivity to contingencies with delay has involved the use of contingencies between the baby's arm or leg movements and the proprioceptive and visual feedback from these movements. Researchers have investigated from what delay babies were able to differentiate a live view of their movements from a delayed view, and whether this varied during development. Results show that during the first six months of life, infants seem to be insensitive to small differences in delays (0.5 to 3 seconds). For example, Rochat and Striano (2000), using the preferential looking paradigm, studied this question in 1- to 5-month-old infants. They presented them with two views of their own legs: a non-delayed view vs. a view delayed by 0.5, 1, 2 or 3 seconds. For all age groups, they found no preference between the two views. This absence of preference between non-delayed and slightly delayed views of the infant's own movements has been replicated for 5-month-old infants when they observe their own leg movements (Hiraki, 2006) or their own face movements (Collins and Moore, 2008, cited in Zwickler et al., 2012 pp. 25-26)[1]. In contrast, infants older than 6 months seem to be less tolerant. In Hiraki (2006) and Collins and Moore (2008) (cited in Zwickler et al., 2012 pp. 25-26), respectively 7- and 12-month-old infants behaved differently for a non-delayed and for a 2-second delayed view of their own movements (but not for the 1-second delay — cf. footnote 1 in Hiraki, 2006).

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[1] Note that, the use of the preferential looking paradigm on all of these studies cannot guarantee that infants before 6 months of age are not sensitive to small differences in temporal properties of sensorimotor contingencies. It could simply be that infants had no preference between the real-time and the delayed view, or it could be that the paradigm is not sensitive enough to show the difference (for a more detailed criticism, see Zwicker et al., 2012).

3.1.3. Conclusion

The fact that in the first months of postnatal life the sensorimotor contingency detection mechanism tolerates a maximum delay of about 3 seconds between bodily actions and their consequences might be related to the need for the infant's brain to discriminate between effects caused by the infant's own actions and those produced by the external world. It could be that the observed maximum delay of 3 seconds ensures that only events generated by the infant itself are encoded as being self-generated. Moreover, the developing ability of the brain to detect small temporal changes within the 3-second window of sensitivity could serve to help the infant distinguish between interactions with social partners and interactions with the physical world around her. Indeed, events occurring without delay or with extremely small delays are more likely to be non-social events and events occurring with longer delays within this window are more likely to be social events (Tarabulsy, Tessier, & Kappas, 1996).

To conclude, contingencies involving a delay of less than 3 seconds seem to be more easily detected by babies. For young babies (less than 6 months of age), there is no evidence that the stability of the delay during the experiment has an effect, as long as the delay remains under 3 seconds. On the other hand, for babies over 6 months of age, variations in delay can diminish their contingency detection abilities.

3.2. Relational parameters

A second way for the infant's brain to detect the contingent link between an action and a change in sensory inputs might be to note the degree to which parameters like the frequency, the intensity, and the duration of this change in sensory inputs follow the variations of one aspect of the action. This has been called the "*relational parameter*" (Gergely and Watson, 1999, p. 105) or the "*intermodal form*" (Rochat and Striano, 2000, p. 523). Two types of contingencies are then to be considered: (i) analog contingencies, which are congruent in the relational

parameter, since one aspect of the contingent stimulus varies according to one dimension of the baby's movements, and (ii) digital contingencies, which are not congruent in the relational parameter but work in an all-or-nothing mode: a fixed contingent stimulus is displayed each time one aspect of the baby's movements reaches a predetermined threshold. We will try to answer two questions: (i) to what extent are infants sensitive to the congruence between variations in action and feedback? and (ii) what kind of sensorimotor contingencies are most easily detected by infants: analog or digital?

3.2.1. To what extent are infants sensitive to the congruence between variations of the action and those of the feedback?

The study of social interactions provides an initial insight in answering this question. As noted by Bigelow and Power (2014), "*in naturally occurring interactions with young infants, maternal responses [...] match the infants' actions in modality, intensity, affect, and tempo*" (p. 559). This fact might mean that infants tend to develop a sensitivity to the presence of such congruence in both the social and non-social contingencies that they experience.

As concerns non-social sensorimotor contingencies, only few studies have assessed to what extent infants are sensitive to the congruence between the variations of action and feedback. Rochat and Striano (1999) tested this sensitivity in 2-month-old infants by using the non-nutritive sucking paradigm. The authors observed infants' behaviour during the exploration of an analog contingency for which the pitch of an auditory stimulus varied according to the baby's pressure of sucking, and the exploration of a digital contingency for which a fixed auditory stimulus was displayed each time the baby's pressure of sucking reached a predetermined threshold. The authors found that the infants tested in the analog condition tended to vary their sucking, but not the ones tested in the digital condition, suggesting that 2-month-old infants are sensitive to the congruence between the variations of the action and those of feedback. Using the same setup, the authors also tested newborns. Here they found no

increase in control, neither in the analog, nor the digital conditions. Taken together, these results suggest that sensitivity to the congruence between the variations of the action and those of feedback emerges between birth and 2 months of age. Note however that the data could also be explained by lack of ability to control amplitude of sucking at birth.

With a similar aim, Fagen and Rovee (1976) used the mobile paradigm to explore the ability of 3-month-old infants to detect the congruence between variations of their kicking rate and those of the mobile's movements. To vary the degree of relation between the kicking rate of the infant and the visual feedback they used mobiles made of more or fewer elements: for the same kicking rate a mobile with few elements generates a smaller visual response than a mobile with many elements. The authors exposed the infants to one mobile during two days, and then switched to another mobile with more or fewer elements. Infants noticed this change: they adapted their kicking rate to maintain the same amount of visual stimulation as before and they showed "negative contrast effects" (crying) when the shift was too abrupt. Mast, Fagen, Rovee-Collier, & Sullivan (1980) replicated this experiment: they trained infants with a mobile having 6 or 10 similar components and tested them with the mobile modified to have only 2 of its components. Again, they found that infants noticed the change in number of components: they increased their kicking rate, they decreased their visual attention and they increased their negative vocalizations. In addition, the authors found that the larger the change was in the number of components, the longer the infants showed altered behaviours up to 24 hours after training with the original mobile.

Taken together, these studies suggest that from 2 months onwards, babies seem to be sensitive to the congruence between the variations of the action and those of feedback and seem able to modify their behaviours in order to explore this congruence.

3.2.2. *What kind of sensorimotor contingencies is most easily detected by infants: analog or digital?*

The previously mentioned study by Rochat and Striano (1999) had shown that infants seem to be sensitive to both analog and digital contingencies. But one might ask which kind is more easily detected by infants, or in other words, does congruence in relational parameter found in analog contingencies facilitate their detection? To our knowledge, apart from Rochat and Striano (1999), only Voltaire, Gewirtz, & Pelaez (2005) directly compared analog and digital sensorimotor contingencies. In their experiment, Voltaire et al. (2005) used a sensorimotor contingency between pressing a panel with the foot, and the appearance of a set of lights. They compared the response rates of 4-month-old infants in an analog condition (i.e. the intensity of the lights varied in proportion to the foot press) and in a digital condition (i.e. the intensity of the lights was not varied). They found that infants in both conditions showed learning of the sensorimotor contingency but peaks in response rates were higher in the analog condition than in the digital condition. Watson (1984) also noted, comparing his work to that of Rovee-Collier, that analog sensorimotor contingencies are better detected by infants than digital contingencies. He explained that this difference could be due to the fact that analog contingencies can be detected by correlating information on two dimensions (temporal and relational) whereas digital contingencies involve only one dimension of correlation (temporal). However, one could take the opposite stance, namely that a one-dimensional correlation should perhaps be easier to detect.

3.2.3. *Conclusion*

Infants from 2 months of age seem sensitive to the congruence between the variations of the action and of feedback found in analog contingencies. They also seem able to detect both analog and digital contingencies; however, it seems that whether a contingency is analog or

digital has consequences on babies' ability to detect the contingency. The effect of each type of contingency (analog or digital) might depend on babies' expectations: the analog might be more beneficial in situations when the baby is used to obtaining analog effects, as for example shaking a rattle more or less quickly to hear sounds at different rates and, conversely, the digital might be more beneficial in situations that require, for example, pressing a button.

3.3. Spatial parameters

The third type of cue that the brain might use to determine whether there is a link between an action and a change in sensory inputs involves the spatial correspondence between the two events. This spatial correspondence can involve a correspondence of location and/or a correspondence in motion. Correspondence in location means that the action and its consequences occur at the same place in space, or are aligned in the visual field. A correspondence in motion means that the trajectory of the action and the trajectory of its visual or auditory consequence are similar.

3.3.1. Correspondence in location

Only one paper, namely Millar and Schaffer (1972), directly addresses the question of correspondence in location. The authors exposed 6-, 9- and 12-month-old infants to a contingency between touching a graspable cylinder and a visual and auditory feedback. They split infants into three groups depending on the angular distance between the cylinder and the contingent feedback: 0° (which corresponds to a perfect alignment in the visual field), 5° (which corresponds to small misalignment in the visual field), and 60° (which corresponds to a large misalignment in the visual field). They found that all infants can learn the contingency when feedback is displayed at 0° or 5°. This learning occurred at the same rate for these two conditions and at all ages. But when the angular distance was 60°, only the 9- and 12-month old infants were able to learn the contingency. The 6-month-old infants behaved similarly to

infants exposed to a non-contingent stimulation. What could explain this difference between 6 and 9 months of age? According to the authors, the difference could be explained by the fact that in the condition where the angular distance was 60° it was impossible for babies to focus their visual attention on the cylinder and on visual feedback at the same time. This would have prevented 6-month-old babies from detecting the contingency - they seemed not able to handle the cylinder without looking at it - while 9-month-old babies seemed not to be hindered in their learning by this arrangement - they seemed able to handle the cylinder at the same time they were looking at the visual feedback box (and therefore not looking at the cylinder).Thus, correspondence in location between an action and its feedback seems to be critical for young babies in order to be able to detect a contingency, but seems to become less important by the end of the first year of life as infants' ability to divide their attention improves.

3.3.2. *Correspondence in motion features*

Correspondence in motion features has been studied through the use of contingencies involving visual feedback of the infant's own movements. Using the preferential looking paradigm, Rochat and colleagues (Morgan and Rochat, 1997; Rochat and Morgan, 1995; Rochat and Morgan, 1998; see Rochat, 1998 for a review) explored precisely what aspects of spatial information were considered by 3- and 5-month-old infants in order to recognize visual feedback of their leg movements. The authors proposed two aspects of spatial features that could be involved: movement directionality and spatial orientation. To distinguish the role of these two aspects, Rochat and colleagues designed three different conditions of an experiment in which they assessed whether infants were able to distinguish a live video of their own legs and a video of their legs where in condition n°1 movement directionality and spatial orientation were modified (observer view with inversion between the right and left legs), in condition n°2 only movement directionality was modified (ego-centered view with inversion between the right and left legs), and in condition n°3 only spatial orientation was modified (observer view

without any inversion between the right and left legs). Note that during the experiment, the infant' own limbs were hidden from her view. The results suggest that movement directionality is a more important aspect of motion in determining contingency than the spatial orientation. Indeed, infants distinguished the live view of their legs from the modified view in the two first conditions — in which movement direction was modified due to an inversion of right and left legs — but they showed no preference between the two views in the last condition — in which there was no variation in movement direction but a modification of the spatial orientation. In addition, Rochat and his colleagues (see Rochat, 1998 for a review) showed that familiar visual characteristics of the limbs were not mandatory for limb movement recognition — they eliminated these characteristics by putting thick striped socks on the infant' legs. The crucial role of movement directionality in discriminating contingent from non-contingent displays was replicated for arm movements in 5-month-old infants by Schmuckler (1996b).

3.3.3. *Contradictory findings*

The experimental findings presented above seem to suggest that for infants to detect a contingency, the infant's action and the resulting effect must correspond in movement directionality. Nevertheless, infants appear to be perfectly able to detect sensorimotor contingencies without any spatial correspondence[2], as in the mobile paradigm, paradigms involving touch events, or in gaze contingent paradigms. This divergence in results could be explained by the cognitive requirements of detecting contingencies between limb movements and both their visual and proprioceptive consequences. Indeed, detecting this kind of contingencies requires that infants compare motor commands with two kinds of sensory feedback, namely information coming from proprioception and from vision. Thus, congruence

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[2] One might argue as Schmuckler & Jewell (2007) that in the mobile paradigm there is still a correspondence in direction (perhaps the mobile moves to the right when the infant moves its limb to the right and vice versa) but it appears obvious that in this case the spatial correspondence is mostly not reliable.

in movement directionality may not be mandatory for simple sensorimotor contingency detection but may be mandatory when contingency detection involves visual and proprioceptive integration of limb movements.

3.3.4. Conclusion

The spatial parameters underlying contingency detection are undoubtedly important in determining self and external world differentiation. It makes sense that spatial correspondence and intermodal integration should be critical and useful when infants detect contingencies involving their own body. In contrast, spatial correspondence is presumably less critical when infants need to detect contingencies involving the physical environment, and even less critical when infants need to detect contingencies with the social environment. Thus, we would suggest that the infant uses the gradient going from spatially congruent contingencies to spatially non-congruent contingencies to distinguish between own body contingencies, contingencies involving the physical external world and contingencies involving social partners. Obviously, this differentiation process would be both progressive and continuous over development: in this way, babies would gradually refine their model of the world as they interact with their environment. Concerning contingency detection, there is no consensus on the need for spatial parameters to be respected in order for a contingency to be detected. However, we can note that for a contingency requiring the manipulation of an object in young babies, both the object handled and the effect of the manipulation should be aligned so that the baby does not have to focus on two different places in his or her visual field. On the contrary, for contingencies that do not involve the baby focusing its visual attention on both the action to be performed and the stimulation, spatial colocation of action and effect does not seem necessary. In addition, congruence in movement directionality between movements and effects seems to be required to help babies to integrate the visual and proprioceptive feedback of their own movements.

4. Amount and frequency of exposure

In this section, we will examine four aspects of exposure conditions to a contingency that influence the "detectability" of this contingency by infants. First, we will try to identify the amount of exposure to a contingency needed to make a baby able to detect it. Second, we will consider how the time window between two repetitions of a contingency affects a baby's ability to detect that contingency. Third, we will show that the probability of triggering the contingent feedback after completing the action (probability of occurrence) influences contingency detection. And finally, we will see how pre-exposure to a contingent or non-contingent situation affects contingency detection.

4.1. Amount of exposure

How much exposure to a sensorimotor contingency is necessary for an infant to detect it? Curiously, this obvious question has not been directly addressed in the literature on sensorimotor contingencies. However, in an attempt to answer this question, we can for example examine the amount of exposure needed for contingency detection in experiments using the mobile paradigm, which is the most frequently used paradigm in the literature. Here, it is generally found that 3-month-old infants need between 3 and 6 minutes of exposure to the contingency to detect it (see the review by Rovee-Collier, 1999). Note that similar or shorter times of exposure are reported for other paradigms such as the non-nutritive sucking paradigm (e.g. 4 minutes in Siqueland and Delucia, 1969), the preferential looking paradigm (e.g. 1 minute in Zmyj, Hauf, & Striano, 2009) or for other operant conditioning paradigms (e.g. 1 to 5 minutes in Wang et al., 2012 — in this case, a contingency between eye movements and a visual stimulation).

Nevertheless, long-term retention of a sensorimotor contingency may require longer exposure. For this question we can again refer to the mobile paradigm: Linde, Morrongiello &

Rovee-Collier (1985) showed that 2-month-old infants exposed for 18 minutes to the mobile paradigm remembered the contingency for one week, while infants exposed for 6 and 12 minutes did not. An additional question concerns the effect of using several exposure sessions instead of a single session. In most experiments, one session seems sufficient for the infant to learn the contingency. However, considering again the mobile paradigm, it appears that exposure spread over several days results in longer duration of long-term retention than the same amount of exposure in a single day. Linde, Morrongiello & Rovee-Collier (1985) exposed 2-month-old infants to a mobile for 18 minutes. They split infants into three groups: one group was trained for 18 minutes for a single session, one group was trained for 9 minutes per day on two consecutive days, and one group was trained for 6 minutes per day on three consecutive days. The authors found that infants in all groups learned the contingency but that infants trained with exposure spread over several days remembered the contingency for much longer (2 weeks instead of 1-2 days). Note that the duration of the long-term retention is dependent on the age of the infants, and increases gradually with age (see Rovee-Collier, 1999 for a review).

4.1.1. *Conclusion*

The take home message is that infants typically need a very short exposure — only a few minutes — to detect sensorimotor contingencies. However, it appears that the number of learning sessions influences long-term retention of this learning. Optimal learning seems to be achieved when learning sessions are spread over several short sessions.

4.2. Time window between two repetitions of a contingency

We can assume that an infant needs several experiences of a contingency to learn it. Thus, after having performed a contingent action, the infant may need to reproduce this action several times to successfully reinforce the link between this action and an associated effect. According

to Watson (1967), there is a time window following the experience of the "action-effect" couple that is favourable to contingency learning: the infant would be more likely to learn a contingency if the re-experience of the "action-effect" couple falls within this time window. Two constraints must be considered to define this time window: on the one hand, the time interval required by the baby to encode the first experience of the "action-effect" couple and, on the other hand, the time interval during which the contingency can be kept in memory by the baby. These two time intervals define respectively the lower and upper limits of the time window during which re-exposure to the "action-effect" couple after its first occurrence is most likely to facilitate the learning of a contingency. Watson (1967) suggested that, for 3-month-old infants, this time window is between 3 to 5 seconds after the experience of the "action-effect" couple, where 3 seconds corresponds to the time needed by infants to register the contingency, and 5 seconds corresponds to the duration of infants' working memory. Millar (1972) has further argued that this time window may be critical at the beginning of the learning of a new sensorimotor contingency but may become less important when learning has already been consolidated. Thus, Millar observed in his studies that "*4-month-old infants would often return to a response-feedback task after having been "distracted" for periods of time well in excess of the critical time interval suggested by Watson, and continue operant responding at the rate where they left off*" (p. 2). Unfortunately, there is to our knowledge no study to date — apart from Watson's — that helps in determining whether there is a critical time window and if so, what that time window might be.

4.2.1. Conclusion

There is no consensus on the delay between two repetitions of a contingency that is most favorable for contingency learning. Moreover, this delay is a difficult parameter to control in an experimental setting as it depends on each baby's individual rate of performing the contingent action during exposure to the contingency. However, this parameter could be a

relevant parameter to consider when explaining the substantial individual differences in ability to learn a contingency discussed in the introduction section of this paper.

4.3. Probability of occurrence

In the majority of experiments involving sensorimotor contingencies, each time the infant makes a motor action, a perceptual consequence occurs. Obviously, in the infant's real environment this is not always the case: some contingencies are "perfect" (as they occur 100% of the time) but others are "less-than-perfect", or "imperfect" contingencies. "Perfect" contingencies are contingencies for which in 100% of cases the performing of the operant action triggers feedback[3], while "imperfect" contingencies are contingencies for which the performing of the operant action triggers feedback only in a certain proportion of cases. A case in point is the social contingency between infants' babbling and mothers' vocalizations. A "perfect" contingency would be that the mother vocalizes if and only if the infant babbled just before. However obviously in real life, this never happens. Social contingencies are always "imperfect": sometimes the infant will babble but the mother does not react and sometimes the mother vocalizes spontaneously (i.e. without the infant babbling before). But to what extent are babies sensitive to the different degrees of "perfection" of contingencies? Are some degrees of "perfection" more easily detected? Watson (Watson, 1984, 1985) tested 4-month-old infants divided into four experimental groups corresponding to four degrees of "perfection" of a sensorimotor contingency:

- **Group 1:** "perfect" contingency — a face appears on a screen if and only if the baby has made a kick.

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[3] Note that there is sometimes confusion in the definition of a "perfect" contingency. Indeed, this can be understood from the temporal, spatial or relational point of view (see section "Contingency parameters") or, as is the case here, from the point of view of the probability of occurrence.

- **Group 2:** each kick of the baby generates the appearance of a face on a screen — but some face appearances (6 per minute) occur without the baby having kicked.

- **Group 3:** appearances of a face on a screen occur if the baby has made a kick — but 25% of the baby's kicks do not produce face appearances.

- **Group 4:** some face appearances (6 per minute) occur without the baby having made a kick and some (30%) of the baby's kicks do not produce face appearances.

Counterintuitively, Watson found that the infants exposed to the "perfect" sensorimotor contingency (Group 1) were the ones that learnt the least, and that infants exposed to the least "perfect" sensorimotor contingency (Group 4) were the ones that learnt best. He explained this result by proposing that "less-than-perfect" sensorimotor contingencies might be more interesting for infants at this age.

Consistent but less clear findings were found by Pomerleau, Malcuit, Chamberland, Laurendeau, & Lamarre (1992). They tested 5-month-old infants with four different degrees of "perfection" of a sensorimotor contingency between touch of an object and movements of this object: (1) 100% of touches triggered feedback, (2) 75% of touches triggered feedback, (3) 50% of touches triggered feedback, and (4) 50% of touches triggered feedback + non-contingent events occurred. They found that infants had similar performance in contingency learning across all five conditions. Nevertheless, they found that infants exposed to the "perfect" contingency showed a higher decrement in their operant responses over the experiment compared to infants exposed to "less-than-perfect" contingencies, suggesting that "less-than-perfect" contingencies enhanced infants' interest.

4.3.1. Conclusion

We can conclude from this section that "imperfect" contingencies seem to be more beneficial for contingency detection as compared to "perfect" contingencies. While it is not clear whether "imperfection" actually increases babies' detection abilities, it does seem to have a positive

influence on babies' interest in the contingent task. According to Gergely and Watson's "biofeedback theory" (1996) the use of "imperfect" contingencies can only be beneficial for babies over 3 months of age. In their view it is only from 3 months of age that babies become more interested in "imperfect" than in perfect contingencies. Younger babies, the authors suggest, prefer to explore "perfect" contingencies, since at that age they are focused on the exploration of their own body. It is noteworthy however that Gergely and Watson's theory was based on the results of a visuomotor matching study in which what they called "imperfect" contingencies were actually time-delayed rather than subject to a probability of occurrence lower than 100% (Bahrick and Watson, 1985). It is also important to note here that Watson's theory is based on the results of a single study, which has never been replicated (although it has been the object of unpublished replication attempts).

4.4. Prior exposure to contingent and non-contingent stimulations

One might ask to what extent (i) prior exposure to a contingent stimulation influences an infant's subsequent learning of a new contingency and (ii) prior exposure to a non-contingent stimulation influences learning of a contingency involving the same stimulation or of a contingency involving a new stimulation.

4.4.1. Prior exposure to a contingent stimulation

Prior exposure to a contingency seems to enhance the subsequent learning of a new contingency. Finkelstein and Ramey (1977) and Ramey and Finkelstein (1978) trained 3- to 9-month-old infants for 3 or 4 days using a variety of different types of contingent stimulation. Then, on the following day, they tested the infant's sensitivity to a new contingency. The contingencies used in training and test involved both different actions and different feedback. In the 1978 paper, training and test sessions also occurred in different contexts (respectively the infants' home and the laboratory). In both studies, the authors showed that at all ages

contingently trained infants showed faster learning rates for the new contingency compared to control infants who during training were exposed to a non-contingent audiovisual stimulation or no stimulation at all.

4.4.2. *Prior exposure to a non-contingent stimulation*

The literature is unclear about whether prior exposure to a non-contingent stimulation has no effect, or whether it enhances or degrades learning abilities for a subsequently presented contingency involving this same stimulation. To understand this, we will separate experiments in which prior exposure to the non-contingent version of the stimulation is of short duration and occurs immediately before the contingent acquisition (i.e. short-term exposure); and experiments where there are several days of non-contingent prior exposure (i.e. long-term exposure).

Positive effects or absence of effects

As concerns short-term exposure, Millar (1972) showed in 6-month-old infants that learning of a contingency is not prevented and is even enhanced by a few minutes of pre-exposure to the non-contingent version of a stimulation. Gekoski and Fagen (1984) also found that 6 minutes of exposure to a non-contingent mobile did not prevent 3-month-old infants from subsequently learning a contingency with a new mobile in the same context. Regarding long-term exposure, Finkelstein and Ramey (1978) showed that 3-month-old infants were perfectly able to learn a new contingency displayed in the laboratory after 3 or 4 days of exposure to a non-contingent stimulation in their homes. Moreover, Gekoski and Fagen (1984) also exposed 3-month-old infants to a non-contingent mobile during 3 or 7 consecutive days and showed that this did not prevent subsequent learning of a contingency with a similar mobile in a similar context (infants' home crib).

Negative effects

In contrast, other studies have shown opposite results, namely lower learning abilities in infants who have been pre-exposed to a non-contingent version of the stimulation. As regards short-term exposure, DeCasper and Carstens (1981) showed that newborns who were pre-exposed to a song for 15 minutes (without any contingency between the song and the infants' behaviour) were not able to learn a contingency presented to them a few hours later between the same song and their sucking, whereas newborns not previously exposed to the song were able to learn the contingency. Concerning long-term exposure, lower learning abilities in infants pre-exposed to the non-contingent version of a stimulation was shown by Watson (1971). He trained 2-month-old infants on 14 consecutive days in their homes with daily exposure to (i) a contingent mobile, (ii) a similar but non-contingent moving mobile, or (iii) a similar but stationary mobile. One day or 6 weeks after the end of this home training, infants were tested at the laboratory with the same contingent mobile. He showed that infants trained in the similar but non-contingent condition did not learn the contingency at all even when tested 6 weeks after the end of the training, while infants from the contingent and similar but stationary groups were able to learn in both testing sessions. Moreover, Watson (1977) (cited in Watson, 1979, p. 49) noted that 2-month-old infants who had already experienced their own non-contingent moving mobile at home were less likely to learn a contingency involving a new mobile when tested at the lab. Negative effects of long-term exposure to *different* but non-contingent stimulation were also observed. For example, Ramey and Finkelstein (1977) found that 6- and 9-month-old infants trained with a different and non-contingent stimulation were less good at detecting a new contingency than infants trained with a different but contingent stimulation. Also, Dunham and Dunham (1990) found that 3-month-old infants whose interactions with their mother were less contingent (the degree of contingency was assessed in a 5-minute session of free play) were the infants that showed lower learning rates in a non-social contingency learning task.

4.4.3. Conclusion

Very clearly, prior-exposure to a contingent situation seems to increase babies' ability to subsequently detect a new contingency. With regard to pre-exposure to the non-contingent version of a stimulation (or to a non-contingent and different stimulation), the lack of consensus in the literature makes it impossible to confidently conclude on how this affects babies' subsequent sensitivity to a similar or new contingency. Nevertheless, it would seem prudent to prevent babies from being exposed to a non-contingent version of a stimulation in order to ensure the successful operation of a contingent experimental setup.

5. Inter-individual differences

5.1. Intrinsic motivation

Given the abundance of sensory inputs and motor outputs that the infant's brain has to process, the problem arises, not only of detecting sensorimotor contingencies, but also of choosing which ones to explore: the infant clearly needs an exploration strategy. The study of exploration strategies in infants is a rich field of research which is distinct from the research on sensorimotor contingency detection and which would deserve its own review. Nevertheless, in order to provide a complete overview of the factors influencing sensitivity to sensorimotor contingencies in infants, it will be useful here to briefly discuss it. First, babies are obviously motivated to explore their environment in order to satisfy their physiological needs, which is known as extrinsic motivation. In addition, a second type of motivation, called intrinsic motivation; seems to guide babies' exploration. We will focus here on this second type of motivation, as it appears to be central to babies' spontaneous exploration behaviours

The concept of intrinsic motivation, also called "curiosity", has been richly documented in psychology (see for ex. Oudeyer, Gottlieb, & Lopes, 2016 for a review). It has recently also been widely used in developmental robotics (Oudeyer et al., 2016), a discipline that seeks to

create agents capable of open-ended and unsupervised learning in a "baby-like" manner. According to this framework, infants' exploration of the environment that does not lead to the satisfaction of physiological needs (i.e. extrinsically motivated) might be explained by the brain's production of an intrinsic reward in situations that provide learning. Sensorimotor contingency learning would be such a rewarding situation per se for infants, and infants' active exploration of sensorimotor contingencies would be organized in order to optimize learning.

As regards the first requirement — namely that learning of sensorimotor contingencies in infants is a rewarding situation — evidence has been found by Lewis, Sullivan and their collaborators (e.g., Lewis, Alessandri, & Sullivan, 1990; Lewis et al., 1985; Sullivan and Lewis, 1989). In their experiments, they measured emotional responses of 2- to 8-month-old infants during a contingent learning session. They found that in the acquisition phase (when the contingency was present) infants who were learning the contingency showed positive emotional responses (e.g. cooing, smiling, vocalizing) and that in the extinction phase (when the contingency was removed), infants who had learned the contingency showed negative emotional responses (e.g. fussiness, cries). Moreover, the authors showed that infants exposed to the same stimulation but not contingently did not show such emotional responses, suggesting that infants' behaviour in the contingency condition cannot simply be explained by the presence (in the acquisition phase) or absence (in the extinction phase) of stimuli. These results seem to confirm that contingent learning in infants might be rewarding *per se* and not only because it gives the baby the opportunity to experience interesting stimuli.

The second requirement — i.e. that infants' active exploration of sensorimotor contingencies needs to be (implicitly) organized in an effective way in order to optimize learning — can be discussed at different time scales. At the developmental time scale, this requirement implies that an infant's exploration preferences should constantly adapt to match the infant's current motor and cognitive abilities. For example, before being able to reach and

grasp objects, the infant would be interested in looking at its hands moving in front of its face or in moving its arms randomly and then by chance touching objects and repeating movements that were rewarded by such change in sensory inputs. Later, when reaching and grasping are mastered, the infant might change its focus of interest and spend most of its playing time manipulating objects. At the time scale of one particular playing episode, the second requirement suggests that the infant's exploration of its environment should be organized in order to optimize its gain in knowledge. We will now review evidence supporting this claim.

Kidd, Piantadosi, & Aslin, 2012 have tested this hypothesis by measuring 7- to 9-month old infants' interest in visual sequences of objects appearing and disappearing. The sequences displayed to the infants varied in their "complexity" (mostly here their predictability): the sequences went from highly redundant sequences which were very easy to predict for the infants, to random sequences which were not predictable for the infants; and between these two extremes, there was a range of degrees of "complexity". The authors found that infants were more interested in the sequences of intermediate complexity (i.e. they had longer looking times for these sequences) than in sequences with too low or too high complexity. Interestingly, the authors found that each infant had its own optimal level of complexity.

Another way developmental psychologists have tested to what extent infants preferentially explore learning situations that optimize their gain in knowledge has been to expose them to situations that go against their expectations — and to consider that infants are aware that unexpected situations potentially provide a high gain in knowledge. Stahl and Feigenson (2015) tested this hypothesis in 11-month-old infants by presenting them with two toys: one toy was a "normal toy" and the other was an "unexpected toy," namely a toy whose behaviour breaks a physical law (it passes through a wall, teleports itself, or does not fall though it is not on a surface). After seeing presentations of an "expected" and an "unexpected" situation, the infants had to choose which of the two toys they preferred to play with. The

authors found that the infants chose the "unexpected" toy significantly more often. Interestingly, the authors observed that when the infants had the opportunity to play with the "unexpected toy", they played differently depending on the physical law previously broken by the toy (e.g. when the toy had broken the law of solidity, infants banged it on the table and when the toy had broken the law of support, infants dropped it onto the table). This last result would suggest that infants' subsequent exploration was driven by their appetite to gain further knowledge about the unexpected characteristics of the toy. In addition, Sim and Xu (2017) showed that 13-month-old infants' preference for exploring sources of unexpected events might be extended to improbable events — this is in opposition to the previous study in which unexpected events were physically impossible. Coherent results were also found in older infants (18 months of age) by Esseily, Rat-Fischer, Somogyi, O'Regan, & Fagard (2015), who showed that unexpected (humorous) events during demonstration may enhance observational learning of a new tool-use action.

Thus, it appears that both at developmental time scale and within a playing session, babies seem to be intrinsically motivated to explore situations that are most profitable for learning, given their current motor skills and expectations about the world. It is important to note that at both time scales, infant's exploration of the environment is also guided by the baby's social partners, which is known as "scaffolding" (Malcuit, Pomerleau, & Lamarre, 1988; Pomerleau et al., 1992). Caregivers organize the baby's exploration space so that learning situations are in accordance with the baby's current abilities and interests.

5.1.1. *Conclusion*

To conclude this section, babies' extrinsic motivation to obtain a contingent stimulation on the one hand, and babies' intrinsic motivation to search out sensorimotor contingencies on the other hand, should be considered in order to understand contingency detection in babies. Regarding extrinsic motivation, social stimulation used as contingent feedback, or

encouragements of a caregiver when the baby succeeds in obtaining the contingent feedback (which is frequently the case in the baby's daily life) might be profitable for contingency detection. With regard to intrinsic motivation, contingencies of intermediate complexity — i.e. neither too easy nor too hard to detect — might be more easily detected by infants. Appropriate intermediate complexity is to be defined according to the age of the baby, or more precisely according to each baby and the evolution of its performance during learning of a contingency.

5.2. Infants' individual abilities and temperament

An obvious way to observe the influence of infants' individual abilities on sensorimotor contingency detection would be to look at the evolution of sensorimotor contingency detection across development. However simply observing an improvement in contingency detection with age does not allow one to determine whether this improvement was caused by maturation or by the appearance of a new sensory, motor or cognitive ability. Moreover, because infants may simultaneously acquire several new abilities, longitudinal observations will not allow one to determine which specific ability caused the improvement in contingency detection.

One way to bypass this issue is to study infants of the same age but having different individual abilities. Developmental psychologists have developed questionnaires and experimental tasks to determine the individual level of an infant in a specific domain. Experimenters can then determine to what extent inter-individual differences in this domain predict inter-individual differences in sensorimotor contingency detection. For example, infants' level of visual attention appears to be a fairly reliable predictor of their contingency detection abilities (e.g., Dunst and Lingerfelt, 1985; Fagen, Ohr, Singer, & Fleckenstein, 1987; Hayes, Ewy, & Watson, 1982). Indeed, Hayes et al. (1982) found that 3-month-old infants with low visual attention (measured in a baseline period as the number of times the infant fixated a light alternating between two positions) did not show learning of a contingency whereas, tested in the same contingent task, infants with a high degree of visual attention did show evidence

of learning. Consistent results were found by Dunst and Lingerfelt (1985) in 2- to 3-month-old infants but using maternal ratings as the measure of infants' visual attention. Additional but less direct evidence of the influence of visual attention on contingency detection was found by Fagen et al. (1987), who observed that visual attention score (measured here using a parental questionnaire that evaluates babies' duration of visual orientation towards stimuli) was a good predictor of the propensity of 3- to 4- month-old infants to become fussy in a 2-day contingent experiment with the mobile paradigm. More precisely, the authors found that babies who cried and did not cry during the experiment significantly differed in their visual attention score: the "cryers" showed lower scores in visual attention than the "non-cryers".

Another way of correlating sensorimotor contingency detection and individual abilities is to compare infants of the same age but coming from typical and atypical populations. One interesting atypical population is preterm infants: these infants may sometimes show impaired abilities in regulation of arousal, visual attention, attention shifting, motor skills, motor control and memory (e.g., Delobel-Ayoub et al., 2009). Thus, some authors have tested preterm infants with the mobile paradigm (e.g., Gekoski, Fagen, & Pearlman, 1984; Heathcock, Bhat, Lobo, & Galloway, 2004, 2005). Compared to typical infants of the same age under the same experimental conditions, preterm infants showed impairment in their ability to detect the mobile contingency. At 3 months of age, they did not detect the contingency (Heathcock et al., 2004, 2005) or needed more time to detect it (Gekoski et al., 1984) and they did not show retention of the contingency (Gekoski et al., 1984). Similar results have been found with other atypical populations, such as infants with Down syndrome (Ohr and Fagen, 1991), spina bifida (Taylor et al., 2013) or congenital heart disease (Chen, Harrison, & Heathcock, 2015). Despite these negative findings it nevertheless seems clear that contingency detection must still be a core mechanism in human learning.

Infants' temperament has also been studied as a potential factor influencing contingency detection. For example, Lemelin, Tarabulsy, & Provost (2002) measured the correlation between 6-month-old infant's level of irritability (scores were obtained from mothers' ratings) and their propensity to learn a contingency between pulling with their arm and appearance of an audiovisual stimulation. The authors found that an infant's level of irritability was correlated with the infant's ability to detect the contingency: the more the infant was rated as irritable, the less the infant was good at detecting the contingency.

5.2.1. *Conclusion*

Overall the findings described above suggest that infants' abilities to detect sensorimotor contingencies might in part be dependent on infant's individual abilities (e.g. visual attention) and temperament (e.g. propensity to be fussy). The large inter-individual variability in learning abilities discussed in the introduction of this article deserves more attention from researchers in developmental psychology, and should not simply be a factor that researchers avoid by omitting less-attentive or poorly performing babies.

5.3. Socio-cultural context

Caregivers from different cultures seem to react differently to their infants' vocalizations, and this both in the modality of responses (e.g., German mothers use more visual responses than Nso mothers; Kärtner, Keller, & Yovsi, 2010), in the frequency of responses (e.g., Cameroonian mothers are less responsive to their infant' vocalizations than Italian mothers; Bornstein, Putnick, Cote, Haynes, & Suwalsky, 2015) and in the interval before responding (e.g., Indian mothers had more "togetherness" with their infants than French mothers; Gratier, 2003). Moreover, there are also inter-individual differences within the same culture, for instance depressed caregivers are less responsive than non-depressed caregivers (see for ex. Field, 2010 for a review). Developmental psychologists have studied to what extent these

differences in caregivers' responsiveness influence infants' sensitivity to sensorimotor contingencies. From early on infants seem to prefer the specific level of responsiveness of their own caregiver (e.g., Watson, 1985). Bigelow (1998) showed that 5-month-old infants were more responsive to strangers who had a level of responsiveness similar to their mother's, compared to strangers who had different levels of responsiveness (either more contingent or less contingent). This result was replicated by Bigelow and Rochat (2006) who found that even 2-month-old infants interacted more with strangers that had a similar level of contingent responsiveness as their own mothers. Moreover, Bigelow and Power (2014) found that the degree of contingent responsiveness of mothers correlates with the ability of infants to detect social contingency: infants with high responsive mothers reacted to the still-face experiment at an age that was 1 month earlier than infants with low responsive mothers. As we saw previously, Dunham and Dunham (1990) found similar results for non-social contingency detection in 3-month-old-infants: the authors found a correlation between the degree of contingency in mother-infant interaction and infants' learning of a contingent task. Also, infants of depressed mothers reacted less negatively to experimentally induced non-contingent interactions, suggesting that they are more used to non-contingent behaviour in their mothers (e.g., Field et al., 2005).

5.3.1. Conclusion

In conclusion, this section suggests that socio-cultural context should be considered in order to understand babies' sensitivity to sensorimotor contingencies. Thus, it seems important to assess the contingency level of the relationship between the caregiver and the baby (see for example Dunham and Dunham (1990), Bigelow and Rochat (2006) or Bigelow and Power (2014) for methods of assessment), to either take this into consideration in the data analysis, or where possible to adapt the contingency to each baby accordingly (i.e. a very responsive setup contingent for babies with very responsive mothers and vice-versa).

6. Conclusion

This literature review has provided a detailed overview of babies' sensitivity to sensorimotor contingencies and suggests practical advice to researchers on how to optimise their experimental designs in such a way that babies can easily detect the contingency employed. In the first section, we showed that babies' ability to detect a contingency depends on the action and feedback involved in that contingency. Thus, it seems preferable to use an action that is part of the baby's motor repertoire, is naturally interesting for the baby at its particular phase of development, is salient, as well as providing multi-sensory and attractive feedback. In the second section, the reviewed studies suggest that contingency detection depends on three parameters of the contingency: the temporal parameter, the relational parameter and the spatial parameter. It therefore seems preferable (i) to use a delay of less than 3 seconds between action and feedback, to not vary this delay during the study (at least from the age of 6 months), (ii) to use an analog rather than a digital contingency (even if this choice may not be critical), and (iii) to ensure that for young babies (before the age of 9 months) the action and feedback are simultaneously visible in the baby's visual field, and to respect a congruence regarding movement direction between the action and visual feedback for the contingencies involving movements of the body as action and feedback. In the third section, we showed that conditions of exposure to a contingency had an influence on babies' ability to detect it. It seems preferable to privilege learning spread over several short sessions, and to provide prior exposure to other contingent situations. In addition, "imperfect" contingencies (i.e. in which the probability of feedback occurring after the action is less than 100%) seem to be more easily detected by babies. The last section of this literature review highlighted the fact that there is a high inter-individual variation in contingency detection and that these variations can be explained by the baby's motivation to detect a contingency, the baby's general abilities (e.g. visual attention) and temperament, as well as the familial and cultural context.

Although this literature review provides a comprehensive picture of sensorimotor contingency detection in babies, the question of the reproducibility of previous studies, as well as the robustness of the conclusions drawn from them remains open. Indeed, current practice in developmental psychology leads researchers (i) to publish only positive findings, so publications concerning a previously shown effect can only confirm that effect, which creates the illusion (sometimes misleading) that the effect is robust, and (ii) to disregard variability from one infant to another by focusing on significant effects observed at group level (despite the unreliability of this method with groups that most often include a small number of babies), rather than exploring inter-individual differences that may explain why an effect is rarely shown by all babies. A response to the first observation has appeared in recent years with the rise of meta-analyses, as well as the emergence of projects such as "Many Babies" (Franck, 2016) promoting the replication of studies around the world in order to assess the robustness of the observed effects. The application of this methodology to studies on contingency sensitivity would thus be beneficial to the field. Concerning the second problem, namely the lack of interest for inter-individual variability, there is a need to focus on understanding what makes some babies "succeed" (here, by detecting contingencies) while others, within or between studies, do not. Obviously, this requires a large number of participants, which might be more easily achieved in the coming years by using new technologies (e.g. wearable sensors) and new analytical methods (e. g. big data) combining laboratory experiments with individual data collected on a daily basis.

Furthermore, there is currently a growing need for a comprehensive characterization of the mechanism of contingency detection as a result of a demand from developmental robotics to create intelligent agents capable of unsupervised learning. Indeed, the main source of learning used by development roboticians is the interaction between the agent and its environment. In this way, roboticians integrate into their algorithms contingency detection

mechanisms similar to the ones observed in humans (Cangelosi and Schlesinger, 2015). This calls for the need for formalization of this mechanism and a precise understanding of its properties in immature agents such as babies. We hope that this paper will be useful to developmental psychologists and roboticians in their respective work and in the establishment of a common language required for the development of closer collaboration between the two fields.

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