How do infants represent others? Biases towards native language and rational agents

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Abstract

Much of the information infants acquire they learn it by observing and interacting with others. However, not all individuals provide information that is functionally and/or culturally relevant. Infants' capacity of identifying *who* is likely to provide useful and comprehensible knowledge is critical for making social learning an optimal process. In this dissertation we explore what kind of strategies provide infants with a basis to identify appropriate partners from whom to learn and interact with. In three experiments we study two cues that likely bias infants' predisposition of attending to and interacting with others: the language agents speak and the rationality of their actions. Our results suggest that during the first and second year of life infants are biased to evaluate more favourably and make sense of actions that are performed by native-speakers or that are rational means of obtaining particular goals. Additionally, infants appreciate that only individuals who share a common language can engage in efficient verbal communication. Our findings shed light on the cues that influence early-emerging social preferences and on the type of cognitive mechanisms that underlie these preferences.

Resum

Bona part de l'aprenentatge dels nadons es produeix durant l'observació i interacció amb altres individus. Tot i així, no tothom proporciona informació funcional i/o culturalment rellevant. Per tal de que l'aprenentatge sigui òptim, els nadons han de ser capaços d'identificar qui proporciona coneixement útil i intel·ligible. En aquesta tesina estudiem quines estratègies són accessibles per als nadons per tal d'identificar amb qui és òptim interactuar i aprendre. A través de tres experiments, investiguem dues característiques que possiblement influencien la predisposició dels nadons a prestar atenció i interactuar amb els altres: quina llengua parlen i com de racionalment actuen. Els nostres resultats mostren que durant el primer i segon any de vida els nadons estan més predisposats a avaluar positivament i entendre les accions d'aquells que parlen una llengua familiar o actuen de manera racional. A més, els nadons entenen que només aquells que comparteixen una llengua comuna es poden comunicar verbalment de manera eficient. Els nostres resultats permeten entendre millor quines característiques influencien les preferències dels nadons i quins mecanismes cognitius guien aquestes preferències.

PREFACE

Think for a moment about all the information that you can find in Google. For example, let's focus on a specific topic, such marine iguanas. If you write "marine iguana" in Google you will find 33.900.000 results. That is, millions of sources of information from which you can acquire knowledge about this species, such as what do they eat, where do they live or what is their binomial nomenclature. Importantly, some of these sources can provide inaccurate, misleading or irrelevant information. To optimize learning through the internet, thus, one should avoid spending time in web pages that likely provide noisy information, and focus the attention on sources of potentially relevant and reliable information.

Learning in infancy may resemble in some sense learning by searching information in Google. Infants are surrounded by an overwhelming quantity of novel information they must filter, make sense of, and acquire. Learning from others, known as social learning, is an optimal strategy to acquire relevant information (Rendell et al., 2011). Infants are surrounded by individuals who have already acquired a lot of functionally and culturally relevant knowledge. However, not all these people are reliable sources of information (Poulin-Dubois & Brosseau-Liard, 2016). As in the case of Google searching, agents may provide inaccurate information about the world or transmit incomprehensible knowledge or refuse to provide appropriate information.

In the present dissertation, we explore what kind of strategies provide infants with a basis to identify appropriate partners from *whom* to learn and interact with. Specifically, we focus on infants' sensitivity to two cues that guide identification of appropriate partners: the rationality of others' actions and the language they speak. With respect to the first cue, obtaining goals through the most rational means available entails that the acting person is proficient in the task (Jara-Ettinger, Gweon, Schulz, & Tenenbaum, 2016). Recognizing who acts more efficiently in the environment is a way to detect who possesses the best abilities to process the environment. Thus, who is the best collaborator and potential teacher. With respect to the second cue, language is a strong indicator of cultural identity (Soley & Spelke, 2016). Speaking a native language indicates a sharing environment but speaking an unfamiliar language does not. The behaviour of the most similar model is, thus, the most functionally and culturally relevant (Wood, Kendal, & Flynn, 2013). In addition, since information is typically transmitted through speech, being able to interpret what the other is saying facilitates the acquisition of knowledge. In *Experimental Part I and II* we investigate if the language spoken by agents, and the rationality of their actions influence how infants represent agents. Then, in *Experimental Part III*, we investigate if infants appreciate that efficient verbal communication between third-parties is constrained to the use of a common language. Our results show that infants are biased towards speakers of their native language and rational agents, and shed light on the type of mechanisms that may underlie these biases.

CONTENTS

1. GENERAL INTRODUCTION

Humans are capable of acquiring a remarkable amount of knowledge across the lifespan that no other species can compare to. We learn about concepts such as music, morality or happiness. We learn to manipulate machines that other humans have created to attain our goals. We discuss theories about the origins of the universe, and we learn the social norms that are crucial to live in our cooperative-structured societies. Growing in such a complex and dynamic environment requires sophisticated learning mechanisms to acquire information efficiently. The process of learning about the world is specially challenging in the first months of life, when cognitive mechanisms are still rudimentary. Infants are surrounded by tremendous amounts of novel information they must filter, make sense of and acquire. How do infants know when and what to learn? How do they focus their attention towards information that is relevant?

Learning from the observation or interaction with other individuals, known as social learning (Rendell et al., 2011), provides infants with a great opportunity to acquire valuable knowledge. Infants are surrounded by agents who have already selected and acquired a considerable amount of information that has cultural relevance. Directing cognitive resources towards the observation, modelling and imitation of others is likely to promote and facilitate the transmission of cultural knowledge (Bandura, 1977). Yet, learning from others indiscriminately is not an optimal strategy (Koenig & Sabbagh, 2013). Individuals may have inaccurate information about the world, transmit incomprehensible knowledge or refuse to provide appropriate information. Knowing *when, what* and *from whom* to learn is critical for the acquisition of relevant and functional cultural knowledge (Boyd, Richerson, & Henrich, 2011; Joseph Henrich & McElreath, 2003; Laland, 2004).

In the present dissertation, we are interested on how infants identify appropriate individuals *from whom* to potentially learn, known as *model-based biases* (Wood, Kendal, & Flynn, 2013). Several studies indicate that infants are selective learners, preferring to learn from some individuals over others (Poulin-Dubois & Brosseau-Liard, 2016). Here, we explore the idea that model-based biases are not limited to learning contexts, but they influence how infants represent agents and their actions more broadly. Because social learning occurs from the observation and interaction with others, we hypothesize that model-based cues can tune infants' general predisposition to engage in such social interactions. To address these issues, we focus on two questions. First, what model-based cues do infants use to identify agents with whom to potentially interact with and learn from? Second, how these cues influence infants' predisposition of attending to and interacting with others?

The first model-based cue that we explore is the **perceived rationality** of others' actions. Irrational actions are actions that one cannot easily make sense of and that may result in unsuccessful outcomes or higher costs (Baillargeon, Scott, & Bian, 2016). We investigate the preference of agents who act rationally rather than irrationally as a potential strategy to avoid acquiring noisy or misleading information. In experimental part I we investigate if infants evaluate rational agents more favorably than irrational ones.

The second model-based cue that we explore is **the language that others speak**. Language is a strong marker of cultural identity (Soley & Spelke, 2016). The information that a native-speaker can provide is potentially cultural relevant (Wood et al., 2013). Being biased to make sense of the actions of native-speakers more than foreign-speakers is likely to privilege the acquisition of relevant and functional cultural knowledge. Also, language serves the function of communicating information between individuals. Understanding that the transmission of information between agents is constrained by the use of a common language is useful to identify potential communicative partners. In experimental parts II and III we explore the emergence of such biases and capacities in infancy.

Critical for the formation of model-based biases is the capacity of making sense of agents and their actions. In the first section of the introduction we review how infants represent agency, including the representation of goal-directed actions and the representation of agents as informants. In the second section, we review current research about model-based biases in infancy. Finally, in the third section of the introduction we present our research plan by discussing the relation between the principles supporting the representation of agency and model-based biases.

1.1. Agency

1.1.1. Action understanding

a. Representation of goals and perceptual states in infancy

In the first half year of life infants represent reaching actions as goal-directed (Woodward, 1998). In her seminal study (*Woodward paradigm; see figure 1.1*), Woodward presented 6 and 9-month-old infants with video-clips depicting an arm that consistently reached one of two objects (*target*). After habituating infants with the same action until they lost attention, the location of the objects was switched. With the new location, the arm either kept reaching for the target object or kept performing the same movement (this time towards the non-target). Infants looking time at screen at both outcomes revealed that they expected the arm to reach for the target object even in the new location, suggesting that they encoded the original action as structured by goals, rather than movements through space. Importantly, goal-attributions are specific to agents (Gerson & Woodward, 2014). When infants were presented with an inanimate object with non-human-like features, they did not expect the object to keep reaching for the target object (Woodward, 1998). Other studies measuring gaze movements extended the evidence that infants make goal attributions by showing that they generate rapid online predictions about how the goal-directed action unfold

(Cannon & Woodward, 2012; Kanakogi & Itakura, 2011). Imitation studies also showed that infants do not automatically imitate the actions of social partners; rather, they selectively imitate the goal-relevant aspects of the action (Carpenter, Akhtar, & Tomasello, 1998; Hamlin, Hallinan, & Woodward, 2008; Meltzoff, 1988).

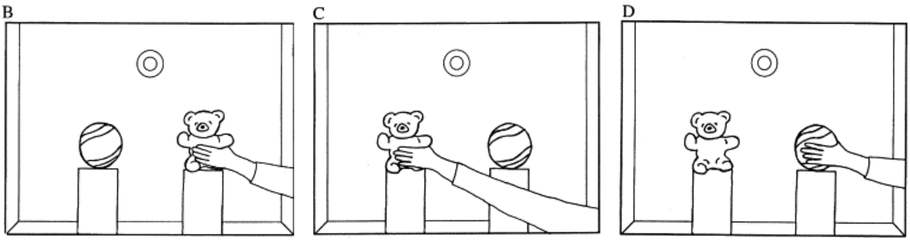

Figure 1.1*. Design of Woodward (1998): Woodward Paradigm. (B) Habituation trial: the arm reaches for the target object. (C) Test trial: same-goal. (D) Test trial: same-movement.*

As the goal of an action is identified, infants expect agents to obtain it through an efficient mean (Liu & Spelke, 2017). In their seminal study Gergely, Nádasdy, Csibra, & Bíró (1995) habituated infants with two animated geometric figures depicting agents that were separated by an obstacle (see figure 1.2). One of the figures approached the other one by taking a curvilinear path through the obstacle. After habituation, the obstacle was removed. Infants saw the figure following either the same curvilinear movement (inefficient action in the new situation) or a novel straight-line movement that was directed toward the ball (efficient action). They looked longer when presented with the inefficient action rather than the efficient one. These results have been replicated through different labs (Kamewari, Kato, Kanda, Ishiguro, & Hiraki, 2005), different ages (Liu & Spelke, 2017) and using non-human like and human-like stimuli (Gergely Csibra, 2008; Sodian, Schoeppner, & Metz, 2004). Together, they suggest first that infants encoded the action of the habituation as a goal-directed action, instead of just encoding the movement. Second, they suggest that infants understood that the physical world (e.g. a wall) constrained the agents' actions. Finally, they suggest that infants evaluated which action available within the constraints of the situation was the most efficient means to the goal and they expected agents to perform the most efficient means available.

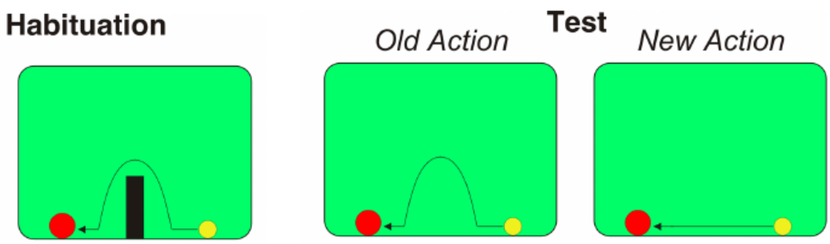

Figure 1.2. *Design of* (Gergely et al., 1995). *(**Habituation**) A ball approaches another ball taking a curvilinear path (**Test**) The obstacle is removed and the ball either keeps taking the old curvilinear path (Old action) or a new direct one (New Action).*

To predict an agent's behavior infants also use information about her perceptual access to objects (Surian, Caldi, & Sperber, 2007). Fifteen-month old infants expect an agent to reach for an object at the last position she saw it, even when their own perceptual states differ from the agent's ones (Baillargeon, Scott, & He, 2010). Infants as young as 6 months of age are sensitive to others' perceptual states and exploit this information to generate online action predictions (Southgate & Vernetti, 2014). These results, together with a several other, provide substantial evidence that infants success in false beliefs tasks (Sodian, 2016). How to interpret this success, however, is a focus of an intense debate. Among the mentalistic interpretations there are several proposals stating that infants may understand that perceptual states provide access to information that determines knowledge and guides behavior (Tomasello, 2018); also that their understanding of perceptual states could reflect a full understanding of beliefs as propositional attitudes (Baillargeon et al., 2010), and finally that this understanding could be limited to an implicit, fast and automatic system that only supports level 1 perspective taking – ability to track others' visual access in physical space (Apperly & Butterfill, 2009). In contrast to mentalistic views, infants' success in false beliefs task could also be based on the application of non-mentalistic behavioral rules (Perner & Ruffman, 2005) or low-level perceptual associations (Heyes, 2014). A full debate about the origins of belief attributions falls outside the focus of the present dissertation. However, in the discussion of experimental part II (pages 117-119), we discuss how our results could make a potential contribution to such debate and propose some future directions to investigate the development of belief attribution.

b. The role of experience in action understanding

As we have seen, from early in life infants represent some actions as goal-directed. However, their understanding of actions is limited and has been proposed to develop in a piecemeal fashion (one action at a time). Action experience seems to have a critical role in this development. Infants do not interpret reaching actions as goal-directed until 4 or 5 months of age (Luo & Baillargeon, 2005), when they start reaching for objects. Similarly, it is not until infants start solving means-end problems, such as pulling a cloth to obtain the toy it supports, that they understand that others act on intermediate objects to attain an end goal (Sommerville & Woodward, 2005).

A study from Sommerville, Woodward and Needham (2005) provides further evidence for the role of experience in action understanding. A group of 3-month-old infants wore Velcro mittens enabling them to pick up and displacing objects; another group of infants did not. Participants where then presented with the Woodward paradigm, in which an arm reached consistently for an object and at test the object location was switched (see figure 1.1). Only infants who had themselves experienced the sticky mitten looked longer when the actress reached for the new object rather than the same object as in the habituation.

In another study, Skerry, Carey and Spelke (2013) used the same Velcro-mittens manipulation, but this time the authors explored the influence of action experience with the expectation of action efficiency. After the training session, 3-month-old infants were presented with an agent who, constrained by an obstacle, reached for an object performing a curvilinear movement. After habituation the obstacle was removed and the agent performed either the same action (inefficient), or a novel direct action towards the object (efficient). Only infants who had experience themselves with the sticky mittens expected the agent to perform the novel efficient action. These findings suggest that having experience with reaching actions boosts infants' understanding of others' similar goal-directed actions.

c. The role of the Mirror System in action understanding

Research using single-cell recordings with adult rhesus macaques found a type of neurons that discharge in response to the production as well as the observation of goal-directed actions (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). These neurons were first discovered in the ventral premotor area F5 and were named mirror neurons (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). More than 20 studies using single-cell recordings have found the presence of mirror neurons in different areas of the macaque brain (J. M. Kilner & Lemon, 2013). The presence of a common neural code between perceptual and motor processes has been proposed to facilitate the understanding of others' actions (Gallese & Goldman, 1998).

Research in humans does not allow using invasive techniques to directly investigate the presence of mirror neurons in the human brain. However, studies have used other techniques to explore the mirror system in humans, from neuroimaging methods (fMRI) to transcranial magnetic stimulation (TMS) to electroencephalography (EEG). These studies have demonstrated that analogous regions that possess mirror neurons in the macaque brain also activates in the human brain during action execution and observation (Morrison, Decety, & Molenberghs, 2012). These regions include the ventral and dorsal premotor cortex, the inferior parietal lobule and the primary motor cortex (J. M. Kilner, 2015). Studies using EEG provide further evidence for the activation of motor areas during action execution and observation. This activation is can be measured as a desynchronization of the resting-state mu-rhythm (~8-13Hz) over central electrodes (Gutsell & Inzlicht, 2010). Because there is no direct evidence of the presence of mirror neurons in the human brain, here we refer to the process of activating one's own motor system while observing others' actions as mirroring or mirror system.

Mu-rhythm desynchronization during action observation has been found in infants as young as 6 months of age (Marshall & Meltzoff, 2011; Southgate & Vernetti, 2014), suggesting that the mirror system is functionally available from early in life. The mirror system has been proposed to be linked with the development of action understanding (Filippi & Woodward, 2015). It is under debate, however, whether infants mirroring is the cause of goal-attribution (Paulus, 2012) or whether motor areas during action observation activate as a consequence of goal identification, having an anticipatory function (Jacob, 2008; Southgate & Begus, 2013). In any case, mu-rhythm desynchronization in the infant brain indicates a neural correlate of the link between action observation and action execution. Some authors have proposed that the mirror system establishes and supports the prelinguistic mapping between self and other correspondence at the level of bodily acts (Marshall & Meltzoff, 2014). According to the *Like-Me* Hypothesis, mapping the similarity between self and other lies at the foundation of social cognition (Meltzoff, 2007).

d. The ontogenesis of self-other correspondence: Like-Me Hypothesis

We have seen a link between action experience and action understanding in infancy, which may be supported by the mirror system. This link is consistent with a psychological theory about the ontogenesis of self-other correspondence – The Like-Me Hypothesis (Meltzoff, 2007). According to Meltzoff, infants come to understand others' actions as intentional based on the understanding of their own intentional agency, together with the capacity to recognize others as "like me". The recognition of *like-me* in this framework, however, is ambiguous and could depend on two streams of information. The first one is recognizing that an observed action is relevantly similar to goal-directed actions in the infant repertoire. That is, recognizing *what* goal-directed action is taking place. As we have seen, having self-generated experience picking up objects with sticky mittens boosts how 3-month-old infants analyze others' reaching actions as goal-directed (Sommerville et al., 2005). The second potential aspect of *like-me* is recognizing that the observed action is performed by an intentional agent. That is, recognizing *whom* is performing such action. As we have seen, infants interpret the reaching action of a human-like feature (an arm), but not of a non-human-like feature (a stick) as goal-directed (Woodward, 1998). Interestingly, infants seem to rely on higher-order social cues to recognize that the entity performing an action is a psychological agent. In one study Meltzoff, Brooks, Shon and Rao (2010) presented infants with a humanoid robot that gazed towards objects in the environment. Infants that previously saw the robot engaging in social interactions (imitative exchanges) were more likely to follow the robot's gaze in subsequent interactions. The results suggest that infants used information about imitative exchanges to attribute psychological intentionality to the agent.

In **experimental part II** we explore the idea that model-based cues can influence the recognition of others as *like-me*. Specifically, we investigate if agents exhibiting a behavior pattern that match with infants' existing knowledge of the world (e.g. speaking their native-language) are recognized as more *like-me* than agents performing an inconsistent behavior (e.g. speaking a foreign language). If this is the case, we would predict that the language that others speak influence how infants make sense of their actions. Considering that the mirror system supports the mapping between self and other, we expect to find this influence in the recruitment of infants' motor areas, measured as a mu-rhythm desynchronization.

The Like-Me Hypothesis, the mirror system and the role of experience in action understanding are one possible part of the story, but they cannot account alone for early action understanding. First, these processes do not explain *where* abstract concepts such as goal, looking at or agent comes from (Carey, 2009a). Second, as we have seen, infants understand actions of geometric figures that they cannot yet do (and in some cases will never do) (Gergely et al., 1995).

e. Core Principles of Agency

The fact that infants expect agents to act efficiently when observing nonexecutable goal-directed actions – biomechanically impossible actions (Southgate, Johnson, & Csibra, 2008) or actions from geometric figures or boxes (Gergely Csibra, 2008; Liu & Spelke, 2017) –, suggests that they are endowed with a concept of goal and efficiency that goes beyond their own motor experience. Further evidence for this possibility comes from the findings we have seen of Skerry, Powell and Spelke (2013). In this study, infants were presented with an arm reaching for an object taking a curvilinear path around a barrier. When the barrier was removed, infants that wore Velcro mittens expected the arm to reach for the object efficiently; infants that wore mittens without Velcro did not. The authors proposed that first-person experience with picking up objects helped infants to individuate which specific movement of the reaching action was intentional. However, the authors argued that infants could not learn from the training session to represent actions as efficient means that are constrained by barriers, because no barriers were present during the training.

These findings, together with work suggesting that non-human animals also represent others’ actions in terms of goals and perceptual states (Flombaum & Santos, 2005; Marticorena, Ruiz, Mukerji, Goddu, & Santos, 2011; Mascalzoni, Regolin, & Vallortigara, 2010), have led some researchers to argue that we are endowed with an innate conceptual representation about *intentional agent*. Infants would begin life with an abstract understanding of agents as entities capable of self-generated motion, who direct their actions efficiently towards objects, and whose actions are influenced by their perceptual access to objects (Spelke, 2016). This idea is embedded in the *core cognition* proposal. In her seminal work, Susan Carey identified at least four core systems: number, object, cause and agent (Carey, 2009b). These core systems would have its roots in our evolutionary history, would be shared with our primate relatives and would exist and function through the life span (Carey, 2009b).

A set of innate core principles would be at the center of the reasoning system about agency (Carey, 2009a). One of the proposed core principles is the principle of rationality. In the Teleological Stance theory, Gergely and Csibra (2003) propose that the principle of rationality is a non-mentalistic inferential principle that guides infants’ early action understanding. In this proposal, infants relate relevant aspects of reality (action, goal-state and constraints of the situation) through the assumption that actions function as efficient means to achieve goal-states. In **experimental part I** we explore if the principle of rationality not only guides how infants predict others' actions, but it provides with a basis to evaluate agents and their actions. Because agents acting efficiently are more rational and competent than agents acting inefficiently, it would be a rational strategy to prefer them.

1.1.2. Informative agents

Another critical property of agents is that they exhibit behavioral patterns that provide information about the world. When surrounded by other agents, we may point towards objects to inform them about interesting events, or we may produce speech to convey information. In this section we review studies showing that infants represent agents as entities who intend to provide information about the environment.

In their seminal work, Csibra and Gergely (2011) propose that human social learning differs from other forms of social learning in other species because it is guided by communicative intentions. The authors argue that human communication evolved to transmit generic knowledge, facilitating the acquisition of opaque cultural knowledge that could not be acquired relying on observational learning mechanisms alone. In their view, the capacity for Pedagogy is human-specific and innate: from very early in life infants have a high sensitivity to ostensive-referential cues such as eye gaze, pointing or infant-directed speech, which facilitates the transmission of generic and cultural knowledge (Gergely Csibra & Gergely, 2009).

Compelling evidence suggest that, in fact, infants interpret agents as referring to objects in the world. One of the cues that infants rely on to attribute intentional referring is language. At 18 months, toddlers expect agents' utterances to refer to objects they are attending to and use this information to map novel words with novel objects (Baldwin, 1991). Preissler and Carey (2004) provided evidence that this mapping is not associative, but referential. The authors taught a novel word to toddlers using pictures. The experimenter asked participants to point at the whisk. When infants had learned to distinguish whisks from other familiar and unfamiliar objects, the experimenter presented participants with the picture of a whisk, as well as with a real whisk. Participants were asked again "show me the whisk". Interestingly, they chose more often the real whisk, although they had just learned about the word whisk when it was paired with the picture of a whisk, and not with a real one. The results suggest that toddlers understand that both language and pictures refer to objects in the world.

In a series of studies Vouloumanos and colleagues reported that even younger infants expect language to refer to objects in the world. Martin, Onishi and Vouloumanos (2012) presented 12-month-old infants with an agent that selectively grasped one of two objects. At test the agent (*communicator*) could no longer reach for the object she liked, but another agent who did not know about the communicator's preference could. Looking at the other agent, the communicator produced either speech (a nonsense word) or non-speech (coughing). Only in the speech condition infants expected the agent to approach to the communicator the object she preferred rather than the other one. The results suggest that infants understood that the communicator spoke intentionally to inform the recipient about her preference for the target object. Moreover, they suggest that infants understood that speech serves the function of transmitting information between agents. Subsequent studies have replicated the same findings with infants as young as 6 months of age (Vouloumanos, Martin, & Onishi, 2014), and using the transmission of intentions rather than the preference for an object (Vouloumanos, Onishi, & Pogue, 2012). In addition to speech, infants also expect pointing, but not a non-communicative signal (a fist) to transmit information between third-parties (Krehm, Onishi, & Vouloumanos, 2014). Together, the findings indicate that from early in life infants expect agents to communicate information about the world through communicative manifestations (e.g. speech and pointing).

In addition to language and pointing, 3- and 6-month-old infants follow the gaze or head direction of others (D'Entremont, Hains, & Muir, 1997). Although some researchers interpret these results as suggesting that infants shift their attention reflexively to the same direction as a head-turn (Corkum & Moore, 1998), other results suggest that infants selectively follow others' gaze depending on the communicative context (Senju & Csibra, 2008). The fact that infant gaze-following or pointing requires ostensive cues, such as eye contact or infant-directed speech, suggests that this behavior serves communicative purposes in early human development.

The results reviewed in this section indicate that infants expect agents to provide information about the world, which constitutes the basis for social learning. In **experimental part III** we explore if infants understand that the transmission of information between agents may be constrained in some contexts. Specifically, we explore if infants understand that efficient verbal communication depends on the use of a common language.

1.2. MODEL-BASED BIASES IN DEVELOPMENT

Substantial work indicates that children in the preschool-age or older do not learn from agents indiscriminately, but they are selective in their allocation of trust (Koenig & Sabbagh, 2013; Nurmsoo, Robinson, & Butterfill, 2010). Children also tend to prefer to interact and affiliate with ingroup rather than outgroup members, evaluating the former more positively than the latter (Dunham, 2018). However, less is known about the origins of selective learning and social preferences for ingroup members in infancy. Here, we will briefly review infants' sensitivity to certain cues that bias their tendency to imitate, interact with, attend to or learn from others. First, we review work showing that infants are biased towards agents who are informative, reliable and competent. Next, we review infants' biases based on cues that, in older children and adults, determine meaningful social categories.

1.2.1. Informativeness, reliability and expertise

As we have seen, infants are sensitive to ostensive cues that determine they are being addressed in communicative settings, such as eye gaze or infant-directed speech (Gergely Csibra & Gergely, 2009). Several studies show that infants attend more to individuals that make eye contact with them (Farroni, Csibra, Simion, & Johnson, 2002) or who communicate with them using infant-directed speech (Schachner & Hannon, 2011). These cues influence infants' own visual exploration (Senju & Csibra, 2008) and learning (Gergely, Egyed, & Király, 2007; Yoon, Johnson, & Csibra, 2008). In addition, by their first birthday infants are sensitive to certain attributes from others that can signal information quality in a learning context, such as reliability, accuracy and expertise (Poulin-Dubois & Brosseau-Liard, 2016).

Fourteen-month-old infants copy more faithfully the actions of agents who show a reliable rather than unreliable emotional reaction – excitement while gazing to a container with a toy (reliable) rather than when gazing at an empty container (unreliable) (Poulin-Dubois, Brooker, & Polonia, 2011). Sixteen-month-old infants prefer seeking information from agents who provide correct rather than incorrect labels for familiar objects (Begus & Southgate, 2012). Infants also preferentially imitate the actions of an actor that previously acted towards an object performing a conventional action (e.g. placing his foot in a shoe) instead of an incompetent one (e.g. placing his hand in a shoe). Even at younger ages, 8-month-old infants prefer to follow the gaze from an individual that in previous contexts provided accurate rather than inaccurate gazes to anticipate a visual reward (Tummeltshammer, Wu, Sobel, & Kirkham, 2014). Finally, infants are sensitive to others' expertise: 12-month-old infants rely more on the emotional information that provides an agent who success in a goal-directed task, as compared to the information provided by an agent who acts incompetently (Stenberg, 2013).

In **experimental part I** we propose that there is a relation between the type of biases we have seen and the kind of expectations that infants generate about others' actions. We argue that agents who act in accordance with the expectations that infants can generate are evaluated more favorably than agents who violate them. We then explore this idea testing the role of the principle of rationality in the identification of model-based cues.

1.2.2. Social groups

Infants are sensitive to several cues that define adult-like social categories. For instance, infants are biases to attend at individuals from familiar groups (longer looking times) in terms of race, gender, attractiveness and language (Anzures, Quinn, Pascalis, Slater, & Lee, 2013; Kelly et al., 2005; K. D. Kinzler, Dupoux, & Spelke, 2007; Quinn, Kelly, Lee, Pascalis, & Slater, 2008; Quinn, Yahr, Kuhn, Slater, & Pascalis, 2002). These biases appear early in development and are highly influenced by experience. To illustrate, 3-month-old infants prefer to look at familiar-race faces independently on their own race. African-Ethiopian infants living in Africa prefer own-race faces, but African-Ethiopian infants living in a predominantly Caucasian environment (Israel) do not (Bar-Haim, Ziv, Lamy, & Hodes, 2006). Similarly, infants prefer faces of the gender of their most frequent caregivers, independently of the gender itself (Quinn et al., 2002).

a. Preference for native vs. foreign speakers

One of the most studied social categories in infancy is language (Liberman, Woodward, & Kinzler, 2017). Language is unique in that infants are exposed to their parents' speech prenatally. From birth, neonates prefer listening to the language of the mother rather than an unfamiliar language or other auditive stimuli (Moon, Cooper, & Fifer, 1993). A few months later, 5- and 6-month-old infants extend the preference for their native language to a preference for the people that speak their native language. Infants preferentially look at a face of an individual that previously spoke infants' native-language with a familiar-accent, as compared to an individual who spoke in a foreign-language or that used an unfamiliar accent (Kinzler et al., 2007). The preference towards familiar speakers goes beyond attentional biases. At 10 months, infants are more likely to interact with a toy offered by a native-speaker rather than a foreign-speaker (Kinzler et al., 2007). Differences in others' race do not seem to prompt a preference to interact with more familiar individuals, as in the case of language (Kinzler & Spelke, 2011).

Other studies indicate that infants not only prefer to attend or interact with native-speakers, but they privilege the information they provide and tend to imitate more faithfully their actions. Seven-month-old infants listen longer to music melodies introduced by a native-speaker than those introduced by a foreign-speaker (Soley & Sebastián-Gallés, 2015). At 12 months infants preferentially select food offered by native-speakers than foreign-speakers (Shutts, Kinzler, McKee, & Spelke, 2009). Infants also imitate more often a novel action (e.g. turning on a light using one's head) when the action was performed by a native-speaker rather than a foreign-speaker (Buttelmann, Zmyj, Daum, & Carpenter, 2013). Finally, infants show more readiness to encode the information that a native-speaker rather than a foreign-speaker provides (Begus, Gliga, & Southgate, 2016).

b. Inferring third-party social relationships

Information about social categories is not only useful to identify appropriate partners, but it is potentially relevant to predict how others affiliate and interact. Even in societies where intergroup interactions are common, people are biased to conform, affiliate and act as the members of their same social group (Henrich & Boyd, 1998). As adults, we use information about social groups to infer the actual and potential relationships between people, to generate expectations about how individuals are likely to act and react and, ultimately, to relate with others (Pietraszewski, 2013). This can be referred to as Coalitional Psychology. We have seen that infants use information about social categories to interact with others selectively. In this section we review work suggesting that they also use social markers to form inductively-rich representations of social groups, which allows them to predict how others will act and interact (Liberman et al., 2017).

For instance, infants expect individuals who approach to each other moving in synchrony to obtain goals using the same means (Powell & Spelke, 2013). At their second year, infants use the similarity of others' actions to infer affiliation: they expect people to be more likely affiliated when performing the same rather than different ritual actions (Liberman, Kinzler, & Woodward, 2018). At a similar age, infants also seem to possess an abstract representation of in-group support: they expect agents to help more faithfully individuals that have showed to belong to the same category ("I'm a bem". "I'm a bem too") rather than a different one ("I'm a tig") (Jin & Baillargeon, 2017).

Language may also be a marker of social group. Nine-month-old infants expect speakers of the same language to be more likely affiliated than speakers of different languages (Liberman, Woodward, & Kinzler, 2016). However, in the case of language, representing language as a marker of social group is not the only type of information infants can use to predict third-party relationships. As we discuss in **experimental part III** (pages 139-140), understanding the conventional and communicative nature of speech may lead to similar predictions. If infants understand that people who share a common language can communicate and people who speak different languages cannot, they may exploit this information to predict how likely is that they interact.

1.3. RESEARCH GOALS AND PLAN

In the present dissertation we aim at studying (1) what model-based cues infants use to identify agents with whom to potentially interact with and learn from and (2) how these cues influence infants' predisposition of attending to and interacting with others. To address these issues, our empirical approach is to explore how the mechanisms supporting action understanding and model-based biases are related. In this introduction we have first reviewed work showing how infants represent agency and what mechanisms support early action understanding. Second, we have reviewed what and how model-based cues influence social selectivity in infancy.

The first link we are interested in is how the mechanisms underlying infant action understanding can influence the identification of potential model-based cues. We propose the idea that the expectations deriving from core principles of agency can provide infants with the basis to evaluate agents and their actions. Findings on the so-called "epistemic unreliability task" provides evidence for this possibility (Baillargeon et al., 2016). There is considerable evidence that infants expect agents to act in a manner consistent with their mental states (e.g., motivational states, epistemic states, and so on). In other words, infants expect agents to act based on the general knowledge that should go along with the information agents have access to. For instance, infants find surprising an agent that shows excitement while gazing at an empty container, as compared to a container with a toy (Repacholi, 1998). They also find surprising that an agent labels incorrectly a familiar object she has visual access to (Koenig & Echols, 2003). As we have seen, infants are more likely to seek novel information from, learn from or affiliate with agents that act in a manner that is consistent with these expectations (Begus & Southgate, 2012; Chow, Poulin-Dubois, & Lewis, 2008). Another example of the relation between expectations about agents and social selectivity comes from the studies on sociomoral reasoning. Infants expect agents to help others in need rather than hindering them. Consistent with this expectation, infants prefer, and expect others to prefer too, prosocial to antisocial agents (Hamlin, Wynn, & Bloom, 2007).

In **experimental part I** we explore if the principle of rationality provides infants with the basis to identify a potential model-based cue that, to our knowledge, has not been investigated before: the rationality of others' actions. Preferring rational individuals who obtain goals efficiently rather than inefficiently is likely to be an optimal strategy to avoid acquiring noisy or misleading information.

In **experimental part II,** we explore the other side of the coin between the relation of early action understanding and model-based cues. That is, we study how the identification of model-based cues can influence the mechanisms supporting action understanding. Specifically, based on the Like-Me Hypothesis, we investigate how model-based cues influence the recognition of others as *like-me* and, consequently, the representation of others' actions. We use the familiarity with the language people speak as a model-based cue. As discussed, we predict that because speaking a native-language matches infants' existing knowledge of agents, but speaking a foreign-language does not, infants would recognize native-speakers as more *like-me* than foreign-speakers. The selective recognition of *like-me* based on language familiarity would influence how infants make sense of others. Because the mirror system is proposed to support the mapping between self and other, we expect to find this influence in the process of mirroring others' actions. Being biased to make sense of the actions of more familiar individuals is likely to influence infants' predisposition of attending to and interacting with them.

Finally, in **experimental part III** we go beyond first-person preferences and explore how infants use language as a cue to make sense of third-party interactions. We have seen that infants expect agents to provide information about the world through the use of speech. However, speech is not a reliable tool to convey information if communicative partners do not share a common language. Based on this idea, we investigate if infants understand that effective communication is constrained by the use of a common language. Moreover, we test if language background (monolingual vs. bilingual exposure) modulates these expectations. Understanding who can communicate with whom not only enables predicting third-party relationships, but it also provides infants with the basis to identify potential communicative partners.

2. EXPERIMENTAL PART I: Efficiency as a principle for social preferences in infancy

Colomer M., Bas J. & Sebastian-Galles N. (under review). Efficiency as a principle for social preferences in infancy. *Journal of Experimental Child Psychology*.

2.1. TITLE PAGE

Efficiency as a principle for social preferences in infancy

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Research highlights

- Fifteen-month-old infants predicted third-party social interactions based on the perceived efficiency of the agents' actions.

- Infants expected a third-party to preferentially approach an efficient rather than inefficient agent.

- The assumption that agents act efficiently provides infants with a basis for evaluating agents and their actions.

Abstract

Two separate research lines have shown first that infants expect agents to move efficiently toward goal-states and second that they navigate the social world selectively, preferring some agents to others, and attributing social preferences to others' agents. Here, we studied the relationship between infants' expectations of efficient actions and their capacities to identify appropriate social partners. We presented 15-month-old infants with a set of videos containing three geometric figures depicting social agents. One agent (observer) watched how the other two agents acted to obtain a reward. Critically, the efficiency of the agents' actions was manipulated. One of them reached the reward taking a direct efficient path (efficient agent), while the other took a curvilinear inefficient path (inefficient agent). A violation of expectation paradigm was used to measure infants' intuitions about the observer's preferences. Two outcomes of the video were presented: the observer approaching the efficient agent (coherent outcome), and the observer approaching the inefficient agent (incoherent outcome). Infants looked significantly longer to the screen in the incoherent outcome than in the coherent outcome. In a second experiment, we rejected the possibility that infants' expectations in experiment 1 resulted from differences in the movement repertoire of the agents. The two studies suggest that infants evaluate agents acting efficiently more favorably than agents acting inefficiently. This evaluation guides their intuitions about others' social interactions.

2.2. INTRODUCTION

The capacity to predict and understand other people's actions is fundamental to navigate the social world. It provides us with tools that support many types of social interactions, such as cooperation, competition or social learning (Tomasello, Carpenter, Call, Behne, & Moll, 2005). It also allows us to identify potential social partners, guiding inferences about how reliable, competent or pro-social someone's behaviour is (Poulin-Dubois & Brosseau-Liard, 2016a). A large body or research has sought to determine what mechanisms support action understanding in infancy. These studies indicate that at their first birthday infants have already a sophisticated understanding of goal-directed actions (Sommerville, Upshaw, & Loucks, 2012). Infants encode others' actions as structured by goals, rather than simply movements through space (Woodward, 1998). The capacity to attribute goals to observed actions has been proposed to be based on the inferential principle of rational action: we assume individuals to act efficiently to reach future goal-states (Gergely, Nádasdy, Csibra, & Bíró, 1995). In the present research we investigated if the principle of rationality provides infants with the basis to navigate the world selectively, evaluating others' actions in terms of its efficiency and attributing social preferences to third-parties.

Substantial evidence indicates that by the first year of life infants expect agents to behave rationally, i.e. acting efficiently to attain their goals (Gergely & Csibra, 2003). In a series of seminal studies (Gergely et al., 1995; Phillips & Wellman, 2005; Sodian, Schoeppner, & Metz, 2004), 12-month-old infants were first habituated with an agent moving in a curvilinear path and efficiently avoiding an obstacle to reach a reward. Afterwards, the obstacle was removed and participants were presented with two possible outcomes: they saw the agent moving as in the habituation (inefficient action in the new scenario) or they saw the agent moving in a new path directed toward the object (efficient action). Infants showed unexpectedness only when the agent performed the same old action rather than when she moved directly to the object. The results suggest that infants have an inductive bias to expect efficient actions from other individuals. Importantly, these expectations are not limited to the assumption that agents move directly towards a goal when no obstacles block their path. Indeed, when instead of being removed the obstacle is replaced by a shorter one, 6-month-old infants also expect agents to take the least costly available path (Liu & Spelke, 2017). In addition, at both 7 and 16 months of age, infants expect agents to minimize action costs based on the number of actions required to attain the goal (Southgate, Johnson, & Csibra, 2008) or the mental effort involved in performing such actions (Scott & Baillargeon, 2013).

Infants not only expect agents to act efficiently, but they are biased to interpret others' actions as rational means (Baillargeon, Scott, & Bian, 2016). In one study, Gergely and colleagues (2002) showed that 14-month-old infants are likely to imitate an apparently irrational action (e.g. switching a light on with agent's forehead) if the agent has a more rational mean available (e.g. agent has hands free), but not otherwise (e.g. agent has hands occupied). Importantly, infants' readiness to imitate apparently irrational actions is limited to pedagogical interactions. Infants are more likely to imitate the agent when she engages them with ostensive cues (eye-contact, infant-directed speech, etc) than when she does not (Király, Csibra, & Gergely, 2013). These findings suggest that, when embedded in pedagogical interactions, infants interpret apparently irrational actions as relevant cultural means to learn (Csibra & Gergely, 2009). However, in the absence of pedagogical explanations, infants interpret apparently irrational actions as uncertain or irrelevant (Gergely et al., 1995). In the latter case, one possible way for infants to interpret agents acting inefficiently is simply by concluding that they do not have enough information to interpret their actions (Biro, Verschoor, & Coenen, 2011). Alternatively, infants may evaluate agents as irrational actors, and use this information to identify appropriate versus inappropriate partners (Baillargeon et al., 2016).

Previous studies indicate that infants tend to evaluate others' agents considering how they acted in previous events (Holvoet, Scola, Arciszewski, & Picard, 2016). Evidence for that comes from tasks on selective learning and sociomoral reasoning. Regarding the former, infants selectively trust, follow actions from, or imitate agents based on cues such as competence, confidence or reliability (Koenig & Sabbagh, 2013; Poulin-Dubois & Brosseau-Liard, 2016). For instance, 13-month-old infants trust more agents who successfully complete a goal-directed task than agents who fail to obtain the goal (Stenberg, 2013). At 14-months infants are also more likely to imitate novel actions from someone who previously completed a task in a conventional manner – e.g. putting a shoe in his foot – rather than someone who performed an unreliable behaviour – e.g. putting a shoe in his hand (Zmyj, Buttelmann, Carpenter, & Daum, 2010). With regards to sociomoral reasoning, previous findings suggest that during the first year of life infants prefer prosocial to antisocial agents (for a review see Van de Vondervoort & Hamlin, 2018) and fair to unfair agents (Geraci & Surian, 2011). For example, infants preferentially reach for agents who helped a third-party to climb a mountain as compared to agents who hindered the climber (Hamlin & Wynn, 2011). Together, these findings suggest that infants are endowed with core principles that not only allow them to predict how agents will act in different situations; they also provide infants with the basis to evaluate agents and their actions. As predicted, infants tend to prefer agents acting in accordance with the information they expect; e.g. infants' expectations that agents will act fairly go along with a preference for fair over unfair agents (Geraci & Surian, 2011). This notion suggests that the principle of rationality can also provide infants with the basis to evaluate others' actions in order to identify appropriate social partners. However, to the best of our knowledge no study has investigated the relation between the assumption of efficiency and infants' capacities to navigate the world selectively.

The current experiment aims at studying if infants consider the efficiency of others' actions to infer third-parties' preferences.

Infants' social selectivity is not limited to their capacity to prefer some individuals over others; they also use information about others' actions to predict third-party preferences. For example, 10 to 12-month-olds prefer, and expect others to prefer, prosocial to antisocial agents (Fawcett & Liszkowski, 2012; Hamlin, Wynn, & Bloom, 2007). Similarly, 13 and 16-month-olds' preferences for fair versus unfair agents are aligned with their expectations about others' preferences (Geraci & Surian, 2011). Infants do not only form expectations about third-party preferences regarding sociomoral information. They also consider cues such as the means people use to achieve a goal: 16-month-old infants expect agents who attain a goal using the same – rather than different – means to be more likely to affiliate (Liberman, Kinzler, & Woodward, 2018)**.** Here, we hypothesized that the capacity to identify efficient means to attain a goal, together with the assumption that agents act efficiently (Gergely & Csibra, 2003), would guide infants' intuitions about others' social preferences. Specifically, we predicted that infants would expect a third-party observer to preferentially affiliate with an agent that previously acted efficiently rather than an agent who acted inefficiently. To convey affiliation, following previous work, we used approach (Geraci & Surian, 2011; Hamlin et al., 2007; Kuhlmeier, Wynn, & Bloom, 2003; Liu, Ullman, Tenenbaum, & Spelke, 2017; Powell & Spelke, 2018).

Fifteen-month-old infants were presented with two agents that attained the same goal at the same time, but the costs they incurred were different. One agent (*efficient agent*) acted efficiently

— going through the most direct path —, while the other agent (*inefficient agent*) acted inefficiently — reaching a resource by making an unnecessary detour. During the actions of the efficient agent and the inefficient agent, an observer remained static in the lower part of the screen. A violation of expectation paradigm was used to assess infants' intuitions about the observer's preferences. Infants saw the observer approaching either the efficient agent or the inefficient agent and their looking time at the screen was measured, capitalizing on the phenomenon that they tend to look longer at unexpected or surprising events. We hypothesized that participants would look longer when the observer approached the inefficient agent rather than the efficient agent.

2.3. EXPERIMENT 1

Participants were presented with a set of animations that depicted the actions and goals of three animated geometric figures. To manipulate the efficiency of the agents' actions we adapted the procedure of Csibra & Gergely (2003) studies, where the cost of a certain goal was related to the trajectory of the agents' actions. To test infants' responses to others' social interactions, we adapted Liu et al.'s (2017) procedure. We used a Violation of Expectation Paradigm (VoE) to measure infants' expectations in a third-party social interaction.

2.3.1. METHOD

Participants

We recruited 24 15-months-old infants (mean age = 450 d, range = 423-468). Sample size was defined following Liu et al. (2017). Fifteen additional participants were tested but excluded from analysis due to fussiness or crying (9), experimental error (4), parental interference (1) or looking at the screen for the maximum amount of time during both test trials (1). Participants were recruited by visiting maternity rooms at the Hospital Quirón and the Clínica Sagrada Família in Barcelona, Spain. All participants were healthy, full-term infants (> 37 GW) whose parents had volunteered to participate in infant studies at the Center for Brain and Cognition, Universitat Pompeu Fabra. The research reported in this manuscript was conducted in accordance with the principles expressed in the Declaration of Helsinki and approved by the local ethical committee (The Clinical Research Ethical Committee of the Parc de Salut Mar). Written informed consent was obtained from the participants' caregiver before the experiment was conducted.

Procedure and Stimuli

Participants were tested in a sound-attenuated room at the "Laboratori de Recerca en Infància" (Center for Brain and Cognition, Universitat Pompeu Fabra). Infants sat on the caregiver's lap in a darkened room decorated with white homogeneous curtains. Video animations were displayed on a 23'' screen (1920 x 1080 pixels) at ~65 cm from participants' face and were controlled using the Psychotoolbox-3 toolbox in MATLAB (The MathWorks).

Participants’ behaviour during the session was recorded using a Sony HDR-HC9E camera (temporal resolution: 25 frames/s). The stimuli were created with Adobe Flash Professional and consisted on three coloured circular agents (blue circle, red circle and yellow circle) with basic facial features located on a green homogeneous background (see figure 2.1). Two obstacles were situated close to each agent performing actions. The yellow agent was always the observer and was situated in the lower and central part of the screen. The role (efficient or inefficient) and order (acting first, acting second) of the two other figures were counterbalanced across participants. The stimuli started with a familiarization phase showing the agents’ goal and their interaction with the observer. In the following pretest phase we manipulated the efficiency of the agents’ actions. Finally, in the test phase infants were presented with a choice scenario, where the observer approached one of the agents in one test outcome and the other in the other test outcome. We used a Violation of Expectation paradigm as a measure of infants' expectations.

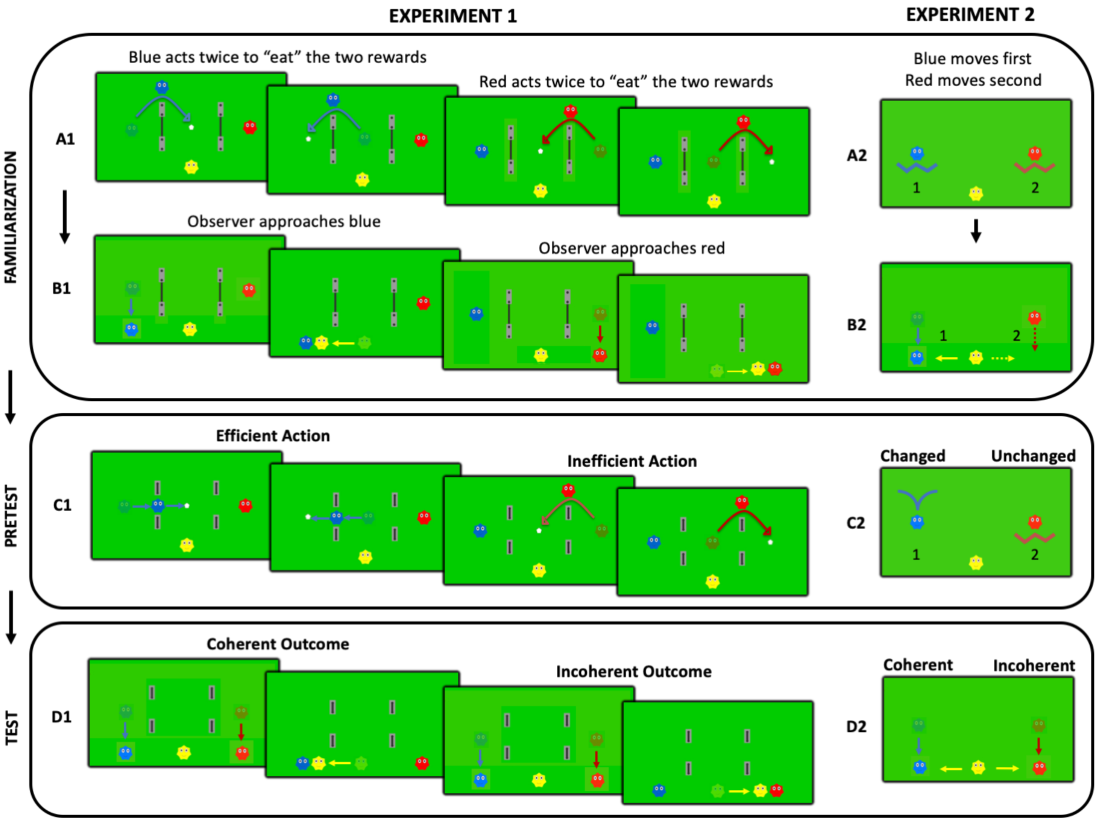

Figure 2.1. *Scenes from the animations presented to infants in Experiment 1 and Experiment 2. The representation of a shaped agent describes the original position of the corresponding agent before starting to act. The arrows describe the path and direction of the agents' movements. (A1) familiarization trial depicting the agents' goal and (A2) agents' movement. (B1 & B2) familiarization trials exemplifying the affiliation scenes, where the observer approached each agent separately. (C1) pretest: actions of the efficient agent (blue) and inefficient agent (red) after the gates of the obstacle opened, and (C2) movement of the changed agent (blue) and unchanged agent (red). (D1 & D2) actions of the agents during the coherent and incoherent test outcomes. In the two studies the order and positions of the agents, as well as the order of the test outcomes, were counterbalanced – except for the observer.*

Familiarization phase: the two agents on the sides showed their goal-directed action, which was reaching and “eating” a small grey pentagon (reward) that appeared close to them. Both agents separately performed the same action. First, the reward appeared at the center of the screen, separated from both agents by an obstacle (1.5 sec). To reach it, the first agent “jumped” over the obstacle performing a curvilinear movement (3.5 sec) and “ate” the reward. After the first action, another reward appeared (1.5 sec) at the other side of the obstacle. The first agent jumped over again to reach it, returning to her original position (3.5 sec). Next, the second agent performed the same set of two actions, ending the first trial (see Movie S1). The same sequence was repeated, resulting in a total of 4 actions per agent. Each trial was followed by a grey background with a small black cross at the centre of the screen (1 sec; cross scene). After goal familiarization, we familiarized participants with the affiliation scenario. Each agent separately moved down the screen (3 sec) and “called” the observer by moving up and down (2 sec). The observer repeated the up and down movement (2 sec) and approached the “calling” agent (3 sec). A cross appeared after the observer approached the first agent to separate the two approaching sequences (see Movie S2).

Pretest phase: The pretest followed the same structure as the first scenes in the familiarization phase but presented a slightly different scenario (see Movie S3). We changed the situational constraint by opening the gates of the obstacle (1.5 sec). Infants saw one of the agents performing the same jumping goal-approach as before (inefficient) and the other agent performing a perceptually novel straight-line goal-approach, going through the opened gate to reach the reward (efficient). Timing was the same as in the first two trials of familiarization, except for the opening of the gate (at the start of each trial). As in the familiarization phase, we presented two trials, each one followed by a cross scene.

Test phase: The test started with both agents moving toward the bottom of the screen and simultaneously "calling" the observer. Next, participants were presented with two test outcomes, with a cross scene between them. In the coherent outcome the observer approached the efficient agent and the video paused (see Movie S4). In the incoherent outcome the observer approached the inefficient agent and the video paused (see Movie S5). The order of presentation of the test outcomes was counterbalanced across participants. The timing was the same as in the familiarization affiliation scenes, except for a pause of 0.5 sec before the observer approached each agent.

Coding and Data Analysis

Statistics were computed on participants' total looking time to the screen at the end of each test outcome until they looked away for 1 sec consecutively or when they accumulated a total of 30 sec looking. The chosen criteria were selected after testing 8 pilot participants (see SI) and following Sommerville, Schmidt, Yun, & Burns (2013). Blinks were considered as looking away if they lasted for more than 0.2 s. One infant looked at the screen for the maximum amount of time during both test outcomes and was excluded. All recordings were coded by a primary coder, who was unaware of the hypotheses of the experiment, and the first author. A high inter-coder agreement was achieved (ICC = .995; see SI). Reported data correspond to the coding of the primary coder. Before performing statistical tests, data was log-transformed to better approximate a normal distribution (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016). A Shapiro-Wilk normality test was run on each data subset of trial type, confirming that our data followed a normal distribution (see SI). All statistical tests were parametric and two-tailed. To facilitate reader's comprehension, figure 2.2 displays the means of participants' total looking times before log-transformation.

2.3.2. Results and discussion

To test infants' expectations in the test phase, we compared their total looking time to the screen (log-transformed) in each test outcome (coherent and incoherent). An ANOVA on outcome type (coherent outcome vs. incoherent outcome) as a within-participant factor found a significant main effect of outcome type [$F(1,23) = 21.25$, $P = 0.0001$]. Participants looked significantly longer at the incoherent outcome (Mean = 15.27 sec; SD = 7.34 sec) than at the coherent outcome (Mean = 9.69 sec; SD = 3.80 sec; see Figure 2.2).

The results showed that infants expected the observer to approach the efficient agent rather than the inefficient one. The data suggest that infants expect other individuals to affiliate with agents who act efficiently versus agents who act inefficiently. However, the present results might have an alternative explanation. In our experiment, the efficient agent performed more distinct actions than the inefficient one. The efficient agent changed her behaviour during the familiarization phase, while the inefficient agent always performed the same action. The novelty of the action performed by the efficient agent might have influenced infants' attention, giving raise to longer looking times. The following experiment tested this alternative interpretation of the results.

2.4. EXPERIMENT 2

In this experiment we explored whether infants' different responses in the coherent and incoherent outcomes of Experiment 1 resulted from the difference in the agents' movement repertoire. Infants were presented with a set of animations that depicted the actions of three animated geometric figures. The procedure was an adaptation of the one used in the previous experiment, except that there were no obstacles and the agents moved without an apparent goal. The movements of the agent were slightly modified in order to attract infants' attention, given the simplicity of the new scenario. As in Experiment 1, the pretest phase included one agent acting as in the familiarization phase (unchanged agent) and one agent performing a novel movement (changed agent).

2.4.1. METHOD

Participants

We recruited 24 15-months-old infants (mean age = 440 d, range = 415-465 d). Sample size was defined following Experiment 1. Eight additional participants were tested but excluded from analysis due to fussiness or crying. The recruitment method and characteristics of participants were the same as those from Experiment 1.

Stimuli and Procedure

The procedure of Experiment 2 was identical to that of Experiment 1 except for changes in the stimuli. As in Experiment 1, the observer (yellow agent) was in the lower and central part of the screen and the two acting agents were on the sides. Unlike Experiment 1, no reward or obstacles appeared in the video (see figure 2.1).

Familiarization phase: the observer remained motionless and the other two agents acted in a non goal-directed manner. Instead of jumping to collect a reward as in Experiment 1, they moved back and forth twice (4.5 sec / trial; total of 2 trials; Movie S6). After goal familiarization, we familiarized participants with the affiliation scenario. Except for the absence of obstacles in the stimuli, the affiliation familiarization was identical to the one used in Experiment 1 (see Movie S2).

Pretest phase: the observer remained motionless in the lower part of the screen. One agent kept performing the same movement as in the familiarization (unchanged agent), moving back and forth. The other agent did a novel movement (changed agent). The changed agent jumped to the left and to the right from her original position (see Movie S7).

Test phase: The test was identical to that of Experiment 1 except for that the obstacles did not appear to the movies (see Movie S4 and Movie S5).

Coding and Data Analysis

The coding and data analysis procedure we used was identical to that of Experiment 1. All recordings were coded by a primary coder, who was unaware of the hypotheses of the experiment, and the first author. A high inter-coder agreement was achieved (ICC = 0.951; see SI). Reported data correspond to the coding of the primary coder. Before performing statistical tests, data was log-transformed to better approximate a normal distribution (Csibra et al., 2016). A Shapiro-Wilk normality test was run on each data subset of trial type, confirming that our data followed a normal distribution (see SI). To facilitate reader's comprehension, figure 2.2 displays the means of participants' total looking times before log-transformation.

2.4.2. RESULTS AND DISCUSSION

To test infants’ expectations, we compared infants' total looking time to the screen (log-transformed) in each test outcome. An

ANOVA on outcome type (coherent outcome vs. incoherent outcome) as a within-subject factor found no significant differences in participants' looking times between outcomes. Infants spent similar time ($p=0.85$) looking to the coherent outcome (Mean = 13.52 sec; SD = 6.43 sec) and the incoherent outcome (Mean = 13.65 sec; SD = 5.96 sec; See figure 2.2). The results showed that infants looked similarly to the screen when the observer approached either the changed agent or the unchanged agent, suggesting that they did not expect the observer to approach one agent over the other.

Comparison of experiments 1 and 2

In further analysis, we compared participants' data of Experiment 1 and Experiment 2 to test whether (1) infants' responses between test outcomes differed based on the manipulation of each experiment, and that (2) infants' general looking times between studies did not differ.

A 2 (outcome type: coherent vs. incoherent outcome) × 2 (Experiment 1 vs. Experiment 2) ANOVA resulted in a significant interaction between Outcome type and Experiment [$F(1,46) = 5.44$, $p = 0.024$] and a main effect of Outcome type [$F(1,46) = 6.97$, $p = 0.011$]. Only the manipulation of agents' efficiency at Experiment 1, as compared to the manipulation of the agents' movements at Experiment 2, influenced infants' responses between test outcomes. Overall, participants looked less time at the screen in the coherent outcome of Experiment 1 compared to the other conditions (see

Figure 2.2), suggesting that this was the outcome infants were more likely to expect. Infants' looking times did not differ systematically based on the experiment (main factor Experiment: p>0.1), but only in the test outcome predicted as expected (coherent outcome of Experiment 1). The results support our interpretation of Experiment 1, indicating that infants' expectations were guided by the efficiency of the agents' movements and not by the novelty of the efficient agent's actions.

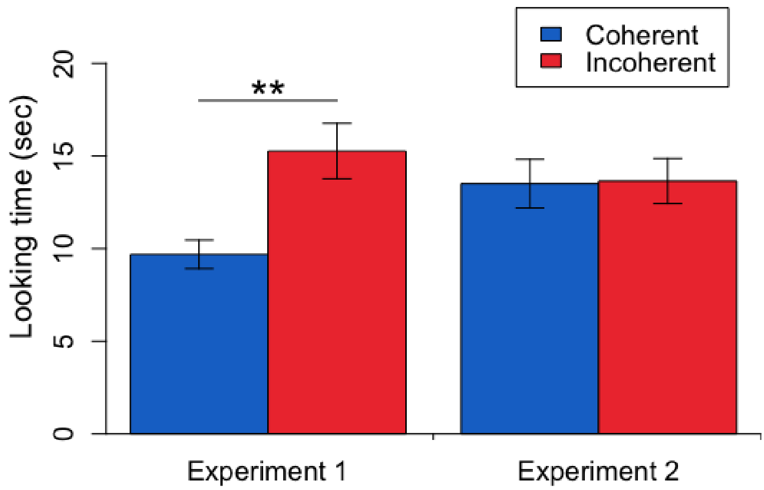

Figure 2.2. *Mean looking time to coherent outcome and incoherent outcome for the twenty-four 15-months old participants in Experiment 1 and the twenty-four 15-months old participants in Experiment 2. Infants looked significantly longer at the incoherent outcome compared to the coherent outcome (Experiment 1) when the efficiency of the agents' actions was manipulated (p < 0.01). In Experiment 1, infants were presented with two agents attaining a reward, one of them by taking a direct path (efficient agent) and the other one by taking an indirect and curvilinear path (inefficient agent). Infants looked longer to the screen*

when a third agent (observer) approached the inefficient agent (incoherent outcome) as compared to the efficient agent (coherent outcome). In Experiment 2, a new group of participants was presented with similar videos, but in this case the only manipulation was the variety of the agents' movement repertoire. In contrast to Experiment 1, infants' looking times at the screen were equivalent either if the observer approached the agent with a more varied movement repertoire or the other one (Experiment 2; $p > 0.1$); All tests were two-tailed. Error bars denote Standard Error of the mean.

2.5. GENERAL DISCUSSION

We tested if infants' expectations of third-party social preferences are influenced by the principle of rationality: the assumption that agents move efficiently toward goal-states. In Experiment 1 we presented 15-month-old infants with a set of videos where the efficiency of two agents' actions was manipulated while a third agent observed them. At the end of the videos, the observer approached one of the two agents and participants' looking time to the screen in each outcome was measured. The results of Experiment 1 indicated that infants looked significantly longer when the observer approached the inefficient agent than when she approached the efficient agent. We interpreted such difference as reflecting infants' expectations of the observer affiliation preferences. Nevertheless, in Experiment 1 the efficient and inefficient agents differed in the number of type of actions they performed. Infants' responses could be interpreted as a preference for the agent with a broader movement repertoire. In Experiment 2, we discarded this interpretation by isolating the manipulation of the agents' movement repertoire. To our knowledge, this is the first research showing that infants not only expect individuals to act efficiently, but they also expect others to prefer agents acting efficiently over agents acting inefficiently.

We propose two different mechanisms explaining *why* action efficiency influenced infants' intuitions about observer's preferences. The first mechanism is related to action predictability. Infants represent efficient actions as goal-directed and they are able to predict agents' subsequent actions when obstacles in the scene change (Gergely & Csibra, 2003). These predictions are based both on the assumption that individuals act consistently, i.e. maintaining their disposition toward a certain goal, and with the assumption of efficiency (Baillargeon et al., 2016). When actions are perceived as inefficient, infants do not hold expectations about agents' subsequent movements (Biro et al., 2011; Gergely et al., 1995). In Experiment 1, when the gates of the obstacle opened, only the efficient agent acted in accordance with the assumption of efficiency, while the inefficient agent's actions deviated from the expectations that infants could generate in the new scenario. We propose that as infants could not make sense of the inefficient action, they evaluated the acting agent as irrational or unpredictable. Such evaluations guided infants' subsequent expectations about the observer's preferences for the efficient versus the inefficient agent.

The second mechanism is related to the representation of competence in the context of utility calculus. T*he naïve utility calculus* proposal claims that humans expect agents to make decisions by maximizing utilities, evaluating rewards in relation to costs. That is, people implicitly assume that other agents will choose actions to maximize expected rewards and minimize action costs, given their beliefs about the state of the world (Jara-Ettinger, Gweon, Schulz, & Tenenbaum, 2016). Previous studies found that 2 year-old toddlers infer people's competence based on the effort they put to attain a goal (Jara-Ettinger, Tenenbaum, & Schulz, 2015). The authors proposed that toddlers' reasoning about others' competence is based on the assumption of utility maximization (Jara-Ettinger et al., 2016). If people choose actions to maximize utilities, agents obtaining a reward with a lower cost will be more competent than those obtaining the reward with a higher cost. Previous findings show that at 10 months of age infants are sensitive to the utility of others' behaviors by relating costs and rewards of their actions (Liu et al., 2017). In Experiment 1, participants saw two agents attaining the same reward, but the costs of their actions differed. Specifically, when the gates opened, the actions of the efficient agent resulted in a higher utility (lower cost) than the actions of the inefficient agent (higher cost). By assuming agents to maximize utilities infants could evaluate efficient actions as more competent than inefficient actions, expecting the observer to approach the efficient agent.

Computing the agents' action utilities, as well as representing agents' actions in terms of predictability are sufficient to attribute preferences to the observer in Experiment 1. However, the two mechanisms just described can lead to different inferences in more complex scenarios. For instance, let us imagine a scenario with four agents; an agent with the role of observer witnesses that agent "A" is more competent than agent "B", and agent "B" is more competent than agent "C". Evaluating agents in terms of predictability would drive infants to represent "A" as predictable and "B" and "C" as unpredictable. However, computing action utilities in a continuous scale would allow infants to infer that not only "A" is more competent than the other two, but also "B" is more competent than "C". The two types of reasoning would lead infants to hold different expectations in a situation where the observer can approach "B" or "C". Future work will help to pinpoint exactly how infants represent inefficient actions in different social scenarios, perhaps by varying the number of agents they are presented with. In any case, both the utility calculus and the principle of rationality are based on infants' assumption that agents act efficiently. The current findings provide evidence that the principle of efficiency guides social selectivity in infancy.

In Experiment 1 not only infants represented differently the actions of the efficient agent as compared to the actions of the inefficient agent. They also used this information to attribute a third-party preference, expecting the observer to preferentially interact with the efficient agent rather than the inefficient agent.

These results are consistent with previous findings showing that the capacity for social evaluation and the ability to infer others' evaluations are aligned by 10 months of age (Hamlin et al., 2007). Evaluating efficient actions more favorably than inefficient actions could emerge very early in ontogeny, since around 3 months of age infants already expect individuals to act efficiently (Skerry, Carey, & Spelke, 2013). Preferring efficient to inefficient actions early in life may be optimal to promote interactions with the best agents to potentially coordinate with and to learn from (Sebanz, Bekkering, & Knoblich, 2006). Another question is whether infants attributed a more positive evaluation to the efficient agent, a more negative evaluation to the inefficient agent, or both. According to previous studies, infants expected agents to act efficiently when the gates of the obstacle opened. Given that the inefficient actions violated infants' expectations, we speculate that their inference of the observer's preference was driven by a negative evaluation of the inefficient agent.

The current findings indicate that the assumption of efficiency provides infants with the basis to evaluate agents and their actions. By 15 months infants evaluate others' actions in terms of efficiency and use this information to predict others' interactions. Guided by core principles of action understanding, together with other mechanisms such as pedagogical learning (Csibra & Gergely, 2009; Király et al., 2013), statistical learning (Monroy, Meyer, Schröer, Gerson, & Hunnius, 2017) or expectation of pro-social behaviors (Hamlin & Wynn, 2011b), infants possess the precursors they need to start navigating the social world in a selective and adaptive way.

Author contributions

M. Colomer (MC), J. Bas (JB) and N. Sebastian- Galles (NSG) developed the concept for the study. Testing was performed by MC and JB. Data collection and data analysis were performed by MC. The manuscript was written by MC, JB and NSG. All the authors approved the final version of the manuscript for submission.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

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2.7. Supplementary Information

This file includes:

Tables 2.S1 to 2.S5

Table 2.S1. Shapiro-Wilk normality test (p-value) of base-10 log-transformed data

	First Author		Primary coder	
	Coherent	**Incoherent**	**Coherent**	**Incoherent**
Experiment 1	0.81	0.33	0.83	0.25
Experiment 2	0.22	0.14	0.18	0.31

Table 2.S2. Mean (and standard deviation in parenthesis) of the base-10 log-transformed data

	First Author		Primary Coder	
	Coherent	**Incoherent**	**Coherent**	**Incoherent**
Experiment 1	0.95 (0.18)	1.12 (0.23)	0.95 (0.18)	1.13 (0.23)
Experiment 2	1.06 (0.22)	1.11 (0.21)	1.08 (0.22)	1.09 (0.21)

Table 2.S3. Mean (and standard deviation in parenthesis) of the raw data in seconds

	First Author		Primary Coder	
	Coherent	**Incoherent**	**Coherent**	**Incoherent**
Experiment 1	9.65 (3.80)	15.01 (7.29)	9.69 (3.0)	15.27 (7.34)
Experiment 2	13.47 (6.54)	13.73 (6.07)	13.52 (6.43)	13.65 (5.96)

Table 2.S4. Raw data in seconds of all participants as reported by each coder.

Participants	First Author		Primary coder	
	Coherent	Incoherent	Coherent	Incoherent
EXP 1				
1	6,00	6,32	5,9	6,37
2	9,00	10,20	9,08	13,79
3	9,12	24,80	9,22	25,12
4	10,60	25,04	10,64	25,29
5	6,28	6,36	6,27	6,37
6	6,48	5,28	6,47	5,29
7	7,00	25,32	7,12	25,72
8	14,08	11,68	14,14	11,74
9	5,92	12,68	5,86	12,88
10	6,64	12,48	6,71	12,68
11	10,88	20,48	11,05	20,78
12	16,68	21,84	15,93	22,1
13	4,36	5,12	4,37	5,09
14	9,48	30,92	9,56	31,32
15	3,60	7,72	3,59	7,73
16	14,52	15,04	14,75	15,22
17	6,8	11	6,81	11,12
18	18,27	23,88	18,51	24,17
19	10,92	15,44	10,95	15,48
20	12,72	13	13,25	13,22
21	8,52	13,96	8,58	14,07
22	10,36	15	10,34	14,07

23	10,56	18	10,6	18,1
24	12,85	8,73	12,89	8,77
EXP 2				
1	14,68	10,84	14,95	11,05
2	9,96	6,16	10,1	6,27
3	23,68	26,20	24,03	26,68
4	19,36	10,8	19,69	10,95
5	10,48	11,01	10,75	11,29
6	8,84	16,64	9,02	17,12
7	12,04	6,84	20,47	6,98
8	7,32	18,00	7,36	11,83
9	10,80	20,92	10,91	21,25
10	10,92	16,64	11,05	16,88
11	16,44	24,88	16,71	16,95
12	24,56	12,84	24,92	12,78
13	7,84	21,96	8,07	22,85
14	19,92	16,16	20,27	16,4
15	24,60	7,00	24,98	7,12
16	6,36	6,04	6,54	6,4
17	3,16	14,04	3,22	14,3
18	11,56	13,56	11,86	13,76
19	21,28	21,44	21,56	21,73
20	9,24	4,72	9,42	4,85
21	6,60	18,52	6,68	18,78
22	10,84	8,44	10,98	8,61
23	9,04	15,80	9,12	16,03
24	11,52	8,04	11,76	6,81

Table 2.S5. Raw data in seconds of the 6 participants tested the pilot. Two more participants were tested but excluded because of fussiness.

Looking away > 1 sec		Looking away > 2 sec		Total number looking away using looking away > 2 sec	
Coherent	**Incohe-rent**	**Coherent**	**Incohe-rent**	**Coherent**	**Incoherent**
8,28	16,64	32	20,16	3	3
11,84	26,48	11,84	29,36	1	3
8,4	6,16	8,4	6,16	1	2
18,32	27,04	18,32	32	2	3
5,8	4,16	29,48	18,04	3	3
9,6	15,12	23,52	15,12	3	1

3. EXPERIMENTAL PART II: Strangers' things: influence of social group familiarity on infants' belief-based action predictions

Colomer M. & Sebastian-Galles N. (submitted). Strangers' things: influence of social group familiarity on infants' belief-based action predictions. *Science*

3.1. TITLE PAGE

Strangers' things: influence of social group familiarity on infants' belief-based action predictions

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Abstract

Two concepts critical for the development of socio-cognitive knowledge are mentalizing and social categorization. The former indicates that by 6 months of age infants predict others' actions based on their goals and beliefs. The latter shows that at similar ages infants are biased to attend and interact with more familiar individuals, considering adult-like social categories such as language or race. We report that these two core processes are interrelated from early in infancy. In a belief-based action prediction task, infants presented with a native-speaker generated online predictions about her actions, as revealed by the activation of participants' sensorimotor areas before the agent's movement. However, when infants were presented with a foreign-language speaker they did not recruit their motor system before the agent's actions. Analysis on pupillometry provided further evidence that familiarity with the language of others influences how infants predict their actions. Selectively tracking others' actions considering familiarity cues is likely to privilege the acquisition of relevant cultural knowledge in infancy.

3.2. MAIN TEXT

Social categorization shapes how and what we think of other people [1]. The tendency to group individuals into social categories and to prefer those who share our group membership is essential to cooperative-structured societies. However, it is also the origin of the darkest episodes in the history of human societies. Categorizing people by their ethnic origin, sexual orientation or race has often resulted in nefarious consequences, such as cases of dehumanization or social discrimination. A growing number of studies over the last decade have investigated the origins of social categorization using a developmental approach. These studies suggest that the precursors of social categorization emerge as early as the first year of life, with infants exhibiting familiarity preferences based on race, gender or language [2], [3].

The role of familiarity on infants' preferences has been studied extensively, but little is known about its influence on other core mechanisms of social cognition [4]. One key aspect when interacting with others is making sense of the reasons guiding their actions, which depends on people's goals and beliefs. It has been shown that the mechanisms supporting action understanding are already in place by the sixth month of life [5]. Infants expect an agent to seek an object where she last encountered it, even if, unbeknownst to the agent, it has been moved since [6]. Research in adults indicates that group membership can modulate the mechanisms supporting the representation of other people's actions [7], [8]. For instance, people are less likely to spontaneously represent the actions of outgroup members than those of ingroup members in a joint action task [9], [10]. Group membership even influences how people represent others' actions while observing them [11]. People show greater neural motor activity when observing the actions of same-race individuals, as compared to other race individuals. To our best knowledge, however, no research has directly investigated the relationship between the precursors of social categorization and the mechanisms supporting action understanding in infancy. This research aims at addressing this.

Children differentiate between native and foreign speakers in order to identify the limits of shared cultural knowledge [12]. At 2 years of age toddlers relate a foreign language with non-conventional actions [13]. Even earlier in development, 6-month-old infants match other-race faces to unfamiliar languages [14]. The speaker's language also influences infants' expectations of helping or hindering interactions. By 12 months, infants find more likely that a native speaker acts prosocially than antisocially, but they do not hold expectations about the speakers of an unfamiliar language [15]. Although these studies do not directly probe the influence of familiarity with others' languages on action reasoning, they provide insight into how these two processes might be related. Overall, they suggest that infants associate representing agents as unfamiliar (e.g. non-native speakers) to the expectation that their behaviour or physical attributes will differ from infants' existing knowledge of the world. Based on this idea, we hypothesized that the preference for native speakers over foreign-speakers in infancy goes along with a facilitation of understanding and interpreting the actions of familiar versus unfamiliar group members. This facilitation may be present at 6 months. At this age, infants generate belief-based action predictions and are biased towards attending more native than foreign-speakers. In the present study we investigated whether 6-month-old infants' belief-based action predictions of an agent differ according to the agent's language. To this end we used a direct neural measure of online action prediction: the so-called "mirror system" [16]. Starting from early infancy, motor areas are recruited in a similar way whether we observe or predict the actions of others, or perform them ourselves [17]. Motor activation is visible in the electroencephalography (EEG) as a desynchronization of the resting-state mu rhythm in sensorimotor areas [18].

Twenty 6-month-old infants were presented with a belief-based action prediction task adapted from Southgate and Vernetti (2014). While watching the videos, their neural activity was measured using continuous recordings of EEG [29]. Crucially, the agent spoke in a native language to one group of infants (10 participants) and in a foreign language to the other group (10 participants). The agents used adult-directed speech to enhance the infants' feeling of unfamiliarity with the foreign-speaker. Participants were first familiarized with the agent's goal of grasping a ball (Figure 3.1A). Then, they saw the agent speaking in a native or foreign language (Figure 3.1B). In the test, the agent always held a false belief about the location of the ball. In A+O- she opened a box believing it contained the ball, while in A-O+ she stayed still, believing that the ball was not inside the box (Figure 3.1C).

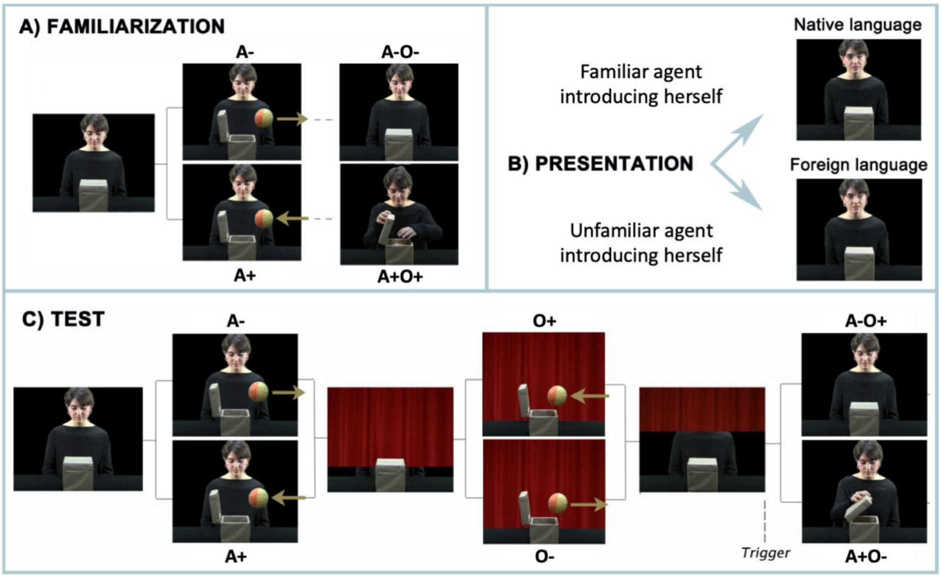

Figure 3.1. *Structure of the videos presented to 6-month old infants.* ***(a)*** *First, we familiarized infants with the agent's (A) goal: grasping the ball (O) after seeing it jump into the box (A+O+), or remaining still after seeing it jump out of the box (A-O-). We presented 2 trials of each condition.* ***(b)*** *Second, the agent introduced herself in the participant's native language to one group (native-language group, Catalan or Spanish, N=10) and in a participant's foreign language to the other (foreign-language group, German, N=10).* ***(c)*** *Third, the agent saw the ball jumping into (A+) or out of (A-) the box at the start of the video. Then a curtain came down hiding the agent and the ball jumped either into (O+) or out of (O-) the box. The curtain then lifted to reveal the agent, who remained still during 1500ms. In the following 1500ms the agent acted based on her (false) belief. In the A+O- condition she tried to grasp the ball. In the A-O+ condition she stayed still. A successful prediction was associated with a mu desynchronization prior to the agent's action in the A+O- condition, but not in the A-O+ condition. We defined the Window of Analysis (WoA) as a 500ms window starting at the "Trigger" (when the curtain had lifted). We repeated both conditions randomly until the infants became inattentive.*

We measured mu rhythm in a 500ms window starting when the curtain had lifted, revealing the agent (Window of Analysis - WoA). In both trial types, the agent stayed still during the WoA. Predicting the agent's intention of grasping the ball on the basis of her (false) belief should result in participants' recruiting their motor system only in A+O-. We expected the native-language group to show a stronger mu rhythm desynchronization (MRD) in the WoA of A+O- as compared to the foreign-language group. No MRD was expected in A-O+ in either group of participants. The mu rhythm activity was obtained by performing time-frequency analysis on the EEG pre-processed data to yield a measure of induced oscillatory brain activation. The time-frequency response for both groups of participants in A+O- is illustrated in Figure 3.2A. A three-factor mixed ANOVA was run to examine the effect of test trial type (A+O-, A-O+), time window (baseline, WoA) and group (native-language group, foreign-language group) on the averaged mu-rhythm activity of each participant. A significant three-way interaction was obtained ($F(1,18)=4.63$, $p=0.045$). Paired t-tests comparing the activation of mu-rhythm between baseline and WoA in each condition revealed significant differences only in the A+O- trial type of the native-language group ($t(9)=2.9$, $p=0.017$). As predicted, the mu-rhythm was significantly decreased ($M=-1.49$, $SD=1.16$) (see Figure 3.2B). There were no differences between conditions in the baseline (all $ts<1$).

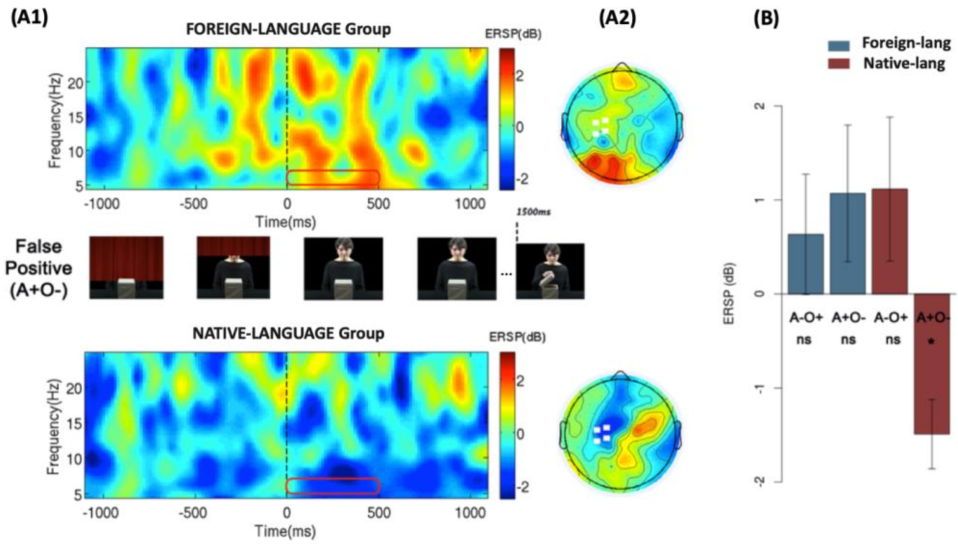

Figure 3.2. ***(A)*** *EEG data of the A+O- test trial for both groups of participants.* ***A1****: Event-related spectral power (ERSP) of the foreign-language group (top) and the native-language group (bottom). Both spectrograms plot the baseline corrected time-frequency data averaged across single trials of each condition and grand-averaged across participants in each group. The plotted data includes the average of channels 30, 36, 37 and 42 located in sensorimotor areas. The average activity within the baseline (400ms interval starting 1000ms before the agent's reappearance) was used to convert the time-varying signal to a decibel (dB) scale (see SI). The vertical line at time 0 indicates the start of the WoA. The red rectangle defines the frequency (5-7Hz) and time (0-500ms) limits over which the analyses were computed (WoA).* ***A2****: Topographic maps showing the average amplitude over the WoA for all channels. White squares indicate the 4 sensorimotor channels that were selected for the statistical analysis.* ***(B)*** *Bars represent the averaged ERSP over the WOA for both trial types and both groups. Error bars show SEM. A paired-sample t-test was computed over each condition to compare the averaged ERSP in the WOA and the averaged ERSP in the baseline window. The symbol "*" indicates a p<0.05 (significant change*

of mu-band power with respect to the baseline) and symbol "ns" means p>0.05 (no significance).

We concluded that participants in the native-language group predicted the agent's actions considering her beliefs and goals. They showed MRD in sensorimotor areas, a neural correlate of action expectation [19], before the agent was going to act (A+O-). In contrast, motor activation was not observed before the agent stayed still (A-O+). This pattern of activation replicated Southgate and Vernetti's (2014) study, likely due to infants' expectations that in familiar contexts, agents, by default, speak their native language. The results demonstrated that the present procedure is sensitive to the generation of online action predictions in infancy. However, the results found in the foreign-language group showed a different pattern of neural activation. No MRD was found in either of the test trial types. These findings suggest that participants in the foreign-language group did not predict the agent's imminent action during the A+O- trials.

Additional analyses were computed to confirm that language familiarity influenced infants' readiness to predict the agent's actions. One way to investigate how infants processed A+O- and A-O+ trials across time is pupillometry. Substantial evidence indicates that, under similar luminance conditions, changes in pupil size reveal changes in the allocation of attention and cognitive load in infants [20]. For example, at 6 months, infants' pupils are more dilated when they are presented with an action that violates the agent's goal than with a rational action [21]. In our study, generating online predictions about the agent's action in A+O- as opposed to A-O- should result in differences in cognitive load within the potential prediction period (WoA), which should be captured by pupillometry. Following our neural findings, we predicted that pupil size would be different between trial types within the WoA for the native-language group, but not for the foreign-language group. In order to investigate pupil changes during the experimental session, the looking behavior of some participants was registered using an Eye tracker. Only 5 participants contributed to the minimum number of trials per condition that was required to be included in the statistical analysis. Due to limited sample size, we tested new participants in the same task, this time only acquiring Eye tracker data. A final sample of 7 participants in the native-language group and 9 participants in the foreign-language group was analyzed. A cluster mass test was computed to explore the presence of clusters of differences in pupil size between A+O- and A-O+ across time. In the native-language group, a significant cluster ($p<0.05$) was found from 11.27s to 11.68s (Figure 3.3), indicating that pupil size changed depending on the presented trial type. As predicted, the cluster started within the WoA, suggesting that differences were driven by infants' online predictions of the agent's actions. Replicating our previous findings with neural data, the foreign-language group showed no significant clusters in the potential prediction period (Figure 3.3; see SI). The pupillometry findings, together with those from MRD, provide converging evidence that infants presented with a native-speaker generated online action predictions considering her goals and visual access to the ball. However, the lack of differences found both with pupillometry and MRD in the foreign-language group indicates that infants did not predict the foreign-speaker's actions. Together, these results suggest that the mechanisms supporting action understanding in infancy can be influenced by top-down processes, such as the recognition of familiar versus unfamiliar agents based on their spoken language.

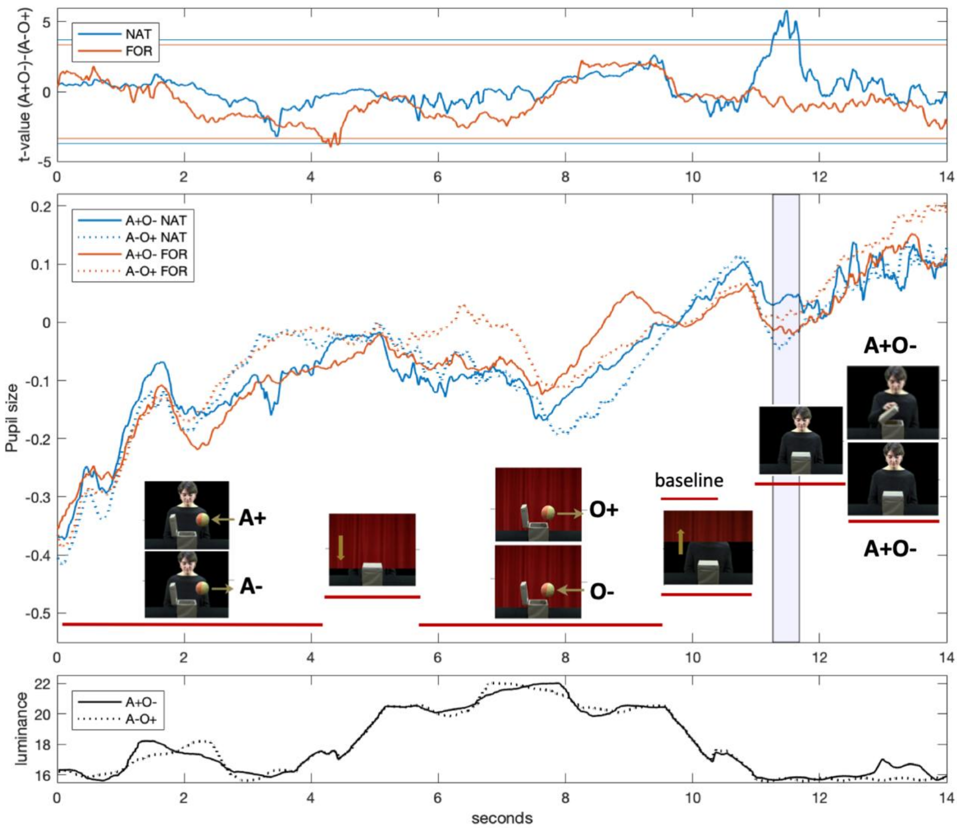

Figure 3.3. (A) *Time course of the t-value describing the statistical difference in pupil size between A+O- and A-O+ trials for both groups (Native-language group – NAT; Foreign-language group – FOR). The difference vector was computed as A+O- minus A-O+ for each participant. The horizontal lines indicate the threshold from which p<0.01 for each group. A cluster mass test with 5000 permutations indicated that the cluster from 11.22 to 11.55s for the native-language group was significant (p<0.05). This window was plotted in Figure 3.3B in a blue rectangle.* ***(B)*** *Time course of the mean pupil size for each group in each condition. The pictures in the bottom of the plot indicate the*

scene corresponding to each time period. The pupil values were baseline corrected, considering a 300ms baseline window that was selected as the window with more valid data within a period from 9.4s (curtain starts lifting) to 10.4s (the agent's face starts being revealed) ***(C)*** *Time course of the luminance vector of the A+O- video and A-O+ video. The luminance was computed as Y = 0.2126*R+0.7152*G+0.0722*B.*

Which mechanisms guide infants' selective action tracking based on the speaker's language? The Like-Me framework [22] proposes that the recognition of self-other equivalences is at the foundation of social cognition. According to this view, infants use their self-experience to form a representational space of actions that guides the mapping between their own bodily acts and those observed in others. In this perception-motor coupling, the mirror neural system plays a fundamental role [23]. For example, 14-month-old infants show greater MRD when observing an agent imitating them, as compared to an agent executing mismatch actions [24]. The current results suggest that the identification of self-other equivalences can be impaired if agents speak an unfamiliar language, as their behaviour considerably mismatch with infants' existing knowledge of the world. We speculate that such a mismatch induces a feeling of dissimilarity with the acting agent, which guides infants' selective action tracking. This idea is consistent with previous findings that infants, and even non-human primates, imitate the actions of familiar agents more faithfully than those of unfamiliar ones [25], [26].

In the first months of life the mechanisms supporting action understanding are still immature. Seven-month-old infants do not systematically mirror others' goal-directed actions [27]. At this developmental stage, tracking others' goals and beliefs and using this information to predict others' actions may be challenging. In the current study we show that 6-month-old infants are ready to do so, but that this ability may be impaired when interacting with a stranger. We suggest that the facilitation of understanding and tracking the actions of more familiar agents privileges the acquisition of reliable cultural knowledge. This idea is supported by previous findings showing that infants encode information presented by a native-speaker more readily than by a foreign-speaker [28]. However, failing to track the actions of foreign-speakers may not be an optimal strategy in certain contexts. In a competitive situation, for example, predicting the actions of strangers is crucial. The current research raises the question of how selective action prediction based on familiarity develops as the mechanisms supporting social cognitive abilities mature. The present investigation provides central knowledge to our understanding of two fundamental processes of social cognition that so far have been investigated separately: the precursors of social categorization and the mechanisms supporting action understanding.

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3.3. SUPPLEMENTARY MATERIALS

This file includes:

Materials and Methods

Supplementary Text

Figures 3.S1 to 3.S3

3.3.1. Materials and Methods

a. Main Study (Electroencephalography)

i. Participants

Analysis included 20 6-month-old infants; 10 infants were assigned to the Native-language group (mean age 6 months and 20 days, range 6.04 – 7.05; 5 females) and 10 infants were assigned to the Foreign-language group (mean age 6 months and 12 days, range 6.01 – 7.0; 6 females). Forty additional participants were tested but excluded from analysis due to crying (8), experimental error (4) or because they did not contribute the minimum number of 3 trials per condition required (28) (due to movement artefacts or fussiness). Participants were recruited by visiting maternity rooms at two private Hospitals in Barcelona, Spain (Hospital Quirón and Clínica Sagrada Família). All participants were healthy, full-term infants (> 37 GW). The research reported in this manuscript was conducted in accordance with the principles expressed in the Declaration of Helsinki and approved by the local ethical committee (The Clinical Research Ethical Committee of the Parc de Salut Mar). Written informed consent was obtained from the participants' caregiver before the experiment was conducted.

ii. Procedure and Stimuli

Participants were tested in a sound-attenuated and darkened room at the "Laboratori de Recerca en Infància" (Center for Brain and Cognition, Universitat Pompeu Fabra). Participants' behaviour during the session was recorded using a Sony HDR-HC9E camera (temporal resolution: 25 frames/s). Infants sat on a caregiver's lap at ~65 cm from a 23’’ screen (1920 x 1080 pixels). Caregivers were asked to close the eyes when the videos started. Videos were projected onto the screen using Psychotoolbox-3 in MATLAB (The MathWorks).

The experiment was structured in three phases presented in the following order: familiarization, presentation and test.

Familiarization

Infants viewed 4 trials of 7 seconds in which an actress always held a true belief about a location of a ball. First, we presented infants with the A+O+ trial in which the actress demonstrated her goal of reaching a ball (Movie S1). The actress appeared in the center of the screen in front of a box. When the lid of the box opened, a ball appeared from the right side of the screen and entered into the box. Then the lid of the box closed and the actress reached towards the box. Following the A+O+ trial we presented infants with the A-O- trial, in which the actress did not reach for the (absent) ball (Movie S2). The trial started with the actress in the center of the screen in front of the box. When the lid of the box opened, the ball appeared inside the box and jumped out until disappearing at the right side of the screen. The lid of the box then closed and the actress remained still until the end of the trial. Following the end of the second trial, the two trials were presented again in the same order. Each of the 4 trials were preceded by an attention getter including a circular flash looming at the center of the screen (3s; *attention getter scene, Figure 3.S1*).

Presentation

An actress appeared at the center of the screen telling a story while making eye contact with participants. For the infants in the Native-language group the agent spoke either Spanish (~18s; Movie S3) or Catalan (~20s; Movie S4), depending on the participants' dominant language (7 viewed a Catalan-speaker). For the participants in the Foreign-language group the agent spoke an unfamiliar language for infants: German (~23s; Movie S5). The actress was highly proficient in the three languages. The presentation trial was preceded by an attention getter scene (3s).

Test

Infants saw multiple times two trial types of 14 seconds that appeared in random order until they lost attention. The trials consisted in the same scene as in Familiarization, except for that we manipulated the actress' belief about the location of the ball. In A+O- trial (Movie S6) the actress first witnessed that the ball jumped into the box (A+). Then the lid of the box closed and a curtain came down hiding the actress. This time, the lid of the box opened and the ball jumped out of the scene (O-). The curtain lifted and the actress reappeared at the back of the display. She stayed 1500ms still (*potential prediction period*) and then she reached towards the empty box (reach outcome; 1500ms). In the A-O+ trial (Movie S7), the actress first witnessed that the ball jumped outside of the box and disappeared from the scene (A-). Then the lid of the box closed and a curtain came down hiding the actress. When the lid of the box opened, the ball appeared again from the right side and jumped into the box (O+). The curtain lifted and the actress reappeared. As in A+O- she stayed still 1500ms (potential prediction period), but then she remained still (no reach outcome; 1500ms).

EEG processing

The brain neural activity was recorded using continuous recordings of electroencephalography with a Geodesic Sensor Net composed of 128 electrodes (Electrical Geodesic, Eugene, USA). Data were recorded with respect to the vertex electrode, sampled at 500Hz and stored on computer disk. Triggers were sent through a parallel port from Matlab to the EEG amplifier and synchronized with the acquisition of EEG data. Triggers were sent at the start and at the end of each trial and each attention getter. A trigger was also sent in test trials at the point where the actress reappeared at the scene, after the curtain had lifted (*test trigger*). The test trigger defined the start of the potential prediction period.

EEG analysis

EEG data were referenced to the average of all electrodes and band-pass filtered from 1 to 60 Hz, with a notch filter in 50 Hz. The electric signal was then segmented offline into EEG trials with 2500ms pre-stimulus and 2500ms post-stimulus onset duration. Trials in which the infant did not attend to the video in the critical parts were rejected from further analyses. Movement and electrical artifacts of the recorded EEG were identified with NetStation Tools filters and rejected trial-by-trial by manual inspection. Time-frequency analyses were performed by applying a continuous wavelet transformation from 4 to 30 Hz to free-artifact trials in each channel, using the function newtimef from EEGLAB toolbox (cycles = [3 0.5], window length = 400, padratio = 4). To eliminate distortion created by the wavelet transform, the first and last 500 ms of each segment were removed. Following Southgate & Vernetti (2014), a 400ms period beginning 1000ms before the test trigger was selected as a baseline. In both trial types the event occurring within the baseline was the curtain lifting before revealing the actress. Averaged activity within the baseline period was used to convert the time-varying signal to a decibel (dB) scale, using the formula $10*\log_{10}(\text{power}(t)/\text{power}(\textit{averaged baseline}))$, where t refers to the signal at each time point. Two time windows were considered for the analyses: the baseline and a 500ms window starting at the test trigger (WoA). The WoA defined the beginning of the potential prediction period, in which the actress remained stationary in both trial types and infants could potentially predict her subsequent behaviour. Following Southgate & Vernetti (2014), we analysed activity across the frequency range from 5 to 7 Hz in sensorimotor areas (electrodes 30, 36, 37 and 42), which includes the presence of motor activation in 6-month-old infants. Average ERSP data for each participant in baseline and WoA were calculated by taking the mean across trials, electrodes and frequency range of interest. To plot the results, we grand averaged the data across participants.

Southgate & Vernetti (2014) found that 3 free-artifact trials per condition are enough to identify motor activation reflecting infants' prediction of the actions of the agent. Infants with less than 3 valid artifact-free trials in either condition were excluded. The Native-language group contributed with an average of 4.1 trials in A+O- (range = 3 - 6) and 4 trials in A-O+ (range = 3 - 7). The Foreign-language group contributed with an average of 3.8 trials in A+O- (range = 3 - 5) and 4.3 trials in A-O+ (range = 3 - 7).

b. Additional analysis (Eye tracker)

First, we explored if infants in each group processed differently the test trials depending on the agent's (false) belief about the location of the ball. We assumed that, in case infants generated predictions about the agent's actions, their cognitive load would be higher when processing the trials in which the agent would act, as compared to the trials in which she would stay still. Following previous literature, we used pupillometry as a measure of cognitive load (Sebastián-Gallés, 2013).

Second, we explored if infants in each group were similarly engaged to the test trials. To test overt visual attention to the trials, we measured infants' looking time at each area of interest (AoI) of the video across time.

i. Participants

Main Study

Participants represented a subgroup of participants described in section 1.1.1, from which we recorded eye-tracking data. A total of five participants were included in the analysis (Native-language group = 2; Foreign-language group = 3). Sixteen additional participants with eye-tracking data were excluded for not contributing to the minimum number of 3 trials per condition required (due to loss of data, bad calibration or fussiness). Due to the limited sample size, we tested a new group of participants in the same task, this time acquiring eye-tracking data without measuring infants' neural activity.

Additional participants

Thirteen participants were tested using the same task as in the Main Study, but without wearing an EEG cap. This time, we only recorded infants' looking behaviour using an eye-tracking. Seven participants were assigned to the Native-language group and six were assigned to the Foreign-language group. Twenty-seven additional participants were tested but excluded from analysis because they did not contribute the minimum number of 3 trials per condition required (due to data loss, bad calibration or fussiness). Participants were recruited by visiting maternity rooms at two private Hospitals in Barcelona, Spain (Hospital Quirón and Clínica Sagrada Família). All participants were healthy, full-term infants (> 37 GW). The research reported in this manuscript was conducted in accordance with the principles expressed in the Declaration of

Helsinki and approved by the local ethical committee (The Clinical Research Ethical Committee of the Parc de Salut Mar). Written informed consent was obtained from the participants' caregiver before the experiment was conducted.

Final sample

A total of 9 participants in the Native-language group (mean age 7 months, 14 days, range 6.09 – 7.27, 6 females) and 9 participants in the Foreign-language group (mean age 7 months, 11 days, range 6.01 – 7.30, 6 females) were included in the analysis.

ii. Procedure and Stimuli

The same stimuli described for the Main Study was used. The procedure was the same as the one described for the Main Study, except for that we did not record neural activity for the extra group of participants (section a.ii pages 72-74).

Eye tracker processing

A Tobii X120 Eye Tracker was used in standalone mode and with a sampling rate of 120 Hz. Eye-tracking data were saved with a set of triggers that defined which part of the experiment was being presented to participants. The triggers corresponded to the ones described in section 1.1.2.4 and allowed us to know when each trial started and ended. Prior to the beginning of the experiment, a 5-point calibration was carried out. Participants that did not provide accurate data for at least 4 points were rejected from analysis.

iii. Eye tracker analysis and results

Data from right and left eye were averaged when both eyes had valid data. In cases in which only one eye provided valid data, we used the signal from the corresponding valid eye. Eye-tracking data was segmented across trials. Trials with less than 70% of valid data were excluded from the analysis. The threshold of 70% was defined based on Cesana-Arlotti et al., (2018). Following our previous criteria with EEG data, participants that contributed to less than 3 trials per trial type were excluded from analysis.

Analysis Pupillometry

Pupil size was baseline corrected across trials before the analysis. For each trial, the beginning of the baseline period corresponded to the moment in which the curtain started lifting (-1600ms before the test trigger) and ended when then the face of the actress started being revealed (-600ms before the test trigger). During this period, the same stimuli appeared in both trial types. Within the baseline period we defined a 300ms baseline window that was used for baseline correction. Valid data samples within the baseline window were averaged and subtracted to the rest of the pupil data. The baseline window was defined as the window within the baseline period with higher percentage of data samples in which participants looked at the area of interest of the screen. The area of interest was defined as the area including the stimuli (*all stimuli*; see *Figure 3.S2-A*). To identify if infants were looking at this area, we used the temporal dynamics of gaze x and gaze y coordinates. The reason to define a flexible baseline window was to get the baseline with more reliable data available in each trial and for each participant. If the percentage of samples within the baseline window was < 70%, the trial was rejected. Due to this criterion, two of the extra participants in the Native-language group were excluded from the analysis. Before statistical tests, data of each participant were averaged for each trial type across valid trials. The Native-language group contributed with an average of 4.43 trials in A+O- (range = 3 - 10) and 4.86 trials in A-O+ (range = 3- 10). The Foreign-language group contributed with an average of 5.22 trials in A+O- (range = 3 - 8) and 6.11 trials in A-O+ (range = 3 - 8).

Following the existing literature on infant pupil dilation (Cesana-Arlotti et al., 2018), we computed a cluster mass test to explore the presence of clusters of differences in pupil size between A+O- and A-O+ across time. The test was computed for each group of participants separately. First, for each group, we computed a *difference vector* across time and participants defined as pupil size in A+O- minus pupil size in A-O+. We then computed the t-values of the difference vector across time bins considering only the participants that provided data in each time bin. Due to the abrupt changes in the t-values vector originated from missing data of some participants in some time bins, the vector was smoothed using a moving average filter with the function smooth from Matlab. The moving average filter was computed every 75ms (span = 9), the default value that the Tobii I-VT fixation filter uses to interpolate missing data (Anneli, 2012). Next, we identified clusters as the sum of t-values thresholded at p=0.01(two-tailed) on consecutive time bins. For each group of participants, we defined the larger cluster as the main cluster. We then tested the significance of the main cluster by computing the same analysis on 5000 permutations. The permutations were computed by randomly assigning the participants to the trial types (A+O-/A-O+). In each permutation, the t-values vector was smoothed with the same filter as the one used in the original test. Finally, we checked if the main cluster of each group of participants was greater than 95% of what we would be found by chance. If the main cluster was greater than 95% of the permutation clusters, we reported the cluster as being significant. Thus, a significant cluster refers to a cluster that is unlikely to be found by chance.

Results Pupillometry

A significant cluster for the Native-language group was found within the window from 11.27s and 11.68s. During the cluster, the same stimuli was presented in both trial types (the actress staying still). The stimuli that preceded the potential prediction period was also the same in both trial types (the curtain lifting). Given that participants were presented with exactly the same stimuli before and during the two trial types, differences in pupil size are unlikely to be originated by differences in luminance. Instead, they likely reflect differences in participants' cognitive load. In fact, the beginning of the significant cluster matched with the potential prediction period or WoA. Within this period, in our main study participants presented with a native-speaker showed to recruit their sensorimotor areas in A+O-, but not in A-O+. The fact that a significant cluster emerged within the WoA for the native-language group strongly suggests that changes in pupil size captured differences in infants' predictions about the agent's action.

Further evidence for the role of action prediction in changes of pupil size is that, consistently with the results of our main study, no significant clusters were found for the Foreign-language group within the potential prediction period. However, a significant cluster for the Foreign-language group was found from 4.18s to 4.35s. Although during this period the stimuli of A+O- and A-O+ was the same (curtain starting to go down), the period was preceded by a different scene. In A+O-, before the curtain started coming down, the ball was inside the box at the middle of the screen. In contrast, the ball in A-O+ was disappearing at the right part of the screen. Given that no theoretical explanation about differences in cognitive load would predict this cluster, and that the stimuli that preceded the cluster was different, it is likely that the cluster simply resulted from differences in luminance or noise.

Analysis AoIs

We defined 3 areas of interest (AoI; See *Figure 3.S2-B*), each corresponding to an important component of the stimuli: *face*, *box* and *ball*. We then computed the percentage that infants looked at each AoI across time for each trial. The percentage of looking time was calculated considering windows of 25 ms. For each trial type and participant, the time course of the looking time percentage at each AoI was averaged across valid trials. The Native-language group contributed with an average of 4.44 trials in A+O- (range = 3 - 11) and 4.89 trials in A-O+ (range = 3 - 10). The Foreign-language group contributed with an average of 5.44 trials in A+O- (range = 3 - 8) and 6.67 trials in A-O+ (range = 4 - 9).

To explore differences looking to each AoI between groups, we computed a cluster mass test following the same procedure as the one used with pupillometry. Because the goal of the analysis was to compare overt visual attention between groups, this time the cluster mass test was performed between-participants for each trial type and each AoI. In order to increase the power of the cluster mass test for detecting differences between groups, this time we identified clusters as the sum of t-values thresholded at p=0.05 (two-tailed) on consecutive time bins. A cluster mass test with the same parameters was also computed to explore if the two groups looked differently to the all the screen. We computed the test for each trial type comparing the percentage of valid data that each group provided in the corresponding trial type.

Results AoIs

No significant clusters were found for A+O- and A-O+ trials in any of the computed tests. These results indicate that both groups of participants tracked the stimuli they saw in a similar manner. Visual inspection of *Figure 3.S3* suggests that both groups of participants showed a dynamic looking pattern, focusing at the more relevant areas of the ongoing video. Participants' majority of gazes were oriented to the box in the moment that the ball either entered inside or outside of the box, or when the box opened/closed. Participants looked longer to the ball area in the moment that the ball either was jumping to the box or jumping outside of the box. Regarding the agent, participants looked more at the agent’s face during the ball jumps when the agent was present rather than when she was not. During the potential prediction period, when the agent stayed still, participants tended to look longer at the agent’s face than at the other areas of the video. During the outcome of each video (action vs. no action), participants maintained their preference for the face area, and they also looked at the ball area when the agent acted (A+O-). The data suggest that participants in both groups attended to the video and tracked the relevant information to predict the agent’s behavior in a similar way.

3.3.2. Supplementary Text

a. Brief general discussion

The pattern of results found with pupillometry is consistent with the pattern of results found with neural activity (EEG). They indicate that participants in the native-language group generated online predictions about the agent’s behavior: they expected the agent to act in A+O-, but not in A-O+. Neither pupillometry nor neural activity provide any evidence that participants in the foreign-language group predicted agent’s actions. One possible interpretation of the results was that participants in the foreign-language group attended less at the stimuli as compared to participants in the native-language group, increasing the likelihood of missing information about the location of the ball. Participants' overt visual attention did not differ between groups: both groups tracked in a similar way the relevant areas of the stimuli. The results suggest that both groups of participants processed a similar amount of information about the location of the ball and the agent's perceptual state. Thus, a lean interpretation such as that infants missed perceptual associations of the stimuli is unlikely to account for the lack of prediction found in the foreign-language group. The eye tracker results support the richer interpretation that we proposed in the main text: the mechanisms supporting action understanding at 6 months of age can be influenced by top-down processes, such as the recognition of native-speakers (familiar) versus foreign-speakers (unfamiliar).

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3.3.3. Supplementary Figures

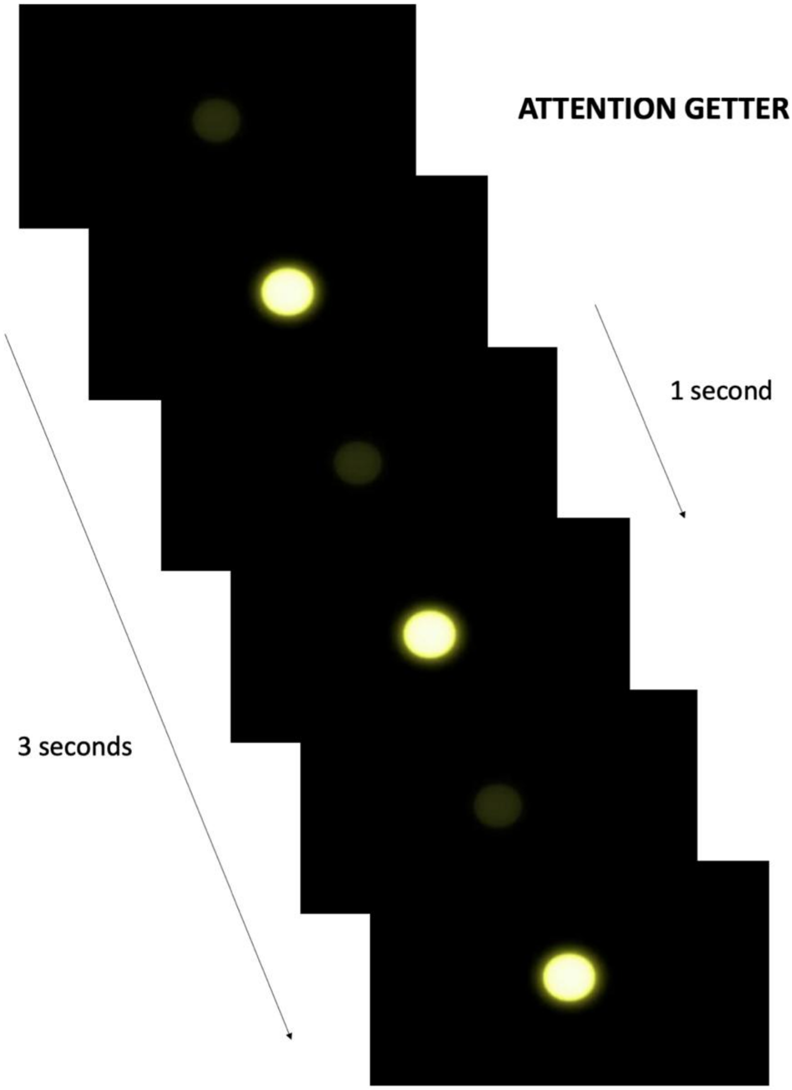

Figure 3.S1. *Representation of the attention getter. A circular flash loomed at the center of the screen three times. Each looming had a duration of 1 second. The total duration of the attention getter was 3 seconds. The attention getter scene was presented before evert trial.*

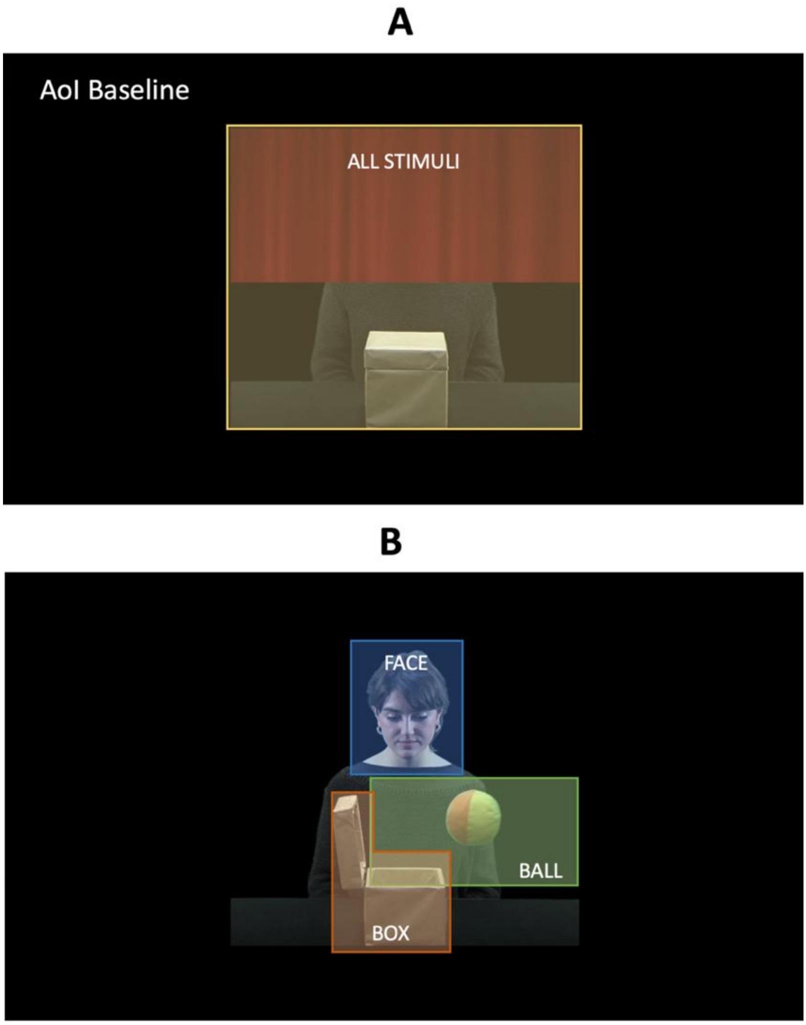

Figure 3.S2. *Representation of the Areas of Interest (AoI) of the stimuli. The black window of each figure represents the screen that was located in front of the participants (A) The yellow square represents the AoI used to define the baseline for pupillometry. (B) Each rectangle represents one of the three AoIs (blue: face, green: ball, orange: box) used to explore infants' tracking of the ongoing stimuli.*

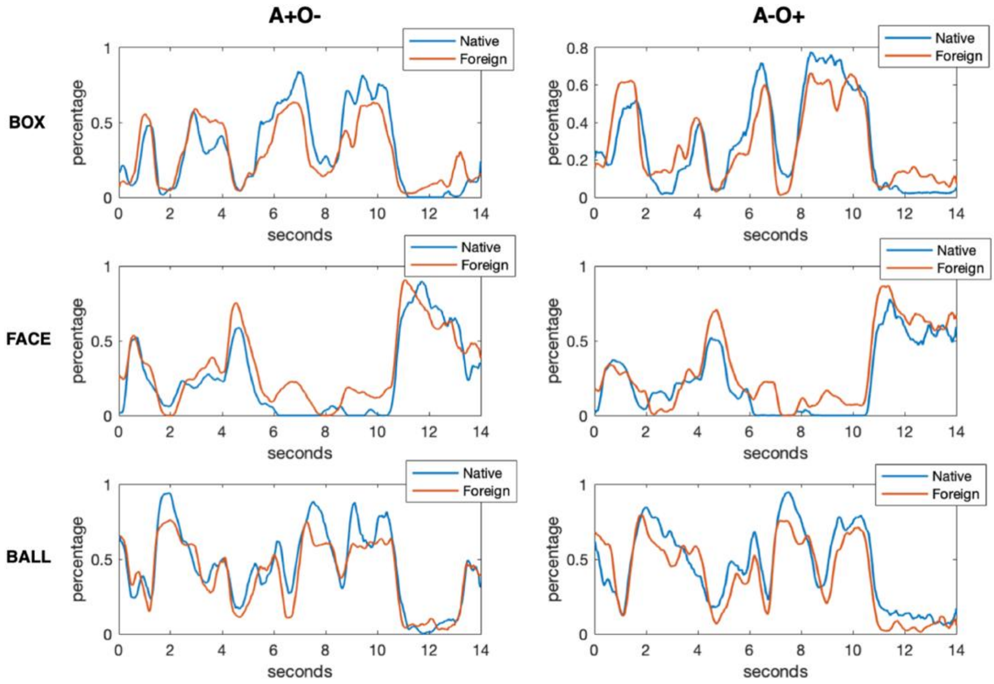

Figure 3.S3. Time course of the percentage of looking time (y axis) at each AoI for A+O- (first column) and A-O+ (second column). The percentage in each time bin was calculated as the number of frames that participants looked inside each AoI divided by the total number of valid frames in the corresponding time bin. Each time bin represented a window of 25ms. Values in the x axis represent the time course of a trial, starting at 0 and with a duration of 14 seconds. Each rectangle plots the mean percentage of the native-language group (blue) and the mean percentage of the foreign-language group (orange). The first raw represents the percentage across time that participants looked inside the *box*. The third raw represents the percentage across time that participants looked inside the *face*. The fourth raw represents the percentage across time that participants looked inside the *ball*.

4. EXPERIMENTAL PART III: Language background shapes third-party communication expectations in 14-month-old infants

Colomer M. & Sebastian-Galles N. (under review). Language background shapes third-party communication expectations in 14-month-old infants. *Cognition*

4.1. Title page

Language background shapes third-party communication expectations in 14-month-old infants

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Abstract:

Infants expect native and non-native speech to communicate, i.e. to transfer information between third-parties. Here, we explored if infants understand that communication depends on the use of shared conventional systems (e.g. speaking the same language), and if linguistic input (monolingual vs. bilingual) influences infants' expectations about who can communicate with whom. Fourteen-month-old monolingual and bilingual infants were presented with a foreign-language speaker (*communicator*) and a native-language speaker (*recipient*). At test, the communicator uttered a foreign-language sentence to inform the recipient about her preference for one of two objects she could not reach. Bilinguals looked longer at screen when the recipient gave the non-preferred rather than the preferred object to the communicator, indicating that they expected her to understand the communicator's message. Monolinguals looked similarly at both outcomes, showing that they did not expect effective communication between speakers of different languages. The results suggest that infants expect speech to convey information between third-parties only when individuals share the same conventional system. In addition, the results suggest that, unlike

monolinguals, bilinguals expect others to have access to multiple conventional systems.

4.2. Introduction

By their first birthday, infants understand that communication functions as a mechanism to transfer information from one agent to another. Six to twelve-month-old infants expect speech, but not non-speech sounds, to communicate between third parties (Martin, Onishi, & Vouloumanos, 2012; Vouloumanos, Martin, & Onishi, 2014; Yamashiro & Vouloumanos, 2018). In a recent study, Vouloumanos (2018) found that this sensitivity to the communicative nature of speech is not restricted to infants' language experience. Infants expect foreign languages to transfer information between peers, suggesting that they view language as a universal mechanism to communicate.

Effective verbal communication, however, is constrained to the use of shared conventional systems (Clark, 1996). That is, a recipient will be able to interpret speech from a communicator only if she comprehends the language used to convey the message. In Vouloumanos (2018), when infants saw a communicator speaking to a recipient, they did not know the languages that the recipient could speak. Still, participants expected the recipient to understand the communicator irrespective of whether she conveyed the message producing native or foreign speech. These results raise the question of whether infants appreciate that communication is constrained to the used of shared conventional systems, or whether this appreciation requires the support of more fully developed social and linguistic capacities. The current study aimed at addressing this issue.

Critical for communication is the assumption that words are conventional symbols that are shared across speakers of a linguistic community (Sabbagh & Henderson, 2007). Sensitivity to the shared conventional nature of words emerges early in life (Diesendruck, 2005). By their second birthday, toddlers assume that speakers share the knowledge of object labels (Henderson & Graham, 2005). However, they do not expect members of the same linguistic community to share non-conventional information such as desires for objects (Graham, Stock, & Henderson, 2006), or idiosyncratic personal facts (Diesendruck & Markson, 2001). Even at younger ages, 9 and 13-month-old infants expect speakers to share the same labels for objects, but not to prefer the same objects (Buresh & Woodward, 2007; Henderson & Woodward, 2012).

Importantly, infants' assumptions of conventionality seem to go along with an appreciation that different languages follow distinct conventional systems. By the second year of life, toddlers use language in context-sensitive ways. Bilinguals, for instance, tend to choose to speak the language that the recipient of the message primarily speaks, even when it is not their dominant language (Deuchar & Quay, 1999; Genesee, Boivin, & Nicoladis, 1996). Already at 13 months, both monolinguals and bilinguals represent words as conventions that should not be generalized to speakers of different languages (Henderson & Scott, 2015; Scott & Henderson, 2013).

These findings on infants' sensitivity to the constraints of conventionality support the possibility that infants consider the languages people speak to reason about who can communicate with whom. In Vouloumanos (2018), both monolingual and bilingual infants expected foreign languages to convey information between third-parties (Vouloumanos, 2018). Here, we predicted that monolingual infants would not expect a foreign language to communicate if the recipient has shown to be a native-speaker. However, bilingual infants may expect speakers of different languages to engage in effective communication. In fact, previous studies found that experience to at least two languages influences toddlers' expectations about the languages people may know (Pitts, Onishi, & Vouloumanos, 2015). Twenty-month-old monolinguals expect agents to comprehend only one language. Bilinguals, however, are more open to the possibility that others have access to multiple communication systems.

Here, we presented 13-to-15-month-old infants with communicative interactions between speakers of different languages in order to explore their sensitivity to the constraints of communication. We tested both monolinguals and bilinguals to investigate the role of language experience in determining who can communicate with whom. Adapting Martin et al., (2012), we initially presented participants with an actress that spoke Hungarian (foreign-speaker) and another actress who spoke Catalan or Spanish (native-speaker). Then, the foreign-speaker (*communicator*) selectively grasped one of two objects (*target*) displayed in the video. Next, the other actress (*recipient*) showed no preference by grasping both objects. At test, the communicator could no longer reach the objects. She used speech (Hungarian) to inform the recipient about her preference for the target, who gave either the target or non-target to the communicator. We measured infants' looking times at each outcome, assuming they look longer at events that violate their expectations. If monolinguals expected communication to be constrained by the language people speak, they should look similarly at both outcomes. However, if bilinguals considered the possibility that the recipient could comprehend more than one language, they should look longer at the non-target outcome.

4.3. Method

Participants

We recruited 48 infants; twenty-four monolinguals (M: 14 months and 13 days, range: 13;26 to 15;15, Female: 12) and 24 bilinguals (M: 14 months and 10 days, range: 13;20 to 15;13, Female: 11). A questionnaire (adapted from Bosch & Sebastián-Gallés, 2001) was administered to determine infants' language background. Monolingual infants were exposed to more than 85% to their dominant language (Mean: 95.96%, range: 86% to 100%). Bilingual infants were exposed to their main language up to 75% of the time

(Mean: 63.8%, range: 50% to 75%). Twenty-four additional participants were tested but excluded from analysis due to fussiness or crying (5 Mon; 8 Bil), experimental error (4 Mon; 2 Bil), parental interference (2 Bil), looking at the screen for the maximum amount of time during both outcomes (1 Bil), or exposure to dominant language between 76% and 85% (2). Participants were recruited by visiting maternity rooms at two private Hospitals in Barcelona, Spain. All participants were healthy, full-term infants (> 37GW). The research reported in this manuscript was conducted in accordance with the principles expressed in the Declaration of Helsinki and approved by the local ethical committee (Clinical Research Ethical Committee Parc de Salut Mar). Written informed consent was obtained before the experiment was conducted.

Procedure and Materials

Participants were tested in a sound-attenuated room at Center for Brain and Cognition (Universitat Pompeu Fabra). Participants' behaviour was recorded using a Sony HDR-HC9E camera (temporal resolution: 25 frames/s). Infants sat on the caregiver's lap at ~65cm from a 23'' screen (1920 x 1080 pixels). Caregivers were asked to close the eyes when the videos started. Videos were projected onto the screen using Psychotoolbox-3 in MATLAB.

The experiment was structured in four phases presented in the following order: introduction, familiarization, pretest and test (Figure 4.1).

Introduction

Two actresses appeared at the center of the screen one after the other telling a story: one actress spoke infants' native language – Catalan (~26s; Movie S1) or Spanish (~23s); the other actress spoke a foreign language – Hungarian (~25s; Movie S2). The language of the native-speaker depended on the participants' dominant language (16 bilinguals and 12 monolinguals viewed the Catalan-speaker). A third part of the participants in each group saw first the foreign-speaker, followed by the native-speaker. The rest of participants saw the videos in the reverse order. Each trial started with a grey background with a small black cross at the center of the screen (1.5s; *cross scene*).

Familiarization

The actress that spoke Hungarian in the introduction (hereafter *communicator*) was situated behind a wall. Her face and arms were visible through a window at the back of the display and two objects were situated in front of her (a red funnel and a green liquid container). Participants viewed three identical trials in which the communicator's preference for one of the two objects (*target*) was presented (Movie S3). The target and location of the target were counterbalanced in each language group. At each trial, the communicator initially looked at a neutral central point of the display (1.5s). She then looked at the object on the left (1.5s) and then at the object on the right (1.5s). Afterwards, she looked and reached for the target (2s) and lifted it in front of her face (1.5s). She then tilted the object back and forth (2s) and remained doing the same action until participants looked away for 2 consecutive seconds or 18 seconds elapsed. Each trial was preceded by a cross scene (first trial: 1.5s; other trials: 1s).

Pretest

The actress that spoke a native language in the introduction (hereafter *recipient*) was visible on the right side of the display. The communicator was absent. The red funnel and green container were located in the same position as in the familiarization trials (in front of the recipient). The recipient demonstrated to have no preference for one object. She initially looked at a neutral center point of the display (1.5s). She then looked at the object on the left (1.5s) and at the object on the right (1.5s). Afterwards, she looked back at the object on the left (1s), reached for and lifted it (2s), tilted it back and forth (2s), placed it back into the floor (1.5s) and removed her hand (1s). The recipient then repeated the same movements with the other object. Then, she remained still (1s) and repeated the interaction with the two objects again. The pretest trial was preceded by a cross scene (1.5s; Movie S4).

Test

Both the communicator and recipient appeared in the scene. In the window at the back of the display only the face of the communicator was visible, and she could no longer reach the objects. The communicator looked neutrally at the centre of the two objects (2s). She then looked at the object on the right (2s), then at the other object (2s) and then she made eye contact with the recipient (1s). The communicator said twice “Ide adnád a “bityét”?” in Hungarian (“Would you give me the “bityét”?) (5s). Participants were then presented with two outcomes, in which the recipient looked at (1.5s), reached for (1.5s) and approached (1s) either the target (*target outcome;* Movie S5) or non-target (*non-target outcome;* Movie S6) to the communicator. At each outcome the video paused with the two actresses looking at the raised object until infants looked away 2 consecutive seconds, or until 40 seconds elapsed. The outcome order was counterbalanced across participants in each language group. Each outcome was preceded by a cross scene (1.5s) with a bell sound.

Coding and Data Analysis

Following Sommerville, Schmidt, Yun, & Burns (2013) statistics were computed on participants' looking time to the screen at the end of each test outcome until they looked away for 1 second consecutively or 40 seconds elapsed[1]. Recordings were coded by a primary coder, who was unaware of the hypotheses of the study, and the first author. A high inter-coder agreement was achieved (ICC > .99). Reported data correspond to the coding of the primary coder. Before statistical tests, data were log-transformed to better approximate a normal distribution (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016). A Shapiro-Wilk normality test was run on each data subset of outcome type, confirming that our data followed a normal distribution. All statistical tests were parametric

[1] The same results were found if computing statistics on participants’ looking time after they looked away 2 seconds.

and two-tailed. To facilitate reader's comprehension, Figure 2 displays participants' looking times before log-transformation.

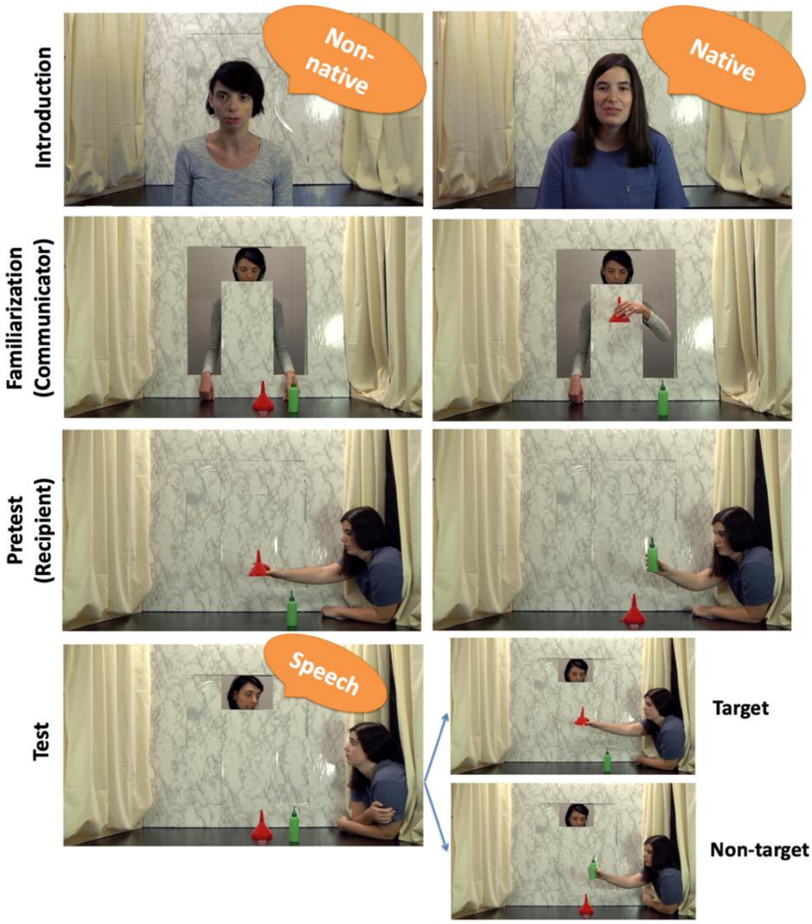

Figure 4.1. *Stimuli. (Introduction) Trials in which each actress tells a story. The communicator speaks a foreign-language (left-column) and the recipient speaks a native-language (right-column). (Familiarization) Trial in which the communicator selectively grasps the target object. (Pretest) Trial in which the recipient grasps both objects. (Test) Trial in which the communicator utteres (foreign) speech to inform the recipient about her preference for the target (left-column). The recipient then approaches either the target (target outcome) or the non-target (non-target outcome)*

to the communicator. The target object, the location of the target and the order of presentation of the outcomes were counterbalanced.

4.4. Results

We computed a mixed ANOVA with outcome type as a within-participants factor (target; non-target) and linguistic profile as a between-participants factor (Monolinguals; Bilinguals). A significant interaction between the two factors was found ($F(1,46)= 6.10$, $p= .017$, $\eta_p^2 = 0.12$). Paired t-test indicated that bilingual infants looked significantly longer at screen ($t(23)= 3.77$, $p < .01$) in the non-target outcome (M= 20.51s, SD= 9.74) than the target outcome (M= 14.19s, SD= 6.59). However, monolingual infants looked equally when the recipient handled either object ($M_{non\text{-}target}$= 17.39s, $SD_{nontarget}$= 9.88; M_{target}= 17.01, SD_{target}= 7.96; $t(23)= -0.32$, $p= .75$; Figure 2). An ANOVA with linguistic profile as between-participants factor and mean looking time in familiarization trials as dependent variable found no differences between groups ($F(1,46)= 1.45$, $p= .23$, $\eta_p^2 = 0.031$), showing that differences in test were not driven by general attentional differences.

A simple linear regression model was calculated to investigate if infants' difference in looking time (log-transformed) between outcomes (non-target - target) could be predicted by the percentage of exposure to infants' dominant language (range: 50% to 100%). The model included previously excluded participants (2) because of their linguistic profile (exposure to main language between 76% and 85%). A significant relationship between looking difference and percentage was found (F(1,48)= 6.031, p= .018; R^2 = .093). The model indicated that the higher was the exposure to infants' main native-language (more "Monolingual"), the smaller was the difference in looking time between the non-target outcome and the target outcome (Figure 2).

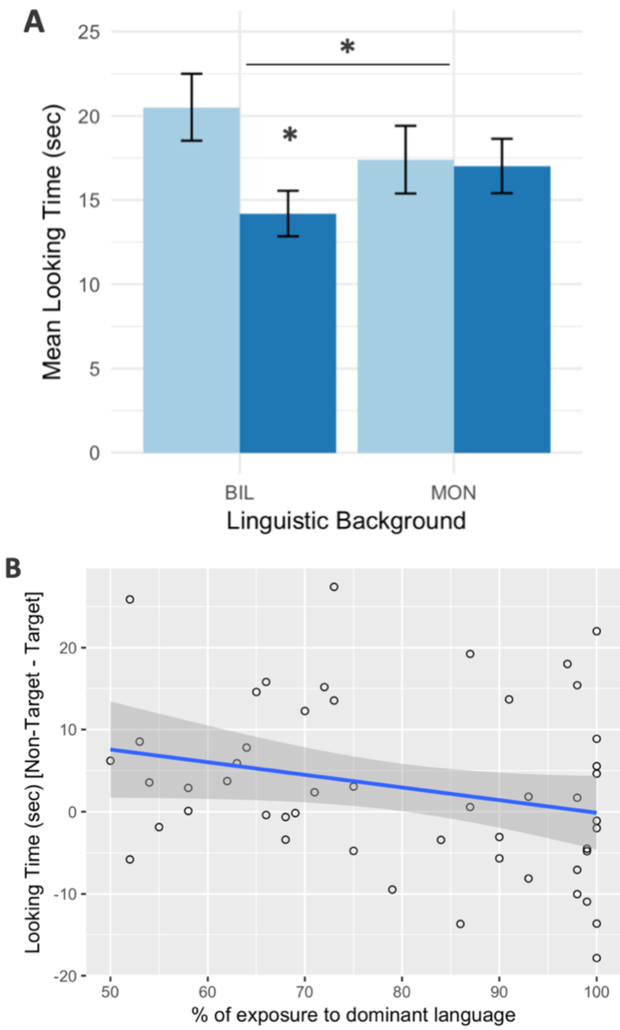

Figure 4.2. *Results.* ***(A)*** *Mean looking time (in seconds) and standard error of the mean for each outcome type (Target: dark blue, Non-target: light blue) for each language group (Bilinguals: left, Monolinguals:*

right). An asterisk (*) represents significance at $p < .05$. ***(B)*** *Linear regression model of the difference in looking time between the Non-target outcome and the Target outcome (Non-target - Target) across the percentage of exposure to the dominant language. Each small circle represents data from a participant. The blue line represents the linear regression function. The blur area around the line represents the 95% confidence level interval for predictions from a linear model ("lm").*

4.5. Discussion

We investigated if 14-month-old monolinguals and bilinguals expect information to be efficiently conveyed between speakers of different linguistic communities. A communicator (foreign-language speaker) used speech to inform a recipient (native-language speaker) about her preference for a target object. Bilingual infants looked significantly longer at the screen when the recipient presented the communicator with the non-target instead of the target, suggesting that they expected the recipient to understand the communicator's message. In contrast, monolinguals looked similarly at screen in both outcomes, suggesting that they did not expect speech to transmit information between speakers of different languages.

Previous studies found that by the end of the first-year infants expect both native and foreign speech to transfer information between third-parties (Martin et al., 2012; Vouloumanos, 2018). Here, we extended these findings by showing that infants expect communication to be constrained to the use of shared conventional systems. In addition, our results indicate that the language environment infants are exposed to influences their expectations about who can communicate with whom. Bilinguals expect speech to transfer information between third-parties irrespective of the language they speak; monolinguals do not.

Why bilinguals expected the recipient to make sense of the communicator's message? One possibility is that, unlike monolinguals, bilinguals did not expect different languages to follow distinct conventional systems. However, previous findings suggest the opposite: thirteen to 24-month-old bilinguals tend to have an enhanced sensitivity about the constraints of conventionality, as compared to monolinguals (Byers-Heinlein, Chen, & Xu, 2014; Henderson & Scott, 2015). A more plausible possibility is that, in addition to considering the constraints of conventionality, bilinguals expected others to comprehend more than one language. In fact, twenty-month-old bilinguals, unlike monolinguals, find plausible that people have access to multiple communicative systems (Pitts et al., 2015). The current results suggest that at younger ages not only bilinguals consider that others may comprehend multiple languages; they assume that speakers of their linguistic community will comprehend foreign-languages.

One alternative interpretation of the current results is that bilinguals expected members of different linguistic communities to cooperate, but monolinguals did not. Previous studies suggest that by 17 months infants possess an abstract expectation of in-group support (Jin & Baillargeon, 2017). Infants expect two adults who belong to the same group, but not members of different groups, to help each other rather than to ignore them. Although it is on debate whether infants use language as a social marker of group membership (Begus, Gliga, & Southgate, 2016; Liberman, Woodward, Keysar, & Kinzler, 2017), there are some studies suggesting this might be the case (Liberman, Woodward, & Kinzler, 2017). However, unlike other investigations, we presented a situation in which the recipient never ignored the communicator's request: she always presented the communicator with an object. It is unlikely that infants interpreted the non-target outcome as the recipient being antisocial, instead of just trying to help but being wrong. Previous results show that in similar scenarios infants expect a (silent) recipient to help a foreign-speaker (Vouloumanos, 2018).

The results of the regression model suggest that the influence of linguistic experience on infants' expectations about who can communicate with whom does not depend merely on exposure to another language. Instead, the more frequently infants are exposed to multiple languages, the more enhanced is their expectation that speakers of different languages will communicate successfully. Importantly, infants generated these expectations even when presented with a language they were not familiarized with (Hungarian), suggesting that they generalized their experience observing communication acts with native-languages to reason about novel communication events.

Much of the information infants learn about the world is acquired through the observation and interaction with other social agents (Csibra & Gergely, 2009; Poulin-Dubois & Brosseau-Liard, 2016). Holding a sophisticated appreciation of the conventional nature of language and its communicative function is likely to provide a fundamentally basis for social learning. Moreover, it is critical to form complex intuitions about the social world, such as how agents are likely to interact between them. In this line, our results are consistent with previous findings showing that 9-month-old monolinguals expect same-language speakers to be more likely affiliated than people who speak different languages (Liberman, Woodward, & Kinzler, 2016). The current study provides evidence that a sensitivity to the communicative function of speech and its constraints is present by 14 months and it is shaped by language background.

Acknowledgments

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5. GENERAL DISCUSSION

In the present dissertation we investigated *how* action efficiency and the language people speak tune infants' predisposition to attend and interact with others. In order to address this issue, in experimental parts I and II we explored if these two cues influence how infants represent agents and their actions. Specifically, in experimental part I we investigated if the principle of rationality provides infants with the basis to generate different evaluations for rational and irrational agents. In experimental part II, we explored if information about the language people speak modulates how infants predict their actions. In experimental part III, we explored if infants appreciate that effective communication depends on the use of shared conventional systems (e.g. common language) and what is the role of language background (monolingual vs. bilingual) in predicting who can communicate with whom. In this final section we first review the main findings of the studies. We then discuss open questions and potential alternative interpretations of each experimental part. Next, we discuss our results in the context of current investigation in the field and suggest future directions. Finally, we expose final conclusions.

5.1 SUMMARY OF THE FINDINGS

5.1.1. EXPERIMENTAL PART I: "Efficiency as a principle for social preferences in infancy"

Understanding others' actions is critical for engaging in social interactions and social learning. The principle of rationality has been proposed as a core principle of social cognition that supports goal-attributions (Gergely & Csibra, 2003). From early in life infants represent others' actions as means to obtain goals efficiently. The aim of this experimental part was to explore if infants consider the efficiency of others' actions as a model-based cue to exploit in the evaluation of agents and their actions.

We presented 15-month-old infants with a third-party two-alternative choice task, where an observer approached either an agent who acted efficiently or an agent who acted inefficiently. Infants looked longer at the screen when the observer approached the inefficient rather than the efficient agent, suggesting that this was the more surprising outcome for them. A control study rejected the alternative interpretation that infants' expectations were driven by the variety of actions that each agent performed. Together, the two studies indicate that infants expect others to preferentially approach agents who act efficiently rather than inefficiently. These results suggest, first, that infants evaluate agents and their actions considering the efficiency of their actions. This evaluation is likely to be supported by the expectations that derive from the principle of rationality. Second, as expected, the results suggest that infants evaluate more favorably agents who act efficiently rather than agents who perform unexpected inefficient actions.

In the investigation of the principle of rationality researchers have used different stimuli depicting agents, from humans (Sodian et al., 2004) to geometric figures (Csibra, 2008). In the case of geometric figures or biomechanically impossible actions (Southgate et al., 2008), infants could not have direct experience with such agents and actions before the experiments. Yet, in these studies they expected agents to act efficiently, suggesting that they possess an abstract representation of actions as efficient means to obtain goals. In our experiment we also presented geometric figures depicting social agents. Also, agents were presented in a 2D dimensional space, which does not correspond with the 3D dimensional space infants navigate in their daily life. Finding that infants evaluate "novel" agents in terms of rationality in such scenario provides further evidence that infants possess an abstract understanding of actions as efficient means. Moreover, the findings suggest that such understanding have an inferential role that goes beyond action prediction of the specific observed action. The abstract representation of efficiency enables infants to evaluate how rational agents are and use this information to form inferences about third-party interactions.

5.1.2. EXPERIMENTAL PART II: "Strangers' things: influence of social group familiarity on infants' belief-based action predictions"

Previous studies found that infants are biased towards speakers of their native-language: they prefer attending at, imitating or learning from agents that speak their native language, as compared to speakers of a foreign language. We studied how preferring native over foreign speakers influences a critical capacity of social cognition: the prediction of others' actions considering their goals and perceptual states. It has been proposed that infants come to understand others' actions as intentional based on the understanding of their own intentional agency, together with the capacity to recognize others as "like me" (Meltzoff, 2007). We hypothesized that infants would represent agents exhibiting a familiar behavioral pattern (speaking a native-language) as more *like-me* than agents exhibiting an unfamiliar behavioral pattern (speaking a foreign-language). Based on this information, we predicted that the presentation of an agent speaking a native-language would promote action prediction, but the presentation of a foreign-speaker would disturb such prediction.

We presented 6-month-old infants with short videos of action prediction scenarios where the protagonist held a false belief about the location of a ball. During the presentation of the videos, infants' neural activity was recorded using EEG. We hypothesized that they would recruit their motor areas, measured as a desynchronization of mu-rhythm, only in the condition in which the agent's belief indicated impending action, rather than when it indicated that the she would stay still (Southgate & Vernetti, 2014). Critically, we manipulated how familiar the agent was for infants. One group of infants saw the agent speaking a native-language before the test phase and the other group saw the agent speaking a foreign-language.

We found that participants in the native-language group generated online predictions about the agent's action based on her perceptual states: they showed significant mu-rhythm desynchronization before the agent was going to act, but not in the condition she stayed still. However, infants in the foreign-language group did not show any evidence of action prediction: they showed no significant mu-rhythm desynchronization in any condition. Additional analysis on pupillometry (eye tracker) with a new group of participants provided converging evidence with the EEG pattern found. The results suggest that the mechanisms supporting action understanding can be influenced by top-down processes, such as the recognition of native-speakers (more familiar agents) versus foreign-speakers (more unfamiliar agents).

An open question is what specific mechanisms were modulated by language familiarity in our studies. In section *5.2.2* we discuss two possibilities: a modulation of the readiness to track others' perceptual states, and a modulation of the mirror system. In any case, we propose that the influence of language familiarity in action prediction is an optimal strategy to privilege the acquisition of potential cultural knowledge. Being biased to make sense of the actions of native-speakers rather than the ones of foreign-speakers likely influences infants' predisposition to interact with them and, ultimately, learning from them.

5.1.3. EXPERIMENTAL PART III: "Language background shapes third-party communication expectations in 14-month-old infants"

According to the Natural Pedagogy theory, the mechanisms that support learning from others' through communicative interactions are the basis of cultural learning (Csibra & Gergely, 2009). Previous studies found that by their first birthday infants understand that speech serves the function of transmitting information between third-parties. However, speech is not an efficient tool to transmit information when communicative partners do not share a common language. Having a sophisticated appreciation of the conventional and communicative nature of language is critical to engage in optimal social interactions and understand third-party interactions. Here, we asked if 14-month-old infants appreciate that verbal communication depends on the use of a common language.

Participants saw an agent (*communicator*) that selectively grasped one of two objects (*target*). At test the communicator could no longer reach for the object she liked, but another agent (*recipient*) who did not know about the communicator's preference could. Looking at the other recipient, the communicator uttered speech and the recipient approached to the communicator either the target (*target outcome*) or non-target object (*non-target outcome*). We tested a group of infants with a monolingual background and a group of infants with a bilingual background. Based on previous findings with toddlers (Pitts, Onishi, & Vouloumanos, 2015), we expected that, unlike monolinguals, bilinguals would expect others to understand more than one language.

We found that 14-month-old monolingual infants looked similarly at both test outcomes, suggesting that they understood that people who speak different languages cannot communicate successfully using speech. In contrast, bilingual infants looked significantly longer at the non-target than the target outcome, suggesting that they expected the recipient to understand more than one language. The results suggest that a sensitivity to the communicative function of speech and its constraints is present by 14 months and it is shaped by language background. This sensitivity is not only critical for predicting third-party interactions, but it also provides infants with the basis to identify potential communicative partners.

5.2. OPEN QUESTIONS, ALTERNATIVE INTERPRETATIONS AND FUTURE STUDIES

Our results in the three experimental parts raise a set of questions and provide the basis for future studies. Across each experimental part, we expose open questions, discuss alternative interpretations and suggest future directions.

5.2.1. Experimental part I: "Efficiency as a principle for social preferences in infancy"

In experimental part I we found that infants expected an observer to preferentially approach a rational rather than an irrational agent. However, another interpretation of the results could be possible (although unlikely, as we argue below). Infants could interpret agents' actions in terms of imitation rather than rational or irrational behaviours. In our experimental setup, the observer approached both agents taking a direct path towards them in the first approaching scene (see Figure 5.1). In the following scene, only the rational agent took a direct path to obtain the object. Although the goal of both actions differed, it could be argued that infants interpreted the movement of the rational agent as an imitation. Previous studies have found that 14-month-old infants like to be imitated, showing more positive emotions towards agents who imitate them (Meltzoff, 2007; Saby, Marshall, & Meltzoff, 2012). Infants could generalize the abstract knowledge of "liking imitators" and expect the observer to approach the rational agent.

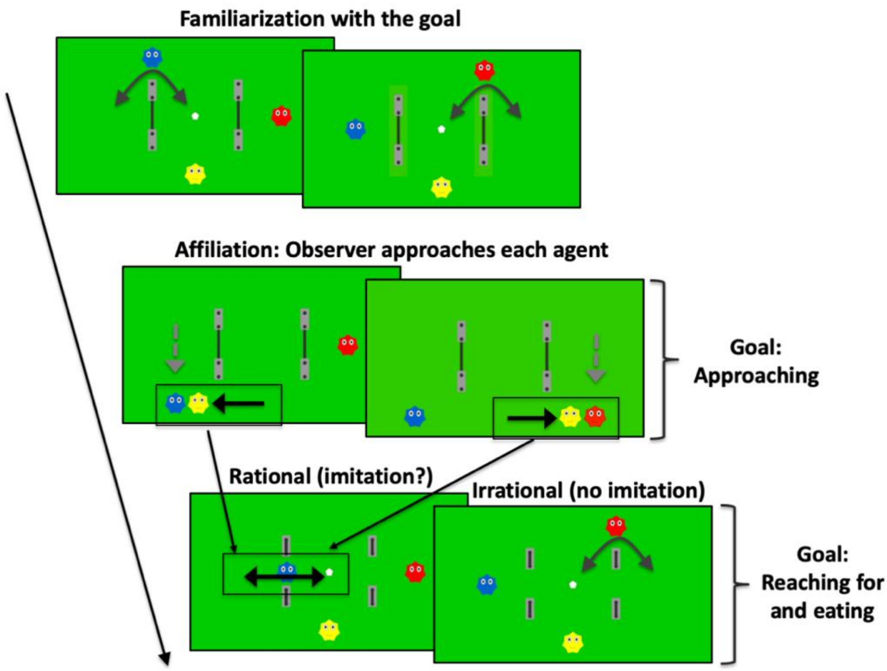

Figure 5.1. *Scenes from familiarization trials in experimental part I (Experiment 1). The arrows describe the path and directions of the agents' actions. The black rectangle indicates the movements that could be interpreted as imitation.*

However, we think that this interpretation is unlikely for three reasons. First, we have seen that infants interpret actions as goal-directed. They encode actions as structured by goals and not by simply movements through space. Because the rational agent and the observer performed different goal-direct actions (approaching vs. reaching for and “eating” an object), we find unlikely that infants represented them in terms of imitation. Second, a recent study shows that infants expect agents who imitate others to preferentially affiliate with them, but not otherwise (Powell & Spelke, 2018). That is, they do not expect agents to preferentially affiliate with other agents who imitate rather do not imitate them, a similar scenario as in our study. Finally, an unpublished work suggests that infants expect agents who are affiliated to act alike only if their movements have no apparent instrumental purpose, but they fail to expect imitation if these same movements are directed towards objects and cause changes in the physical environment (Powell, Schachner, & Spelke, 2014). Based on these three arguments, we propose that the most likely interpretation of our study is the one we provide in experimental part I: infants evaluate agents and their actions based on the expectations that derive from the principle of rationality, preferring agents who act efficiently.

A further question is how infants evaluate actions that are apparently irrational but that may have an opaque social meaning. This is the case, for example, of cultural actions or rituals. Ritualistic actions are characterized by being instrumentally inefficient and having an unclear purpose (Hobson, Schroeder, Risen, Xygalatas, & Inzlicht, 2018). We have seen that, in pedagogical contexts, infants imitate an agent turning on a light using her forehead, an apparently inefficient action to obtain the instrumental goal (Király, Csibra, & Gergely, 2013). These findings suggest that infants are biased to interpret actions embedded in communicative demonstrations as rational means (Gergely, Bekkering, & Király, 2002). Another characteristic of rituals is that they are shared across members of a social group (Legare & Souza, 2012). In an ongoing study, we are investigating if infants use the representation of social groups to interpret apparently inefficient actions as rituals. We present 14-month-old infants with two groups of four agents whose members move in synchrony. The members of one group move towards a ball to reach it taking an efficient direct path (efficient group). The members of the other group, however, move towards the ball taking an unnecessary curvilinear path (inefficient group). At test the last member of each group moves towards the ball taking the curvilinear path. We predict that infants will expect the member of the inefficient rather than the efficient group to more likely take the inefficient path. Our prediction would indicate that infants form inductively-rich inferences about social groups and exploit this information to identify rituals.

5.2.2. Experimental part II: “Strangers’ things: influence of social group familiarity on infants’ belief-based action predictions”

An open question of experimental part II is what specific mechanisms supporting action prediction were modulated by language familiarity. We consider two potential mechanisms: the readiness of infants to track others’ perceptual states (*mentalizing*) and the mirror system (*mirroring*). A modulation in mentalizing would influence action prediction and, ultimately, the recruitment of motor areas. A modulation of the mirror system would result in similar findings. Although our data cannot reveal what of these two mechanisms was modulated, here we discuss the two possibilities and the potential general contribution to the field.

Concerning mentalizing, a few studies in adults and children show that social group markers can influence the attribution of mental states and level I perspective taking (McLoughlin, Tipper, & Over, 2017; Schneider, Grigutsch, Schurz, Zäske, & Schweinberger, in press; Todd, Hanko, Galinsky, & Mussweiler, 2011). To our knowledge, this question has not been investigated in young infants. It is possible that in our study agents’ social group modulated how infants tracked their perceptual states. If this is the case, our result would make a relevant contribution on the debate about the origins of Theory of Mind (ToM). First, the results would be incompatible with lean interpretations (Heyes, 2014), which propose that infants pass false beliefs tasks guided by the identification of perceptually novel events. According to lean accounts, infants encode events in terms of the relation between colors, shapes and movements, instead of agents and their actions. In our study, however, we controlled how infants looked at the relevant areas of the stimuli and we found that both groups (native-language and foreign-language groups) showed similar overt visual attention. Yet, the native-language group predicted the agent's actions considering her perceptual state and the foreign-language group did not. Perceptual processing cannot account for this different pattern.

Another account about the origins of ToM is the two-systems proposal (Apperly & Butterfill, 2009). In this view, infants are endowed with an early-developing, fast, automatic and inflexible system that supports the basic (and limited) ability of tracking others' perceptual and epistemic states. Our results would also challenge this account, showing that early-developing mechanisms supporting the sensitivity to others' perceptual states are flexible. However, our results would support two possible interpretations about infants' competence to track perceptual states. First, a richer interpretation indicating that tracking others' beliefs is modulated by attentional and motivational biases, serving a learning function. Second, a non-mentalistic interpretation according to which infants predict others' actions following a set of behavioral rules, and these rules are limited to agents that act *like-me* (e.g. individuals that speak a familiar rather than unfamiliar language). This second idea is based on the proposal of Perner and Ruffman (2005), , which held that infants use rules such as "agents tend to reach for an object on the last position they saw it" to predict behavior. Future work is needed to confirm if the precursors of ToM are modulated by top-down information. We believe that exploring the automaticity and flexibility of the mechanisms that support level 1 perspective taking is a potential approach to shed light on the origins of ToM.

The other potential mechanism that could be modulated by familiarity is the mirror system. Several findings support this possibility. Adults show greater mirroring when observing actions of same rather than other race agents, and this modulation correlates with their level of prejudice (Gutsell & Inzlicht, 2010; Liew, Han, & Aziz-Zadeh, 2011). The perceptual-motor coupling during joint action, which likely reflects predictive embodied simulation of the partner's movements, is also influenced by the familiarity with others' race (Sacheli et al., 2015). A recent unpublished study from Amanda Woodward's lab suggests that the modulation of mirroring based on social markers is present in infancy. The authors found a correlation between familiarity and mirroring of others' actions. Eight- to 12-month-old infants saw either an agent of their own race or another race performing actions. For some infants the other race was not completely unfamiliar, since they were raised in a multicultural neighborhood. The authors used the ZIP code to approximate how common was the other-race in infants' environment. They found a correlation indicating that the less common was the out-group race for infants, the less mirroring they showed when observing the out-group actions.

The results just reviewed support the interpretation that familiarity with social cues such as race or language modulate the mirroring of others' actions. The results also provide interesting questions for future research. Does the linguistic environment of infants influence how they mirror the actions of non-native speakers? In our study we ensured that our participants in the foreign-language group have never listened to German. Would a language that is non-native, but that may be present in infants' environment, change the results? The case of English in Barcelona would be a good example, since some infants are occasionally exposed to it, but others are not. Another aspect to study would be language background. In our study, only one participant in the foreign-language group was bilingual (dominant language = 65%). Because of the limited number of participants, we could not test the role of language background in action prediction. Are bilingual or multilingual infants more flexible than monolingual infants in showing attentional and motivational biases based on language familiarity?

5.2.3. Experimental part III: "Language background shapes third-party communication expectations in 14-month-old infants"

We found that bilinguals expect a native speaker (*recipient*) to make sense of speech uttered by a foreign speaker (*communicator*), but monolinguals do not. This result suggests that bilinguals expect native speakers to have access to more than one language. An open question is whether this expectation is bidirectional or unidirectional. That is, do infants expect a speaker of a foreign-language to understand a message transmitted with native-speech? This question could be addressed by running a new study with the same procedure of experimental part III, except that now the communicator would be a native-speaker and the recipient a foreign-speaker (see Figure 5.2A). Finding that bilinguals are more surprised in the non-target rather than the target outcome, as we found in experimental part III, would indicate that they expect a foreign-speaker recipient to understand native-speech, and they also expect her to help the communicator. However, finding a contrastive pattern in looking time with the results of experimental part III could have two interpretations. Infants could expect a foreign-speaker recipient to know multiple languages, but they could have no expectations about her prosocial or antisocial behaviour. Alternatively, bilinguals could expect that someone who speaks an unfamiliar language has no access to their familiar language. This brings us to consider the next issue.

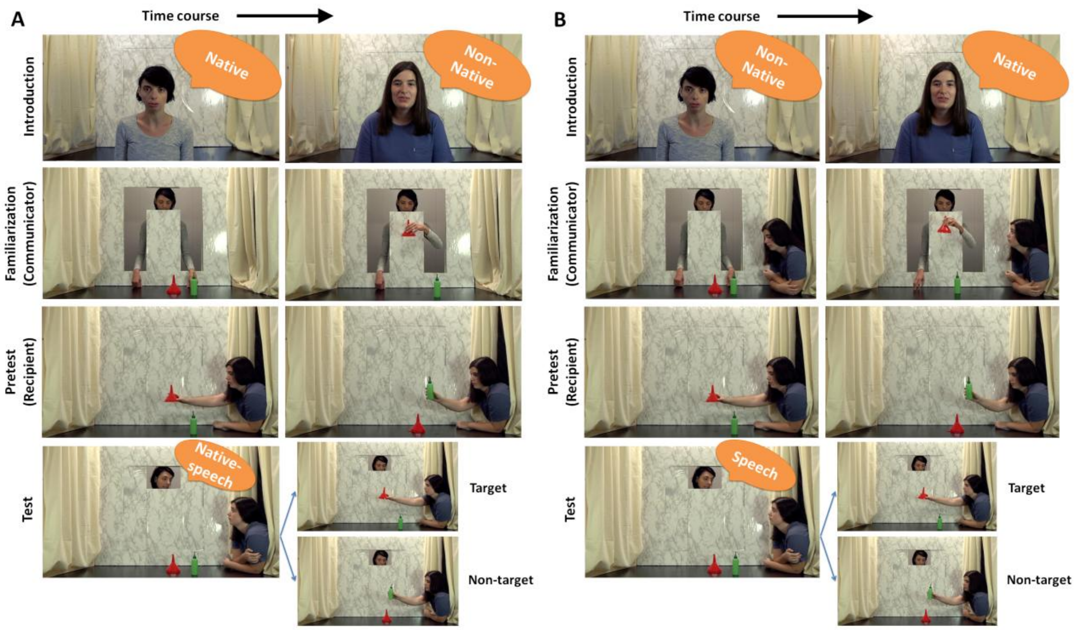

Figure 5.2. *Procedure of potential future studies. (**A**) Same procedure as experimental part III, except for that the communicator speaks a native-language and the recipient a foreign-language.* ***(B)*** *Same procedure as in experimental part III, except for that the recipient is present during the familiarization.*

Our results in experimental part III could be interpreted in terms of communication, as well as in terms of helping behaviour. With respect to helping behaviour, bilinguals could expect members of different linguistic communities to cooperate, but monolinguals could expect the opposite or have no expectations. However, we find unlikely that infants' expectations in experimental part III were guided by inferences about affiliation rather than communication. First, in our scenario the recipient always approached an object to the communicator, suggesting that she aimed at helping her. Findings showing that infants expect agents to help out-group less than in-group members use helping versus ignorance behaviours, which differs from our scenario (Jin & Baillargeon, 2017). Second, 12-month-old infants expect native-speakers to act prosocially (Pun, Ferera, Diesendruck, Kiley Hamlin, & Baron, 2018) and, in our study, the recipient was a native-speaker. However, infants have no expectations of whether a foreign-speaker will act prosocially or antisocially (Pun et al., 2018). Thus, different results could arise if, as discussed in the previous paragraph, we present a foreign-speaker as a recipient and native-speaker as a communicator. Finally, language background is more likely to influence expectations about communication, which are related with speaking one or more than one language, than expectations about affiliation.

Testing a new condition in which communication is not needed would help to provide further support for our interpretation in terms of communication. For instance, we could present infants with exactly the same stimuli, except for that the recipient would be presented in the scene when the communicator is showing her preference for one object (see Figure 5.2B). In this case, communication would have no role in defining if the recipient acts prosocially or antisocially in the test. With this condition, we predict that both monolinguals and bilinguals would expect the recipient to be prosocial, i.e. to approach the target object to the communicator. If this is the case, the result would confirm our main interpretation of the findings from experimental part III.

Additionally, it would provide an alternative interpretation of the results of (Liberman et al., 2016). The authors found that 9-month-old infants expected speakers of the same language to affiliate rather than disengage. In contrast, infants expected speakers of different languages to disengage rather than affiliate. The authors interpreted the results as showing the role that language have on social identity and affiliation. We propose that infants' inferences about third-party social relationships could be supported by inferences about communication, rather than inferences about affiliation or social identity. Infants would expect people to engage in communication when they share a common language to communicate, but not otherwise.

5.3. OVERALL INTERPRETATION AND FUTURE DIRECTIONS

Infants are surrounded by a large amount of novel information they must learn. In such a complex environment, infants need mechanisms to efficiently attend to information that is functional and has cultural relevance. We have seen that social learning is a potentially easy way of acquiring valuable information (Rendell et al., 2011). Infants are surrounded by individuals who have already selected and acquired valuable knowledge; however, not all individuals are reliable sources of information. Social learning in infancy raises the challenge of *whom* to learn from. In the present dissertation we have seen two strategies that likely bias infants' predisposition of attending to and interacting with others. First, infants evaluate agents acting efficiently more favourably than agents acting inefficiently. Second, information about the familiarity with the language people speak influences how infants make sense of their actions. Additionally, we found that infants understand that the transmission of information between individuals is constrained to the use of a common language.

From an evolutionary perspective, being biased towards rational agents and native-speakers could be adaptive (Wood et al., 2013). First, obtaining goals through the most rational means available entails being proficient in the task (Jara-Ettinger, Gweon, Schulz, & Tenenbaum, 2016). Recognizing who acts more efficiently in the environment is a way to detect who possesses the best abilities to process the environment and, thus, who is the best collaborator and potential teacher. Second, language is a strong indicator of cultural identity (Soley & Spelke, 2016). Speaking a native language indicates sharing environment but speaking an unfamiliar language does not. The behaviour of the most similar model is, thus, the most functionally and culturally relevant.

A critical question is *what* are the mechanisms that provide infants with a basis to identify relevant model-based cues. In the present dissertation we have explored how the mechanisms underlying action understanding are related with the identification of model-based cues. Specifically, we have explored three mechanisms that could entail model-based biases. First, the principle of rationality, the assumption that agents act efficiently

(Gergely & Csibra, 2003). Experimental part I suggests that infants evaluate more favourably agents who act in accordance with the expectations that derive from the principle of rationality. Second, the Like-Me Hypothesis, proposing that infants come to understand others' actions as intentional based on the understanding of their own intentional agency, together with the capacity to recognize others as "like me" (Meltzoff, 2007). Experimental part II suggests that infants identify individuals from familiar groups (e.g. native speakers) as more *like-me*, making more sense of their actions. Finally, the idea that communication is at the core of social learning (Gergely Csibra & Gergely, 2009) and that it is constrained by the language people speak. Experimental part II shows that infants have a sophisticated understanding of the conventional and communicative nature of language, which they can use to predict third-party interactions and likely promotes the identification of potential communicative partners. Although these mechanisms are specific to social cognition, they are interrelated with two processes that have a role in other domains. First, the detection of surprising or unexpected events. Second, the identification of novel or familiar stimuli. In the next paragraphs, we review the role of surprise and novelty/familiarity in non-social learning processes. We then discuss the role of surprise and novelty/familiarity in relation to social learning and our results.

Across many modalities, recognizing unexpected or surprising observations has a central role on the learning process. One example is the role of prediction error on associative learning in adult humans and in nonhuman species (den Ouden, Kok, & de Lange, 2012). Work on prediction error shows that when an observer is learning the specific parameters of a motor movement in order to attain a goal, her brain constructs a cycle of predictions, drawn from previous knowledge, that are continuously compared with the currently experienced observation. Crucially, if predictions are wrong, the brain signals an error that is used to update and improve the next prediction cycle (Tseng, Diedrichsen, Krakauer, Shadmehr, & Bastian, 2007). Recent work by Stahl and Feigenson (2019) also indicates that surprise has a critical role in monitoring information-seeking in non-social contexts. At 11 months of age, infants prefer to explore objects that participated in an unexpected event (e.g. a ball passes through a solid wall, violating the principle of solidity) rather than an expected event (e.g. the ball stops by the solid wall). Interestingly, infants selectively seek the information about objects that is relevant to explain the unexpected event they saw. In addition, surprise has also been found to enhance learning: infants learn better a new property of an object when the object has an unexpected behavior (Stahl & Feigenson, 2015). Surprise also promotes generalization of linguistic patterns and rules in infancy (Gerken, Dawson, Chatila, & Tenenbaum, 2015).

The other type of information that monitor information-seeking is the novelty or familiarity with the stimuli. Infants tend to show a *novelty preference* when exploring objects, preferring to look at and interact with novel items rather than items they have already encountered (Feigenson, 2016). According to models of active learning (Twomey & Westermann, 2018), infants are curious learners who actively direct their attention to stimuli that provides novel information. To maximize learning, the *Goldilocks effect* proposes that infants avoid attending to stimuli when it is either highly predictable (too simple) or highly unexpected (too complex). Instead, they actively spend time looking at the stimuli when it is of intermediate predictability (Kidd, Piantadosi, & Aslin, 2012).

What is the role of surprise and novelty/familiarity in selective social learning? In the process of identifying appropriate partners *from whom* to learn, similar mechanisms that tune object exploration in non-social contexts could have a critical role in selective social learning. Yet, social learning is a unique form of learning in that information transmitted socially is already filtered and can be easier to acquire. Thus, the mechanisms that bias infants' attention in non-social learning may serve an opposite function in selective social learning. This is, in fact, what results from comparing the results of experimental part I and the work of Stahl and Feigenson (2015). Stahl and Feigenson found that infants preferentially explored objects whose behavior violated the expectations that derive from the principles of physics. For example, infants preferred to explore an object that passed through a solid wall rather than an object that, as expected by the principle of solidity, was blocked by the wall. As expected from the social domain, in experimental part I we found the opposite pattern. Infants expected a third-party to affiliate with an agent who acted in accordance with the expectations that derive from the principle of efficiency, acting efficiently rather than inefficiently.

A similar pattern is found in the case of novelty/familiarity. If presented with two objects, a familiar one and a novel one, the strategy that maximizes the acquisition of novel and relevant information is to explore the novel object (Feigenson, 2016). However, in the case of social learning, preferring to attend to and interact with the more familiar agent is more likely to optimize learning. This is especially true in the case of language, which is used as a tool to transmit information and indicates cultural identity. As we have seen in the introduction, infants show familiarity-based preferences for certain cues that in adults indicate social categorization, such as race or language. Consistently with this idea, in experimental part II we found that infants are more ready to make sense of the actions of native rather than foreign-speakers.

To sum up, our results suggest that a supramodal capacity of recognizing surprising events and familiar stimuli interrelates with domain-specific mechanisms of social cognition (e.g. principle of rationality or like-me) to form model-based biases. We interpret these model-based biases as optimal strategies to privilege the acquisition of functional and cultural knowledge. However, these biases could not only arise from an information-seeking motivation, but also from an affiliative motivation. Another critical characteristic of agents, in addition to provide information about the world, is that they engage with other agents. It is an open question whether the preference for native over foreign speakers, for example, arises from a representation of agents as best sources of information, or as in-group members, or both (Begus, Gliga, & Southgate, 2017; Kinzler & Liberman, 2017). Future directions emerging from the present dissertations are exploring directly how action efficiency and language familiarity influence infants' tendency to affiliate with others or to learning from them. In the case of information-seeking, a possible approach would be following the procedures of Stahl and Feigenson (2015). In their work, after they found that infants preferred to explore objects that behaved surprisingly, they also investigated how infants learned properties about these objects, and how specific this learning was. We could explore if infants learn better, for example, from an agent who acts efficiently. Also, we could investigate if this learning is specific to learning actions, or it is also generalized to other modalities such as word learning. In the case of affiliation, a possible approach would be to manipulate how informative and familiar are two agents. Are infants only biased to affiliate with the familiar agent when she is informative, or does the readiness to interact with the familiar agent remain even when she is uninformative?

5.4. CONCLUDING REMARKS

In this dissertation we explored how infants identify appropriate agents *from whom* to potentially interact with and learn, known as model-based biases. To address this issue, we have related the mechanisms that guide early action understanding and social selectivity in infancy. We found three potential mechanisms or capacities that likely provide infants with the basis of navigating the social world selectively. First, the principle of rationality guides the identification of rational versus irrational agents. We have seen that infants evaluate more favourably rational ones. Second, recognizing others as *like-me* based on the identification of familiar cues (speaking a native-language) bias infants' predisposition to make sense of others' actions. Finally, understanding that communication is constrained by the use of a common language allows infants to predict third-party interactions and identifying potential communicative partners. These three strategies or capacities likely bias infants' predisposition of attending to and interacting with others and, ultimately, learning from them.

We have also discussed similarities and differences in monitoring information-seeking in social versus non-social learning contexts. We propose that a supramodal ability to recognize surprising events and novel/familiar stimuli plays a critical role in monitoring attention both in social and non-social contexts. This ability is interrelated from early in infancy with the expectations that derive from mechanisms that are domain-specific. Importantly, unlike in the case of object exploration, infants tend to evaluate more favorably agents who act in accordance with the expectations that derive from core principles of social cognition.

The present thesis provides evidence on the influence of two model-based cues in early social selectivity: action efficiency and language familiarity. It also contributes to understand what mechanisms guide the identification of these model-based cues. Our empirical approach to relate early action understanding and model-based biases also sheds light on the nature of some mechanisms that guide action understanding in infancy. Finally, our experiments raise new questions and provide a basis for future research on the field.

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APPENDIX

Link to Supplementary Materials:
https://drive.google.com/open?id=1kEz_trbz2su5ZgPGX8kEAchYjMU0VWWY

1. Experimental part I "Efficiency as a principle for social preferences in infancy"

Movie S1. Familiarization trial depicting the agents' goal (Experiment 1)

Movie S2. Familiarization trial including the affiliation scenes (Experiment 1)

Movie S3. Pretest trial (Experiment 1)

Movie S4. Test trial I (coherent; Experiment 1)

Movie S5. Test trial II (incoherent; Experiment 1)

Movie S6. Familiarization trial depicting the agents' movement (Experiment 2)

Movie S7. Pretest trial (Experiment 2)

2. Experimental part II “Strangers’ things: influence of social group familiarity on infants’ belief-based action predictions”

Movie S1. Familiarization A+O+ and A-O- trials.

Movie S2. Agent presentation in Spanish.

Movie S3. Agent presentation in Catalan.

Movie S4. Agent presentation in German.

Movie S5. Test A+O- trial.

Movie S6. Test A-O+ trial.

3. Experimental part III “Language background shapes third-party communication expectations in 14-month-old infants”

ExpIII_RawData.xlsx. Raw data for Experimental part III.

Movie S1. Recipient speaks a native-language (Catalan)

Movie S2. Communicator speaks a foreign-language (Hungarian)

Movie S3. Familiarization trial.

Movie S4. Pretest.

Movie S5. Target outcome.

Movie S6. Non-target outcome.