The role of ostensive-referential communication in action understanding during infancy and early childhood

The role of ostensive-referential communication in action understanding during infancy and early childhood

Psychology Department

Lancaster University

DISSERTATION

This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

submitted by

Christian Kliesch *MA, MSc*

Declaration

I declare that the thesis is my own work, and has not been submitted in substantially the same form for the award of a higher degree elsewhere.

C. Kliesch

Christian Kliesch

Lancaster, 27 September 2018

Abstract

This thesis investigate how the presence of communicative signals such as direct gaze and infant-directed speech might help infants and young children to understand, anticipate, and segment actions. For this, the thesis draws upon a range of methodologies, such as electroencephalography (Chapter 2), eye tracking, pupil dilation (both Chapter 3), and behavioural research (Chapter 4).

Chapter 2 and 3 both investigate whether the presence of communicative signals, such as infant directed speech and direct gaze, increase infants' understanding of actions as meaningful. The ERP experiments on 9-month-old infants reported in Chapter 2 found limited evidence that the presence of communicative signals enhances the N400 response, a correlate of semantic understanding. Furthermore, there is limited evidence of a complex response taking into account the presence of communication and action congruency in the Pb component in the second experiment, in which referential signals were added and the structure of the presentation was changed. Meanwhile, Chapter 3 found no evidence that communicative signals enhance anticipatory looking in 7-month-old children.

Chapter 2 and 3 also investigate the possibility that communication enhances arousal. However, neither the Nc component reported in Chapter 2, nor the Pupillary Light Reflex investigated in Chapter 3 provided evidence in support of this hypothesis.

Instead, communicative signals may play a different role in supporting action understanding. Chapter 4 investigates whether addressing infants within (rather than after) a two-step action can increase their imitation of the action manner. The study shows that communicative signals can contribute to the segmentation of low salience actions, but children imitate salient actions irrespective of the position of the address.

These results are discussed in terms of Natural Pedagogy Theory and domain general, statistical learning accounts, such as curiosity learning.

Acknowledgements

In a social situation it is impossible to not communicate

— Paul Watzlawick, Pragmatics of Human Communication

In many ways this thesis is the culmination of my undergraduate degree in Psychology at the University of Glasgow, my Master in Evolution of Language and Cognition at the University of Edinburgh and my work as a research assistant at the MPI for Evolutionary Anthropology in Leipzig. In particular, Chapter 4 represents a fusion of thoughts and ideas that I encountered during my studies.

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Statement of Authorship

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Through signing this Statement, the supervisors and co-authors agree that:

1. the student's contribution to all the papers above is correct;
2. the student can incorporate these papers within the thesis;
3. the contributions of all the co-authors for each paper equals to 100% minus the involvement of the student

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Chapter 1

Introduction: Communicating the meaning of actions in infancy

Culture and its transmission are considered to be what makes humans unique (Dennett, 1996; Tomasello, 2009, 2016). Unlike many other species, humans can transmit cumulative cultural information for many generations, allowing them to develop a rich set of behaviours that are not genetically predetermined (Csibra & Gergely, 2009, 2011; Hill, Barton, & Hurtado, 2009; Laland & Brown, 2011; Mesoudi, 2013; Richerson & Boyd, 2005). This flexible social learning system relies largely on human language and communication (Richerson & Boyd, 2005), which in turn is subject to cultural learning (e.g. Kirby, Cornish, & Smith, 2008).

The repertoire of human cultures consist of a set of behaviours, actions and communication systems that are passed on from one generation to the next. At its foundation are the basic action units and structures that allow for the interaction with the environment and other agents specifically. Social learning mechanisms form the basis of how actions are transmitted from one generation to the next. However, social learning already requires the learner to make considerable inferences about the action units, objects and movements involved, and some actions cannot be understood without knowing the actor's intentions and beliefs. This poses a problem for infants, who do not yet have the full socio-cognitive understanding of higher order mental representations that are necessary to compute such information.

In order to explain the efficient transmission of culturally relevant information to the next generation, it has been argued that infants are already prepared to learn from their caregivers by relying on socio-communicative signals that inform them that a specific piece of information is relevant to them (Csibra & Shamsudheen, 2015). In infants, this expectation may be triggered by a subset of social signals, such as direct gaze, infant-directed speech, and contingency (Csibra, 2010). Because these signals allow infants to identify learning contexts, they have been called *pedagogical* signals (Csibra & Gergely, 2009, 2011).

To date, a large body of research has looked at how such communicative signals contribute to learning. For example, studies have found that the presence of communicative signals increases gaze following, and thereby ensures that infants' attention is focussed on the same objects and events as their caregivers (e.g. Farroni, Massaccesi, Pividori, & Johnson, 2004; Hoehl, Reid, Mooney, & Striano, 2008; Moll & Tomasello, 2004; Senju & Csibra, 2008; Symons, Hains, Dawson, & Muir, 1996; Wahl, Michel, Pauen, & Hoehl, 2013). Communicative signals have also been shown to facilitate learning in general (e.g. Hoehl, Michel, Reid, Parise, & Striano, 2014; Michel et al., 2015; Michel, Wronski, Pauen, Daum, & Hoehl, 2017). They also help infants to associate words to meaning (e.g. B. Ferguson & Waxman, 2016; Medina, Snedeker, Trueswell, & Gleitman, 2011; Parise, Handl, Palumbo, & Friederici, 2011) and facilitate children's imitation of actions (e.g. Brugger, Lariviere, Mumme, & Bushnell, 2007; L. P. Butler & Markman, 2012, 2013; Király, Csibra, & Gergely, 2013; Hoehl, Zettersten, Schleihauf, Grätz, & Pauen, 2014; Kupán et al., 2017; Nielsen, 2006). However, less is known about whether and how communicative signals influence infants' understanding of actions, particularly in early infancy. This PhD thesis will contribute to the question of how communication influences infants' interpretation of everyday actions by looking at whether, and through which mechanisms, communicative signals may affect infants' understanding of actions.

This chapter will provide the introduction to this thesis by laying the theoretical foundations for this research. It will review the literature on infants' understanding of actions by discussing action understanding in general, and action understanding through action segmentation and understanding actions as teleological. Going back to social learning in communicative contexts, it will further discuss how a subset communicative signals act as an early signal of communicative relevance in infancy, as suggested by Natural Pedagogy theory (Csibra & Gergely, 2009, 2011). There are numerous studies that suggest the influence of communicative signals on children's processing of objects and actions. However, alternative accounts argue in favour of an emergent understanding of the communicative function of these signals and/or suggest that any enhanced learning in the presence of these signals is due to an increased arousal. The final section of this chapter will review different methodologies used to study action and social learning in infancy, and look at the development of imitation, anticipatory looking and the neural signatures of action understanding and communication in particular.

The experimental component of this thesis consists of four experiments utilising event-related potentials (ERP), anticipatory looking, pupil dilation and behavioural data. The first two experiments in Chapter 2 investigate infants' semantic understanding of everyday actions by measuring ERPs in 9-month-olds.

Furthermore, it investigates whether communication directly influences infants' semantic interpretation of actions, or whether communication modulates action understanding through attention or arousal. Chapter 3 reports an experiment on whether communication helps 7-month-old infants to anticipate the outcomes of familiar, unfamiliar and novel actions using eye-tracking. The final study in Chapter 4 investigates whether communicative signals, such as direct gaze and infant-directed speech, support children's interpretation of actions by helping them to segment actions at event boundaries. In the general discussion in Chapter 5, I argue that the findings of the first two experimental chapters provide limited evidence in support of the notion that communicative signals facilitate the learning of actions. However, neither the results presented in Chapter 2 nor Chapter 3 suggest that the effect of communicative signals lead to increased arousal, preempting some alternative explanations to Natural Pedagogy Theory. Therefore, Chapter 5 further discusses alternative accounts of action understanding that rely on an emergent understanding of the function of communicative signals, without relying on arousal as a mechanism for learning.

1.1 Action understanding in infancy

It has been argued that humans understand others' actions semantically within a wider context, similar to how words are understood within a sentence (Amoruso et al., 2013; Reid et al., 2009). There is a strong link that connects actions, language and communication, and the foundations for all three processes emerge during infancy. It has been suggested that infants' emerging understanding of actions is the source of pre-linguistic meaning (Arbib, 2005; Kaduk et al., 2016; Pulvermüller, 2012). Although children tend to learn most verbs later than nouns (McDonough, Song, Hirsh-Pasek, Golinkoff, & Lannon, 2011, but see Imai, Haryu, & Okada, 2005, and Waxman et al., 2013 for a discussion), an understanding of actions is predictive of children's later language acquisition. For example, infants' understanding of everyday actions is predictive of their later word learning (Kaduk et al., 2016) and 30-month-olds show improved verb learning for actions that they had a chance to imitate first (Gampe, Brauer, & Daum, 2016). Furthermore, verbs that are common or describe imaginable actions are learned early (Braginsky, Yurovsky, Marchman, & Frank, 2019; McDonough et al., 2011). Further research shows how actions contribute to learning features about the environment that are necessary for language acquisition. Actions can help to establish links between objects and their uses (B. Ferguson, Graf, & Waxman, 2014). For example, by the age of 11 months, children categorise objects by their function (Träuble & Pauen, 2007). The relationship between word learning and action understanding is bi-directional and action words also help children predict actions (Gampe & Daum, 2014). Therefore, action understanding is closely intertwined with children's linguistic and communicative abilities.

Infants show a semantic understanding of the actions of others, taking into account the goals and intentions of an agent (Csibra & Gergely, 2007; Reid et al., 2009). There is evidence that infants already have a basic understanding of others' actions. Infants' understanding of action semantics can be measured through anticipatory looking in eye-tracking and the N400 ERP component in semantic priming paradigms. Anticipatory looking shows that the child can predict the outcome of an action movement even before its conclusion and in order to do so needs to have a representation of the goal of the action. The N400 is a well-researched ERP component known from the adult language literature and commonly found in semantic priming paradigms with words, gestures and actions (Amoruso et al., 2013; Kutas & Federmeier, 2011). Other measures include behavioural measures, particularly paradigms using rational imitation and children's persistence to carry out inefficient action means (e.g. L. P. Butler & Markman, 2012, 2013; Király et al., 2013; Schleihauf, Graetz, Pauen, & Hoehl, 2017).

Understanding an action involves the ability to contextualise and predict an ongoing action within its preceding and following actions and its perceptual context. Visual and auditory features, such as the salience of an outcome or movement, impact action understanding and determine whether infants are able to learn action meanings. More salient outcomes are more readily anticipated or imitated than less salient ones (e.g. Adam et al., 2016; Elsner, 2007; Elsner & Pfeifer, 2012; Henrichs, Elsner, Elsner, & Gredebäck, 2012; Moher, Anderson, & Song, 2015). The salience of an action's manner also determines children's imitation and 12 and 18-month-old infants are more likely to imitate a salient hopping action, compared to a less salient sliding action (Carpenter, Call, & Tomasello, 2005). Once recognised, actions can be learned by association, for example by visual similarity or by associating certain movements with their outcomes. These studies suggest that infants are selective in their imitation of actions and that the saliency of outcome and manner plays an important part in determining whether children anticipate or imitate an action.

It is probably no coincidence that many studies find that children are able to predict and anticipate the outcome of eating actions (Hunnius & Bekkering, 2010; Reid et al., 2009; Reid, Csibra, Belsky, & Johnson, 2007). Hunnius and Bekkering (2010) provide evidence that 6-, 8-, 12-, 14-, and 16-month-old infants and adults anticipate goal-directed actions using a range of objects—a phone (to the ear), a brush (to the hair) and a cup (to the mouth). Whilst some participants were presented with the congruent outcomes, e.g. a cup going to the mouth, others saw an incongruent outcome, e.g. the cup going to the ear. Anticipation during the first trial of the action was low and did not reliably distinguish between congruent and incongruent outcomes, but infants were able to anticipate the congruent, meaningful actions (e.g. a cup going to the mouth) after nine exposures. Unlike adults, they were not able to anticipate incongruent action outcomes (e.g. the cup going to the ear) after repeated presentations.

These results are corroborated by neuropsychological evidence by Reid et al. (2009) who investigated whether 7- and 9-month-old infants and adults predict action outcomes. Based on an ERP paradigm, they presented participants with short action sequences consisting of a series of three pictures. The first two pictures primed a feeding action, the third picture concluded the primed action and either supported the anticipated outcome by showing the food in the mouth, or showing an unanticipated outcome, e.g. the food being moved to the forehead. The data revealed that 9-month-old infants and adults show an increased N400 for the unanticipated outcome, which suggests that, 9- but not 7-month-old infants show an adult-like response and experience semantic incongruence for unanticipated action outcomes.

Infants' ability to predict such eating actions is also culture-dependent. Whereas 8-month-old Chinese infants are able to anticipate that chopsticks (but not spoons) go to the mouth, Swedish infants of the same age have the opposite prediction (Green, Li, Lockman, & Gredebäck, 2016). However, these predictions are exclusive to eating actions and do not extend to picking up food from a bowl, where neither group of infants anticipated chopsticks or spoons to pick up food items, indicating that infants' understanding of actions is still limited.

In summary, within their first twelve months of age, infants show evidence of understanding a range of actions that they are likely to have learned from experience. Nevertheless, beyond these basic features other aspects of action understanding also play important roles in infants' action understanding, namely (1) the segmentation of action events into appropriate units, (2) understanding these action units as intentional and goal-directed, ie. *teleological* and (3) being able to understand actions presented in communicative contexts as *pedagogical* demonstrations that are targeted towards the infant. These topics will be discussed in the next sections.

Action segmentation through event segmentation

Before actions can be learned and understood they need to be segmented from the ongoing stream of information that the infant perceives. Events are segments of continuous input that are processed by the perceiver as a single unit. Event Segmentation Theory argues that the goals and intentions used to interpret events are hierarchically organised and that the way that an ongoing stream of actions is organised influences how it is interpreted. The problem of segmenting actions and other events within an ongoing stream of information is comparable to the problem segmenting speech sounds in an ongoing speech stream and we can draw upon domain-general theories of chunking to make predictions about the processing of actions within the wider events they are embedded within.

There are two independent theoretical approaches to the segmentation of actions, Event Segmentation Theory (Zacks, Speer, Swallow, Braver, & Reynolds, 2007; Zacks & Swallow, 2007; Zacks & Tversky, 2001) and Cognitive Chunking (Christiansen & Chater, 2016; Isbilen & Christiansen, 2018). Event Segmentation Theory looks at how movement cues and higher-order knowledge contribute to the segmentation of an ongoing stream of an action or a general event and influence how it is interpreted and remembered. Like Event Segmentation Theory, the Cognitive Chunking account (Christiansen & Chater, 2016; Isbilen & Christiansen, 2018) argues for a hierarchical processing of the input. Importantly, Cognitive Chunking also suggests that any input is processed immediately and is discarded if it cannot be interpreted. Consequentially, the on-line processing capacity of the cognitive system is a bottleneck that determines how much information can be processed at any point in time. More information can only be processed by forming higher order abstractions that abstract away from the richness of the signal that can be used to make further predictions about the data. Consequentially, Cognitive Chunking predicts that a learner's limited cognitive capacity acts as a source of abstraction and restructuring of information.

An unfolding action sequence provides a considerable amount of information that a learner can use to segment it into its appropriate units. For example differences in velocity and movement kinematics are reliably used to segment actions (Zacks, 2004; Zacks, Kumar, Abrams, & Mehta, 2009) and from 15-months onwards, children are able to use the velocity of a goal-directed action to predict its target (Stapel, Hunnius, & Bekkering, 2015). This low-level information is an important source of breaking up actions into smaller units and adults are able to use both featural (e.g. using a fist to turn on a lamp) and configural (e.g. using an arcing path to run on the lamp) information to identify deviations of familiar actions (Loucks & Baldwin, 2009).

How faithful an action goal or its manner is imitated also depends on the salience of its units and a repeated finding in the literature is that salient outcomes are more likely to be linked to the action and are therefore more likely to be imitated (cf. Elsner, 2007; Hauf, Elsner, & Aschersleben, 2004). Already 6–8-month-old infants are more likely to detect changes at event units, but are less likely to notice changes *between* them (Hespos, Saylor, & Grossman, 2009). Furthermore, infants are able to detect event boundaries at inflexion points where one action turns into another. Nine-to-eleven-month-old infants prefer looking at a continuous stream of actions if a sound matches the inflexion points between different action units (Saylor, Baldwin, Baird, & LaBounty, 2007). Similarly, ten- to eleven-month-olds became disinterested in actions that are paused at event boundaries but show renewed interest if these events sequences are paused mid-stream, suggesting that they perceive these as different to the event sequences they have been familiarised with.

Event boundaries also form an important source of information for learning about actions and their effects. Therefore it is not surprising that infants show better retention of objects presented at event boundaries (Sonne, Kingo, & Krøjgaard, 2017), but the occlusion of event boundaries has a detrimental effect on the memory of the action sequence in 16- and 20-month-olds, with the latter age group being particularly negatively affected (Sonne, Kingo, & Krøjgaard, 2016). By the end of their second year, toddlers use event segmentation cues to map novel verbs to different event units (Friend & Pace, 2011).

Both, Event Segmentation Theory and Cognitive Chunking, predict a bidirectional relationship between the way that an ongoing stream of information is segmented (bottom-up) and prior knowledge about the event (top-down) that is used to interpret an incoming stream of information. Infants as young as 7–9 months are able to use the statistical probability of events following each other to identify segment boundaries (Stahl, Romberg, Roseberry, Golinkoff, & Hirsh-Pasek, 2014). If they are familiarised with an abstract agent engaging in a continuous sequence of several actions, they will look longer during a subsequent test session if the test sequences depict a previously unseen order.

Loucks and Meltzoff (2013) found that three-year-old children do not only interpret action units sequentially, but that they reproduce the hierarchical structure based on the overall goal of an action sequence. When imitating a series of actions, such as putting a doll to bed or a doll driving a car into a garage, children will not mix up different parts of the action sequence with units of a different one, even if the original presentation did so. These results show that by the age of three years, children reliably use higher order action representations and that these representations in turn influence how actions are imitated.

Finally, there is evidence that caregivers actively adapt child-directed action presentations in ways that potentially aid action segmentation. Previous research has shown that parents overemphasise the movements of an action using so-called ‘motionese’ (Brand, Baldwin, & Ashburn, 2002; Brand & Shallcross, 2008; Koterba & Iverson, 2009; Rutherford & Przednowek, 2012; Williamson & Brand, 2014). Furthermore, they are more likely to use *communicative signals* between different action units (Brand, Shallcross, Sabatos, & Massie, 2007; Brand, Hollenbeck, & Kominsky, 2013) to highlight action units and goals. A previously untested question is whether children use this information to segment events into appropriately-sized chunks and consequentially influence how children understand an action within its wider context. Chapter 4 addresses the question to what extent communicative signals might help to segment events and thereby change the way that they are imitated.

Teleology

Infants understand actions *teleologically*, i.e. they interpret actions in terms of goals, intentions, outcomes and situational constraints (Csibra, 2003; Csibra, Bíró, Koós, & Gergely, 2003; Csibra & Gergely, 2007). Given knowledge about any two of these, an observer can reconstruct the third. This allows an observer to predict the progression of actions, but also to look for causes, consequences and intentions of actions that are not immediately apparent to them (L. P. Butler & Markman, 2014; Csibra et al., 2003; Király et al., 2013), whilst also ignoring accidental actions (Carpenter, Akhtar, & Tomasello, 1998). Evidence that infants understand actions teleologically comes from a wide range of studies that have used abstract objects and movements to investigate infants' understanding of goals (Csibra & Gergely, 2007; Eshuis, Coventry, & Vulchanova, 2009; Woodward, 1998), others have used familiar actions to investigate whether infants are able to anticipate these outcome (e.g. Hunnius & Bekkering, 2010; Reid et al., 2009).

The strongest evidence for infants' teleological understanding of actions comes from studies that demonstrate that they show a basic understanding of rationality (Csibra, Gergely, Bíró, Koós, & Brockbank, 1999; Gredebäck & Melinder, 2011). For example, by the age of 9 months, infants expect that an abstract object takes the direct path when moving to a goal location (Csibra et al., 1999). Infants also interpret the behaviour of others according to the same principle and by the age of four months, watch an irrational feeding action, such as putting food into someone else's hand, rather than bringing it straight to the other person's mouth. When an actor feeds another actor, infants show greater pupil dilations (indicating arousal and/or expectancy violations) to the actor putting food into the others' hand, instead of feeding them directly. However, the pupil dilation is at baseline when an obstacle prevents the expected feeding action (Gredebäck & Melinder, 2011). This response is not just due to the novelty of the action. Instead, infants are able to judge the rationality of the action, and do not show increased pupil dilations for scenes where an obstacle prevented the expected trajectory and provides a rational explanation for the different trajectory. However, only 12-month-olds actually anticipate feeding action and look to the recipients' mouth before the conclusion of the feeding action, suggesting that they are able to anticipate the goal of the action (Gredebäck & Melinder, 2010).

More evidence comes from studies on rational imitation that provide evidence for the importance of situational constraints in action understanding. From 14 months onwards, infants are able to disregard accidental actions marked vocally by 'Whoops!' compared to those marked as intentional by 'There!' (Carpenter et al., 1998). Gergely, Bekkering, and Kiraly (2002) found that toddlers are more likely to imitate an adult model using their head to turn on a lamp when the model had their hands free. If the model's hands were occupied, children were more likely to copy the goal of the action only by using their hands. Imitation of the head touch goes down, however, when the model's hands are occupied because they are holding a blanket. In this condition, the model's behaviour can be explained by the actor not having their hands free to turn on the light. However, Beisert et al. (2012) found that toddlers are also more likely to copy the irrational action (using the head instead of the hands to turn on a lamp) when the actor is covered by the blanket but can still use their hands, as evidenced by putting up two smileys next to them. Even though the actor has demonstrated that they are free to use their hands, infants still copy the head-touch, suggesting that they may not base their decision on whether or not to imitate the model on an understanding of the model's constraints. Instead, it is possible that many studies appear to find positive results for infants' mentalising capacities that are actually driven by perceptual distractors (see also Heyes, 2014a, 2014b).

Communication as a source of meaning

Human social learning relies on communication to share thoughts, ideas, intentions and motivations behind the action. Some social learning theories, such as Natural Pedagogy (See next section), have also argued that infants' early understanding of communication allows them to learn, predict and imitate socially relevant actions. Therefore, before discussing Natural Pedagogy, it is important to discuss its theoretical foundations in theories of human communication and cognition, in particular Relevance Theory (Sperber & Wilson, 1995; Wilson & Sperber, 2012).

Pragmatic theories of dialogue (Grice, 1957, 1975; Sperber & Wilson, 1995; Wilson & Sperber, 2012) and language evolution (Scott-Phillips, 2015) have argued that human communication is different to other animal communication systems, as it uses two channels to exchange information. These theories are grounded in Grice's (Grice, 1957, 1975) distinction between non-natural (communicative) and natural meaning. Natural meaning describes meaning derived from relationships in the environment, for example between a certain type of clouds and the likelihood of rain or a certain type of spots indicating measles. Because of this, natural meaning describes a direct relationship between the sign and the signified. For communicative meaning, the decoding of the meaning of an utterance, gesture or an action starts with the recognition of the speaker's (or in the case of actions, demonstrator's) intention to communicate, and the actual content (informative intention) is reconstructed by inference. This intention to communicate has also been called *ostensive intention*, whereas the intention describing the content is the *informative intention* (Sperber & Wilson, 1995; Wilson & Sperber, 2012).

Sperber and Wilson (Sperber & Wilson, 1995; Wilson & Sperber, 2012) argue that speakers and listeners use the principle of relevance to create and interpret a message. According to the relevance principle, successful communication requires that a message is constructed in such a way that it is simple and familiar enough to be understood, but also contains sufficient novel information, so that it is interesting to the listener. The interpretation of a message therefore depends heavily on the cognitive system, and interpretations that require the least cognitive effort to extract a meaningful interpretation of the content should be preferred.

An important implication of this inferential model of communication is that, within a communicative context, the same message can have different meanings. For example, the meaning of the sentence "Isn't the weather nice today?" is determined by its context, and may be understood either as sincere on a hot summer day or–in the case of the typical British weather–as ironic. In order to understand the different informative intentions, the listener needs to know about the state of the referent of the communicative intent, e.g. whether the weather is actually nice, or whether the speaker has a propensity towards irony.

While it is unlikely that infants are able to understand inferences such as irony, there is evidence that in the presence of communicative signals, children take into account prior knowledge to interpret actions. For example, when presented with a stuffed animal hopping or sliding into a house, 18-month-old children have a strong tendency to imitate the outcome of an action (e.g. putting a mouse into a house), but not the action's manner (e.g. whether the mouse hopped or slid Carpenter et al., 2005). However, children increase their imitation of manner if they have previously been told about the outcome, and the manner is a novel aspect of the demonstration (Southgate, Chevallier, & Csibra, 2009).

This behaviour suggests that toddlers may take into account prior information to infer whether and which parts of an action demonstration are relevant.

However, for much younger infants, already recognising the communicative intention poses a problem as it requires an understanding of higher order mental representations (Gergely, Egyed, & Király, 2007). In order to address this problem, different mechanisms have been proposed to explain whether and how human infants learn in social contexts: Natural Pedagogy Theory (Csibra & Gergely, 2009, 2011) argues that humans have evolved a specialised learning mechanism that allows them to recognise when a caregiver directs relevant information towards them, so that infants can learn cultural knowledge quickly and efficiently. However, there are a number of accounts that posit that no such mechanism is necessary to account for cultural learning, and that children's understanding of communicative signals is acquired through domain-general processes of learning (e.g. Corkum & Moore, 1998; Gredebäck, Astor, & Fawcett, 2018; Heyes, 2016a; Yu & Smith, 2013).

1.2 Natural Pedagogy

In order to solve the problem of the complexity of processing ostensive-inferentially presented information, Natural Pedagogy (Csibra & Gergely, 2009, 2011) argues that in the presence of communicative signals, such as direct gaze, infant-directed speech and response contingent behaviour, infants actively search for potentially relevant information in the environment. Because these signals indicate the presence of a communicative intention to the child, they have also been called *ostensive signals*. By marking communicatively presented information as relevant to the learner and reduce the cognitive effort required in determining when *relevant* information is presented to them, before infants master the more complex aspects of human communication.

According to Natural Pedagogy, sensitivity to ostensive signals is necessary because many human cultural activities are complex and opaque, and their open-endedness makes it difficult for infants to determine when they observe culturally relevant information (cf. Csibra & Gergely, 2011). The process of recognising communicative intentions is difficult and computationally complex, because "teaching in humans exhibits at least two properties (open-endedness and content opacity) that make the recognition of teaching episodes without ostension untenable" (Tatone & Csibra, 2015, p. 49). Therefore, Natural Pedagogy (Csibra & Gergely, 2006, 2009, 2011) proposes that infants are sensitive to a subset of communicative signals from birth onwards. Csibra (2010) identifies three of them: direct gaze, infant-directed speech, and contingent responses. If infants encounter one of these signals, a referential expectation is triggered that facilitates the attention and encoding of relevant information and provides the foundation for faster and more generalised learning (Csibra & Shamsudheen, 2015).

In the presence of such signals, infants actively seek out the meaning of communicatively presented information, and expect novel, generalisable and type-relevant information (Csibra & Shamsudheen, 2015). Importantly, Natural Pedagogy suggests that such ostensively-communicated information is more generalisable because infants perceive pedagogically demonstrated actions to be representative of other actions of the same type (Csibra & Shamsudheen, 2015; Gergely et al., 2007). By triggering a referential expectation and marking the relevance of an action, ostensive signals allow infants to identify culturally relevant actions from potentially confusing background noise, thereby making the acquisition of opaque, but culturally relevant information faster and easier.

Communicative signals: development

Communicative signals is a general term for different classes of social signals that indicate the presence of communication or its disambiguation. Within the class of communicative signals, we can distinguish *ostensive* signals, i.e. signals that make the intention to communicate manifest, from *referential* signals that link the signal to its referent. Ostensive signals make the intention to communicate manifest and are the basis for inferential communication, since they make the speaker's intention to communicate manifest to the listener.

The most obvious ostensive signal is someone's own name. Addressing someone by their name makes it obvious that they are the intended target of the mesage. Infants from 5 months onwards prefer to listen to their own name over a foil with the same stress pattern (Mandel, Jusczyk, & Pisoni, 1995). Further evidence from six-month-olds suggests that by this age infants listen longer to an auditory stimulus and show increased hemodynamic activity in the fronto-central areas after hearing their own name (Imafuku, Hakuno, Uchida-Ota, Yamamoto, & Minagawa, 2014). Furthermore, electroencephalography has shown that they distinguish their own name from other names 100–380 ms after the word onset, and crucially also show differentiated object processing (Parise, Friederici, & Striano, 2010). After hearing their own name, infants showed a delayed but more sustained Nc component, suggesting a difference in attentional processing (Parise et al., 2010). Eye contact and hearing their own name also revealed activation in adjacent, but non-overlapping regions in the left frontal cortex, suggesting that the infant brain processes these ostensive signals in similar ways (Grossmann, Parise, & Friederici, 2010).

Natural Pedagogy draws considerable support from the observation that sensitivity to some communicative signals, such as direct gaze, infant-directed Speech and contingent responsivity, appears to be present at birth (Csibra, 2010).

Direct Gaze: There is considerable evidence that infants use others' gaze to learn about the world. Newborns already prefer to look at faces with direct gaze over averted gaze (Farroni, Csibra, Simion, & Johnson, 2002). Their preference for faces is driven by the contrast polarity of the human eye (Farroni et al., 2005), suggesting that since birth the eyes (and direct eye contact in particular) are a centre of attention and a source of information (Reid, Striano, Kaufman, & Johnson, 2004). Infants' representation of eyes becomes more specific later in life, and from 3 months onwards they show a preference of human eyes over primate eyes, a distinction they do not yet make shortly after birth (Dupierrix et al., 2014).

Infants start to follow others' eye movements by four months (Farroni, Johnson, Brockbank, & Simion, 2000). However, it is currently debated whether infants' preference for human eyes translates into increased gaze following, as infants show considerable variation in their use of ostensive signals. This might either indicate that the sensitivity to ostensive signals is innate, but infants modulate their sensitivity towards ostensive signals from very early on, or that the use of ostensive signals is learned. Infants initial interest in faces gradually declines (Johnson, Dziurawiec, Ellis, & Morton, 1991) and from four months onwards, infants rely less on simple gaze cues when interacting with caregivers they know well, but gaze remains an important cue for their interactions with strangers (Gredebäck, Fikke, & Melinder, 2010). Sighted children of blind parents also show a reduced face scanning and gaze following, compared to children of sighted parents and this difference increases with age (Senju, Tucker, et al., 2013; Senju et al., 2015; Vernetti et al., 2018). Vernetti et al. (2018) found that 6–10-month-old infants born and raised by blind parents did not show differences in face processing, compared to children growing up with sighted parents. Senju and colleagues (Senju, Tucker, et al., 2013; Senju et al., 2015) highlight that the current evidence does not allow us to conclude that gaze-following is fully learned, as it is possible that children who grow up with blind parents may be desensitized to gaze being a reliable signal. In fact, 8-month-olds showed reduced gaze following for a model that did not reliably cue the appearance of an object on a screen (Tummeltshammer, Wu, Sobel, & Kirkham, 2014).

Like gaze following, the evidence that ostensive signals directly modulate learning of the referentially presented information is debated. The earliest evidence that direct gaze influences infants' memory encoding is from four-month-old infants (Reid & Dunn, 2015), and objects previously cued by direct gaze show a diminished slow wave in a later retest (Reid et al., 2004). Whereas some authors report that infants look longer at objects cued by an actor that engaged in direct gaze (Michel, Pauen, & Hoehl, 2017; Reid & Striano, 2005), others report reduced attention to previously cued objects as indicated by the Nc ERP component, potentially because they processed objects more efficiently during the first cued exposure (Wahl et al., 2013; Michel, Wronski, et al., 2017).

Infant-directed speech: Similar effects have been found with infant-directed speech: Its use reduces the latency with which 4-month-old infants look at target objects after encountered infant-directed-speech (Marno et al., 2015). Infants also prefer the rising and falling intonations of infant-directed speech (Pegg, Werker, & McLeod, 1992) and parents modify their speech accordingly (Fernald, 1985; Fernald & Simon, 1984; Fernald & Kuhl, 1987; Liu, Tsao, & Kuhl, 2007; Kitamura, Thanavishuth, Burnham, & Luksaneeyanawin, 2001; Piazza, Iordan, & Lew-Williams, 2017; Rutherford & Przednowek, 2012).

Direct gaze and infant-directed speech share similar behavioural and neural responses in infants. By the age of six months, infants are more likely to follow gaze when the gaze shift is preceded either by direct gaze or infant-directed speech (Senju & Csibra, 2008). Furthermore, infant-directed speech and direct gaze share a typical ERP signature (Parise & Csibra, 2013) and a particular pattern of alpha oscillations from 4-months onwards (but not two months) (Michel et al., 2015).

Contingency: The third ostensive signal is caregivers' contingent reactivity to the infant (Csibra, 2010), i.e. that parents respond to children's actions. Such contingent responsitivity is a natural aspect of communicative interactions such as dialogue and interactive play and parents respond contingently to their infants in similar ways across a wide range of cultures (Kärtner et al., 2008). Already newborns increase their sucking when it is accompanied by sounds (Floccia, Christophe, & Bertoncini, 1997). After three months, infants prefer imperfect contingencies, ie. responses that are not perfectly aligned to their own behaviour (Bigelow, 1998, 1999). By the age of 8-months, infants are more likely to follow the orientation of agents that respond contingently to their gaze, even if these agents are tea-pot-shaped and lack direct gaze, speech or other human features, suggesting that they potentially expect relevant information in the direction indicated by contingently-responding agents (Deligianni, Senju, Gergely, & Csibra, 2011). They also prefer observing agents that respond to each other contingently and make different predictions about where an agent will go if the agent has previously engaged with another agent in a turn-taking-like exchange of a tone sequence (Tauzin & Gergely, 2018). However, infants do not make such predictions if the agent simply repeated the other's tone sequence (Tauzin & Gergely, 2018).

Fewer studies have investigated whether ostensive signals directly affect the processing of information in infants, although this type of evidence is essential to support Natural Pedagogy's argument that the presence of communicative signals directly influences the processing and integration of information. Here, the strongest evidence comes from behavioural studies on older children or using neuropsychological methods investigating object encoding. Behaviourally, Marno and Csibra (2015) have shown that 18-month-old infants are more likely to imitate a communicatively presented action, even if it is on average less successful in achieving the desired outcome than a non-communicatively presented one. Evidence for a difference in the encoding of communicatively presented information comes from nine-month-old infants, who show a bias for an object's identity at the expense of its location when addressed by an adult using infant-directed speech and direct gaze (Yoon, Johnson, and Csibra, but see: Silverstein, Gliga, Westermann, and Parise), with similar findings in adults towards direct gaze (Marno, Davelaar, & Csibra, 2014).

Furthermore, in the presence of ostensive signals, infants and toddlers should generalise information about the object or matter presented. This is evident in the studies by Gergely et al. (2007) and Egyed, Király, and Gergely (2013). Eighteen-month-olds expect an actor to prefer the same object that a different actor previously ostensively expressed interest in, compared to when the other actor had expressed the interest without addressing the child ostensively (Egyed et al., 2013). According to these studies, the fact that these object-related biases carried over only in the ostensively communicated conditions is evidence that children form a generalised object-centred, rather than a person-specific representation.

However, another function of communicatively presented actions might be that they are more resilient to counter evidence than actions that are observed in incidental contexts. Hernik and Csibra (2015) found that when 13.5-month-old infants were presented with a device that could peel and another that could unpeel bananas, infants were better at understanding the link between the different tools and their outcomes in communicative contexts. They looked longer when the previously demonstrated function of the banana peeler/unpeeler was reversed after ostensive communication, but only if a clear goal leads to a clear discernible outcome, i.e. the state of the banana changed (Hernik & Csibra, 2015). Although infants picked up on a goal's functions in the absence of ostensive communication, their expectations about action conclusions were short-lived and decreased after the second incongruent presentation. Only after being addressed ostensively did they show resilience towards unexpected outcomes and continued to anticipate the previously (and communicatively) demonstrated outcomes in spite of repeated counterexamples.

Taken together, these results provide evidence that infants are sensitive towards the three communicative signals—direct gaze, infant-directed speech and contingent behaviour—suggested by Csibra (2010). However, the extent to which they use these signals to guide their own actions is, at least for younger infants, mixed.

1.3 Alternatives to Natural Pedagogy

There is ample evidence to show that infants are interested in social stimuli. Critiques of Natural Pedagogy reject the claim that direct gaze and infant-directed speech are privileged (Deák, Krasno, Triesch, Lewis, & Sepeta, 2014; Heyes, 2016a) or are more than attention-getters (Gredebäck et al., 2018; Szufnarowska, Rohlfing, Fawcett, & Gredebäck, 2014; Triesch, Teuscher, Deák, & Carlson, 2006; Yu & Smith, 2013). Furthermore, they dispute that ostensive signals create a referential expectation without prior experience, instead communicative meaning manifests itself in the interaction provided by the caregiver. Despite this, some of these theories still propose that ostensive signals influence infants' learning, albeit through different mechanisms and a different developmental trajectory. Rather than being inherently communicative, they become communicative through the interaction between caregiver and infant.

The role of social signals is a particularly controversial aspect in the discussion between Natural Pedagogy and its alternatives. Natural Pedagogy predicts that infants use a subset of social signals to identify learning contexts (Csibra, 2010). One of these instances is infants' increased propensity to follow gaze after encountering infant-directed speech or direct gaze by six months of age (Senju & Csibra, 2008). However, infants are also sensitive to non-ostensive signals and increase their gaze-following towards agents that shiver or engage in other attention-getting activities (Gredebäck et al., 2018; Fawcett & Gredebäck, 2014; Szufnarowska et al., 2014, but see: Csibra, Hernik, Shamsudheen, Tatone, & Senju., 2018). According to these accounts, infants learn to follow gaze, in the same way as they learn the meaning of other social signals. Taken together, social signals such as direct-gaze and infant-directed speech play a role in initiating social learning within the first 2-4 months and other social signals, such as hand movements (Fausey, Jayaraman, & Smith, 2016) and their own name (Parise et al., 2010), are quickly added and supplement and supersede infants' use gaze and infant-directed speech. However, the underlying mechanism as to why social signals lead to increased gaze following is still debated. Whilst Natural Pedagogy suggests that infant-directed speech and direct gaze create a referential expectation of novel, generalisable information, critics argue that they are simply more attention-grabbing and arousing (Gredebäck et al., 2018; Szufnarowska et al., 2014). Natural Pedagogy does not rule out that communicative signals increase infants' attention or arousal. However, an increase in arousal is necessary for alternative accounts of infants' social learning. Therefore, Chapters 2 and 3 of this thesis will also investigate correlates of infants' arousal during communicatively and non-communicatively presented actions.

Alternative accounts to Natural Pedagogy have suggested that this referential expectation develops through the interaction with caregivers (e.g. Deák et al., 2014; Triesch et al., 2006; Yu & Smith, 2013). Although some of these accounts still require a perceptual preference towards communicative signals, such as direct gaze (Triesch et al., 2006), communicative signals, at least early in development, may not carry a referential expectation towards meaningful content with them. This expectation only develops through rewarding stimulation in the presence of communicative signals. Therefore, as long as direct gaze and infant-directed speech are perceptually interesting on their own, simulations show that the referential expectation can be learned if gaze following is rewarded by intrinsically interesting outcomes (Corkum & Moore, 1998; Michel, Wronski, et al., 2017; Michel, Pauen, & Hoehl, 2017; Triesch et al., 2006). Indeed, not all cues are equal and infants will only learn to follow gaze for face-like objects in which the 'eyes' match the contrast polarity of the human eye (Michel, Wronski, et al., 2017; Michel, Pauen, & Hoehl, 2017). This is mirrored by computational models on gaze-following. In models developed by Triesch et al. (2006) simulated agents were able to acquire gaze following given a basic set of rewards and preferences. However, models were only successful if infants showed a perceptual preference to eyes in the first place. Such a perceptual preference towards eye gaze does not necessarily imply that they immediately generate referential expectations.

Other studies have highlighted the high prevalence of social signals during early life and therefore may contribute to their relevance to infants in guiding their learning. The constrained environment that infants experience (Piantadosi & Kidd, 2016) might privilege the communicative signals discussed by Csibra (2003), because of the role they play in providing a predictable environment to the child. For example, direct gaze might be such a relevant social stimulus because faces are one of the most frequent visual stimuli children experience during their early months of life (Fausey et al., 2016). Their prevalence contributes to a highly structured environment that might allow a child to develop an understanding of social signals as communicative from the bottom up by providing 'a curriculum for learning' (Smith, Jayaraman, Clerkin, & Yu, 2018). Therefore, even a perceptual preference can be scaffolded by the environment.

Other critics have argued that communicative signals are simply arousing to infants and by providing a more arousing context, support social learning by enhancing gaze following (Gredebäck et al., 2018; Szufnarowska et al., 2014) and memory encoding (cf. Kensinger & Corkin, 2004). Furthermore, infants may exploit additional cues that would not traditionally be considered ostensive, such as hand movements. At the age of 12 months, hand movements play a more important role in guiding an infants' attention than gaze, because they are a more reliable cue of an adult's object manipulation than gaze (Yu & Smith, 2013). The link between ostensive communication and infant learning is not straightforward either, as data from word learning shows. At 18 months, children privilege object salience over gaze information in associating objects and words (C. Moore, Angelopoulos, & Bennett, 1999). Only by 24 months, children reliably choose the referenced object, rather than a visually salient distractor (C. Moore et al., 1999). Findings like these highlight the complex relationship between communication, perception and learning.

Currently, such alternative accounts are largely underspecified with regard to theory and because of that, have largely focussed on inductive data mining of infants' early development (e.g. Fausey et al., 2016; Yu & Smith, 2013). Furthermore, many empirical papers draw upon a wide range of different theories, with little overlap and a lack of clear research agenda. Because of this, it can be difficult to assess theoretical predictions that generalise beyond a few limited experiments. Natural Pedagogy is subject to the opposite criticism, as few studies have investigated whether social signals are used in caregiver-child directed interactions as predicted by this theory. For example, research into infants' understanding of humour suggests a more complicated relationship between social signals and teaching.

Parents' use of ostensive-referential signals is not restricted to pedagogical interactions. Parents use more ostensive signals while joking, but more referential signals (such as pointing and gaze shifts) are used when the action presentation was generalisable such as in pretence and sincere contexts (Hoicka, 2016). Such findings highlight the importance of referential signals in social learning, since establishing reference may be an equally important aspect of successful transmission of information (cf. Spike, Stadler, Kirby, & Smith, 2016). Therefore, Experiment 2 in Chapter 2 also explores the effect of referential signals, in addition to ostensive signals, on infants' neural correlates of action understanding. Natural Pedagogy is also critiqued because it requires an early understanding of communicative intent. R. Moore (in preparation) argues that ostensive signals cannot function as a marker for learning contexts as proposed by Csibra (2010). The mere act of recognising communicative intent cannot explain which inferences children make from the interaction without relying on a complex understanding of belief states and perspective taking. Therefore, a simple code-based understanding of communicative intent is insufficient to explain infants' learning in a situation. A more complex understanding of communicative intent, however, would be too computationally complex and not solve the problem of how infants understand ostensive-referential signals. Consequentially, it would require an explanation for the very thing it attempts to explain (R. Moore, in preparation).

Contingency embodies communication

Parents' contingent behaviour on the child's actions structures the input in important ways. On the one hand, pedagogical interactions are structured by parents to exploit infants' attention and therefore facilitate learning. On the other hand, they allow infants to learn the ostensive function of communicative signals.

Contingent responsivity (e.g. Deligianni et al., 2011; Q. Wang et al., 2012) is in itself a highly predictive process that mirrors natural dialogue. The timing of cues is a natural aspect of interactions (R. Moore, 2014; Rochat, 2007). By providing structure to actions and timing it to the learner's needs. Caregivers exploit their children's attention and children show faster word learning in shared attention contexts because adults name objects that are already in the focus of children's attention (Axelsson, Churchley, & Horst, 2012; E. V. Clark, 2010; Tomasello & Kruger, 1992; Tomasello, Strosberg, & Akhtar, 1996; Stephens & Matthews, 2014). Stimulus-response contingency (e.g. Deligianni et al., 2011; Q. Wang et al., 2012) is particularly useful to learning, as it times responses to the learner's attention.

Mothers are more likely to name or look at objects, after the child has vocalised, looked at the mother or handled an object, thereby decreasing potential noise that might disrupt associative learning (Chang, de Barbaro, & Deák, 2016). Parents of 11-month-olds are more likely to respond to vocalisations when the child looks at their parents, and parents' responsivity is predictive of children's language development of up to two years later (Donnellan, Bannard, McGillion, Slocombe, & Matthews, 2019). Heyes (2016a) notes, the adaptive function of pedagogical interactions depends "on what the teacher intends and knows, rather than on what the infant intends and knows" [p. 286].

Adjustments in action structures mirror adjustments in infant-directed speech

Infant-directed actions share many of the structural adjustments that are found in language. For example, infant-directed speech has many features that contribute to the learning of syllables, words and sentences. When interacting with infants, caregivers accentuate features that help to segment and interpret the speech input, providing similar structural adjustments that are also used in foreigner directed speech (Eaves, Feldman, Griffiths, & Shafto, 2016; Uther, Knoll, & Burnham, 2007). The overemphasised syllables contribute to the segmentation of words (Floccia et al., 2016; Schreiner & Mani, 2017) and phonemic categories (Eaves et al., 2016). The action-equivalent 'motionese' also overemphasises actions and their boundaries (Brand et al., 2002), making action demonstrations easier to segment and allow children to extract which parts of an action are relevant. Furthermore, ostensive signals are particularly prevalent at segment boundaries (Brand et al., 2007), and are useful to segment the continuous stream of actions. They provide ways of temporal reference, in a similar way that pointing and gaze direction provide spatial reference (cf. Saylor et al., 2007).

Sparking curiosity to sustain attention

But not all aspects of infant-directed speech make it more predictable. For example, the falling and rising intonations in infant-directed speech are less predictable compared to adult-directed speech, but the degree of novelty potentially increases infants' arousal and interest in speech itself, which in turn facilitates learning (Räsänen, Kakouros, & Soderstrom, 2018). This supports models of curiosity-based learning, according to which infants actively seek out information that is sufficiently different to be novel, but not too different that it cannot be integrated into their existing knowledge (Twomey & Westermann, 2015, 2017).

The different conceptualisation of the role of social signals emerges because Natural Pedagogy and statistical learning accounts have different evolutionary accounts of the human ability to engage in cultural learning. Whilst Natural Pedagogy draws upon an innate sensitivity towards a subset of communicative signals that create a referential expectation that the following information is meaningful, so far domain-general statistical learning accounts have not given an explicit evolutionary account of human cultural learning, possibly with the exception of Heyes (2012, 2016a) and Oudeyer and Smith (2016).

Appealing to curiosity as the driving force of infants' learning (Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Kidd, Piantadosi, & Aslin, 2012; Oudeyer & Smith, 2016; Mather & Plunkett, 2011; Twomey & Westermann, 2017) might offer an intrinsic motivational factor that facilitates how infants learn the relevance of social communicative signals, particularly since curiosity shares a fundamental property of communication: the provision of novel, relevant information (Grice, 1957; Sperber & Wilson, 1995; Wilson & Sperber, 2012). Curiosity may act as a driver to increase learning in general and actively search for sources of input that are sufficiently familiar *and* novel, so that they can be used to acquire novel information and integrate it into existing knowledge. Because of the role that parents have as caregivers, they provide a highly structured input (cf. Goldstein et al., 2010) to fulfil the child's physical and emotional needs (Heyes, 2016a).

In conclusion, interactions between caregivers and children are not only more predictable, but caregivers actively shape the input children receive and exploit their social and attentional needs. Through this process, parents scaffold infants' learning. Infants may still possess an attentional bias towards communicative signals, such as direct gaze and infant-directed speech, however the referential expectation that is necessary for facilitating learning only develops through infants' interactions with caregivers.

1.4 Methods to study how communicative signals affect action semantics

This PhD uses a wide range of different methodologies to investigate how communicative signals might influence the processing of actions in infancy. Chapter 2 uses EEG to investigate the neural signature of action processing after communicative and non-communicative signals in 9-month-old children. Chapter 3 investigates a similar question but uses eyetracking measures–namely anticipatory looking and pupil dilation–in 7-month-olds instead. In Chapter 4, uses a behavioural measure to study whether communicative signals might influence the interpretation of an action by providing different segmentation information in 18-month-old children. The following sections will provide a brief summary of each of these methodologies and the developmental trajectories of the underlying mechanisms.

EEG

The advance of neuroimaging methods, in particular, EEG, has allowed us to study infants' understanding of meaning much earlier than behavioural studies have. Furthermore, it is possible to compare infants' neural responses to adults to make inferences about the extent that infants already have (or don't have) an adult-like understanding of actions and their meaning.

Key developments in the social brain are the processing of faces, direct gaze, the understanding of motion and others' actions and joint attention (Grossmann & Johnson, 2007; Ní Choisdealbha & Reid, 2014). Several neural markers are important for the processing of social and action-related development in infancy. Some of these components, like the Nc, are infant-specific and no equivalent Others, like the N400 or N170, are well-studied in adults and infants, however generally show a later onset and peak, compared to their adult equivalents (de Haan, 2007; Kuefner, De Heering, Jacques, Palmero-Soler, & Rossion, 2010).

From birth onwards, infants prefer looking at faces and face like configurations (Farroni et al., 2005), and a recent study suggests that even at the fetal stage infants prefer looking at face-like top-heavy configurations (Reid et al., 2017). Facial information is processed in the fusiform face area, which responds stronger to intact, rather than scrambled faces, houses, or other body parts (Kanwisher, McDermott, & Chun, 1997). The fusiform face area already responds to the passive viewing of faces in 2-month-old infants (Tzourio-Mazoyer et al., 2002).

In ERP studies, the N170 ERP on the occipito-temporal scalp is associated with the perception of faces (Bentin, Allison, Puce, Perez, & McCarthy, 1996; Kuefner et al., 2010). From four years onwards, the N170 only shows small decreases in latency over development (Kuefner et al., 2010). In adults, the N170 shows a faster response to upright, compared to up-side-down faces (Bentin et al., 1996), an effect not found in six-month-old infants, who only distinguish between human and ape faces (de Haan, Pascalis, & Johnson, 2002). The N170 is sensitive to emotional facial expressions (Hinojosa, Mercado, & Carretié, 2015).

In infants, the processes associated with the N290 (corresponding to facial features and configurations) and P400 ERP (corresponding to the integration of emotional processes) components (de Haan & Nelson, 1999; de Haan et al., 2002; Leppänen, Moulson, Vogel-Farley, & Nelson, 2007; Peykarjou & Hoehl, 2013). Already from 3-months onwards, infants show a faster N290 response towards faces, compared to cars. Furthermore, at four months, the N290 is also highly sensitive to the configuration of the eyes and face (Farroni, Johnson, & Csibra, 2004), suggesting that from very early in life show sensitivity towards faces and eyes.

Neural signatures for meaning and action

The neural marker of meaning is the N400 ERP component. The N400 is a time locked response to a violation in the meaning of a word, gesture, action or similar stimuli within their wider context (Kutas & Federmeier, 2000, 2011). In adults, the N400 is characterised by a negative deflection peaking around 400ms for stimuli that do not fit into a primed context. Recently, it has been argued that the N400 amplitude responds to probabilistic predictions of the content within its wider context (Rabovsky, Hansen, & McClelland, 2018).

Numerous studies report the absence of the linguistic N400 in infants as old as 12 months (Friedrich & Friederici, 2005a, 2005b, 2010), however, Friedrich and Friederici (2011) were able to detect a very late (600-900ms) N400-like effect in 6-month-old children in a study on word learning. This effect was only found directly after a training with word-picture associations, and the effect disappeared when infants' memory was tested on the following day. Therefore, infants may interpret words as being referential even from 6-month on, but are not able to form stable memory associations. Furthermore, infants as young as 9 months show a reliable N400 response towards familiar word-picture associations if tested on their own mother's voice (Parise & Csibra, 2012).

The action N400 emerges around the same age, and it is found in 9-, but not 7-month-olds Reid et al. (2009). This is slightly later than infants are able to anticipate the outcomes of familiar eating actions (Green et al., 2016; Hunnius & Bekkering, 2010; Kochukhova & Gredebäck, 2010). However, already by the age of five months, infants respond to familiar actions with a Positive Slow Wave, a marker of familiarity (Michel, Kaduk, Ní Choisdealbha, & Reid, 2017).

Infants' understanding of actions is also indicated by activity in motor-related frequency bands, and 12-month-old infants show greater activation in the *mu*-frequency band for unexpected, compared to expected actions (Stapel, Hunnius, van Elk, & Bekkering, 2010). Nine-month-old infants show greater activation when observing others' actions in the same frequency bands that are active when they are executing actions themselves, irrespective of whether they are able to carry out the observed actions themselves (Southgate & Begus, 2013).

Infants' learning and attention is also indexed by increased activity in the theta band, but the responsivity of theta activity to different stimuli changes over maturation (Michel et al., 2015; Orekhova, 1999). Likewise, although adults show increased power in the theta band towards unexpected than expected action outcomes, no such effect has been observed for 7- and 9-month-old infants (Reid et al., 2009). Theta band activity may also indicate an information-seeking process, and 11-month-old infants show greater theta activation when they are being addressed by someone speaking their language (Begus, Gliga, & Southgate, 2016).

Eye-tracking and anticipatory looking

Eye-tracking is a particularly suitable method to study infants' action understanding, as it allows us to investigate whether infants are able to anticipate the outcome of actions before their conclusion. Furthermore, anticipating movements and actions of others forms a key aspect of communication and dialogue (Huettig & Altmann, 2005; Sebanz & Knoblich, 2009; Yamashiro & Vouloumanos, 2018).

Infants are able to anticipate grasping actions from six months onwards, taking into account the goal and hand shape of the action, an ability that improves with age (Ambrosini et al., 2013). From 15-months onwards, infants also use the velocity of the reaching movement to anticipate whether the outcome is a small or large target location, which 9- and 12-month-old infants were not yet able to do (Stapel et al., 2015). Hunnius and Bekkering (2010) found that already by 6-months of age, infants are able to anticipate action outcomes for the use of familiar objects, however even after repeated observation infants do not readily associate new goal locations to familiar actions.

Infants' ability to predict actions also depends on perceptual features, in particular, the salience of any of the three aspects of action understanding – manner, outcome and situational constraints. The salience of the goal and the rationality of the actions contribute the to their ability to predict and imitate actions (e.g. Adam et al., 2016; Elsner, 2007; Elsner & Pfeifer, 2012; Moher et al., 2015). By twelve months, infants are more likely to anticipate a human hand (but not a mechanical claw) reaching for a high saliency goal consisting of multiple objects, compared to a low saliency goal consisting of only one object (Adam et al., 2016). Infants at 12 months of age are faster at anticipating actions towards a large, compared to a small goal (Henrichs et al., 2012).

Generally, many of these studies have found that infants find human reaching movements, as exemplified by arms or hands easier to predict than those of robot claws or rods (Adam et al., 2016; Woodward, 1998). However, familiarising infants with a human operating a claw prior to demonstrating its effect potentially allows them to anticipate claws like human hands (Boyer, Pan, & Bertenthal, 2011).

Pupil dilation

The primary function of the pupils is the control of the amount of light entering the eye. At constant light, the pupils continuously oscillate, as they are constrained by the sympathetic and parasympathetic activity of the brain (Hepach & Westermann, 2013, 2016). Because of the involvement of the sympathetic and parasympathetic nervous system, different cognitive processes also influence the dilation of the pupils, beyond what would be expected by the change of brightness in the environment. They have indicated higher pupil dilation during cognitive load (Porter, Troscianko, & Gilchrist, 2007; Verney, Granholm, & Marshall, 2004), others' emotions (Aktar et al., 2018; Geangu, Hauf, Bhardwaj, & Bentz, 2011; Jessen, Altvater-Mackensen, & Grossmann, 2016) and expectancy violations (Jackson & Sirois, 2009; Wetzel, Buttelmann, Schieler, & Widmann, 2015).

Cognitive responses are linked to different components in the pupil dilation. Online measures of the pupil dilation are based on the pupils' immediate response to the presentation of the stimulus. For example, 8.5-month-old infants show an increased event-related pupil dilation towards a re-emergence of a train from a tunnel, if the train has a different colour than the one it had upon entering the tunnel (Jackson & Sirois, 2009). Pupil dilation measures are also linked to the processing of social information in developmental samples. For example, 14 month-olds, but not 10-month-olds, show increased pupil dilations towards actions that do not fit an emotional context, e.g. when an angry actor performs a positive action (Hepach & Westermann, 2013). Furthermore, 6- and 12-month-old infants show increased pupil dilations when hearing a recording of another child's distress (i.e. crying), compared to positive or neutral vocalisations (Geangu et al., 2011). Some of the early responses to the semantic mismatch of words and pictures have been linked to the N400 component in ERP research (Kuipers & Thierry, 2011).

Other pupillary responses reflect a slower, emotional response, like the change in re-dilation of the pupils in the pupillary light reflex (PLR). The PLR is the automatic response of the pupils towards the change from a dark to a bright light. When the light suddenly increases, the pupils constrict, and this initial constriction is followed by a re-dilation. This process lasts for about 5 seconds, before the pupils resume their normal oscillations again. Before the pupils are fully re-dilated, the pupil size is affected by emotional arousal (Hepach & Westermann, 2016).

The PLR develops in infants between 30–35 weeks (Robinson & Fielder, 1990) and has been implicated in children's socio-emotional development (Hepach, Vaish, & Tomasello, 2017). Children from two years onwards show an increased pupil dilation towards situations in which they observe another person in distress but cannot help (Hepach, Vaish, & Tomasello, 2012; Hepach, Vaish, Grossmann, & Tomasello, 2016) and when they accidentally caused harm to someone but a third person (rather than the child) helps the victim (Hepach et al., 2017). Previous research has also shown an enhanced PLR at 9–10 months to be predictive of an Autism diagnosis at 36 months (Nyström et al., 2018), and that siblings of children diagnosed with autism also show an enhanced PLR (Nyström, Gredebäck, Bölte, Falck-Ytter, & EASE Team, 2015). The link between the emotional response in the PLR signal and the social learning differences in autism make the PLR an interesting candidate to investigate whether children's learning in social contexts is linked to their emotional processing. Currently, the PLR has not been used to study whether communicative signals affect the PLR or action understanding directly. However, its slower response might offer an interesting window into children's understanding of a social context over a longer period of time. Furthermore, since previous research has linked the PLR to arousal, finding an increased PLR after communicative signals would potentially support arousal-driven accounts of the effects of communicative signals on learning.

Behavioural measures: imitation

Behavioural measures, in particular, their imitation, are still one of the most important sources of our understanding of children's learning of actions. The literature on early imitation discusses two distinct stages of imitation that present during infancy. Studies on neonatal imitation of a basic set of actions, such as tongue protrusions, mouth openings, lip protrusions and index finger protrusion (Meltzoff & Moore, 1977, 1989; Meltzoff et al., 2017; Nagy, Pal, & Orvos, 2014) are highly contested (Anisfeld, 1991; Ray & Heyes, 2011; Heyes, 2016b; Jones, 1996, 2007; Oostenbroek et al., 2016). However, by the second to the third month of their life, infants show no evidence of matching tongue protrusions or other potentially imitative behaviours disappears until six to eight months of age (Jones, 2009). By this age, they start to imitate basic vocalisations, such as 'ah' (Jones, 2007). The vocalisation of 'Eh-eh' follows at 12 months, and infants imitate tap-table movements by 12, 'Bye bye' by 12, clap hands by 10, sequential finger movements by 16 months, putting their hand on the head by 16 months and reliably imitate tongue protrusions by 18 months (Jones, 2007). Hence, the second year represents the emergence of learned imitative behaviours (Jones, 2007, 2009).

Only a few studies investigated the imitation of actions in communicative and non-communicative contexts. Behavioural studies on toddlers also support the argument that communication affects action imitation. Fourteen-month-old infants are more likely to imitate an unnecessary head-touch instead of using the preferred hand to activate a lamp in an ostensive context, but not when they are merely observing the actor without being addressed (Király et al., 2013). However, they only do so when the action has an apparent goal (i.e. the switch turns on the light), but not when the action has no clear goal, i.e. the head touch does not lead to the light being switched on (Király et al., 2013). In addition, Nielsen (2006) presented 12, 18 and 24-month-old children with an actor engaging in a series of actions of which not all were necessary to achieve the desired outcome, and presented these actions either by an aloof or communicative model. Whereas the 12-month-olds only copied the necessary actions, 18-month and 24-month-olds prioritised communicatively presented actions. These studies show that ostensive signals influence children's imitation of actions from 18 months onwards.

However, other studies have found that children take into account ostensive signals only from about four years in order to decide how to learn actions, and instead use the intentionality of an action to guide their own object exploration. L. P. Butler and Markman (2012, 2013) show that 3- and 4-year-old children respond differently both to whether an action is presented communicatively as well as if the action is presented accidentally. In this study, an experimenter demonstrated 3- and 4-year-old children the magnetic properties of an object either accidentally, intentionally while communicating with the child or intentionally with no communication. While there was no difference between the age groups in the exploration of a non-magnetic variant of the object in the condition without communication, the results show that communication significantly increased exploration by 4-year-olds, but not 3-year-olds. At the same time, reduced exploration in the accidental condition was found in for 3-year-olds, but not 4-year-olds. This suggests the importance of intentionality and communication changes between 3 and 4 years of age in terms of understanding actions. Schmidt, Rakoczy, and Tomasello (2011) obtained similar results in 3-year-old children that either observed an action being introduced as familiar or made up on the spot, and during which they either observed the action incidentally or were directly addressed by the actor: For familiar actions, children were less likely to protest and showed increased imitation, but being addressed communicatively did not change their protest or imitation. Therefore, for younger children, the intentionality of an action might be more important than the communicative presentation (L. P. Butler & Markman, 2013; Schmidt et al., 2011).

1.5 Communicative signals and action understanding: Summary

This question forms the core of the thesis that will be investigated in the three experimental Chapters 2, 3 and 4 using a wide range of methodologies. Chapter 2 described a set of experiments using EEG to investigate whether ostension on its own, or ostension in combination with referential signals change infants' and adults' interpretation of actions as meaningful. Chapter 3 describes an eye-tracking study on 7-month-old infants to investigate whether ostensive signals help them to anticipate familiar, unexpected and novel action outcomes. Chapter 4 takes a different perspective on the contribution of ostensive signals towards action understanding by discussing a behavioural experiment on toddlers' use of ostensive signals in segmenting actions.

The evidence suggests that infants and toddlers take into account numerous signifiers of ostensive communication, beyond the three basic ostensive signals suggested by Csibra (2010), to inform whether or not to generalise or imitate new, socially presented information. However, there is a discussion on whether or not infants show an inherent sensitivity towards a subset of these signals. If pedagogical signals are indeed special in putting infants into a 'learning mode' that makes infants more likely to understand actions as symbolic and meaningful, then they learn to pick up cues that modify these expectations very early in life. Currently, there is little research on the underlying mechanisms of how communication might affect social learning, particularly in pre-verbal children.

In particular, there is little research on how communication affects infants' representations of meaning. For example, it is unclear whether communication directly affects the interpretation of an action, or modulates action understanding through mechanisms of attention and arousal. In order to address this question, the experiments presented in Chapter 2 and 3 provide measures of attention and arousal. The EEG studies reported in Chapter 2 allow us to contrast a semantic understanding of actions, as measured by the N400 component, with one driven by arousal, as measured by the Nc component. Furthermore, the eye-tracking data presented in Chapter 3 uses anticipatory looking as a measure of action understanding and prediction, but also providing analyses of pupil dilation to record infants' arousal towards ostensive and non-ostensive signals. Therefore, both studies can provide important information in testing the potential contributions of arousal in infants' use of communication during action comprehension. Finally, the role of ostensive signals as providers of structural information about actions and action sequences provides an important potential mechanism of allowing infants to learn about actions and their meanings. Chapter 4 also contributes to the discussion of the underlying mechanisms of the contribution of communication towards action understanding by suggesting that communicative signals also contribute to the segmentation of action sequences. Taken together, this thesis will be looking at whether communicative signals modify infants' interpretation of actions, whether communication increases the arousal, and whether communicative signals can help toddlers to segment everyday actions.

Chapter 2

Paper One: The effect of communicative signals on the semantic interpretation of actions: Two ERP studies

Human culture can be defined as the transmission of concepts, beliefs and behaviours that are not genetically determined as such, but transmitted from one generation to the next through social learning (Laland & Brown, 2011; Mesoudi, 2011; Richerson & Boyd, 2005). The capacity of humans to engage in such social learning has been considered key in the transmission of cognitively opaque, culturally arbitrary actions. Human social learning is rooted in a basic understanding of communication (Sperber & Wilson, 1995). Whereas most animal communication systems are based on direct mappings between signals and meanings that are either innate or learned through associations, human communication is inferential and the meaning of an utterance is reconstructed (Scott-Phillips, 2015). Every human communicative act has two channels—the first makes the intention to communicate manifest, the second to transmit the content of the information (Sperber & Wilson, 1995). Once the communicative intention is manifest, the interlocutor can inferentially reconstruct the *meaning* of the communication, i.e. the content of the utterance (Scott-Phillips, 2010a, 2010b, 2015; Sperber & Wilson, 1995). Because the actual content of the message is inferred, the same message can have a different meaning depending on the context. Infants may already be sensitive to a subset of these communicative (ostensive) signals (Csibra, 2010): direct gaze, infant-directed speech and contingent reactivity. They act as a code-based communicative system that puts infants into a receptive mode towards acquiring new information through social learning. In the presence of these signals, infants are more likely to follow gaze (Senju & Csibra, 2008) and imitate actions (Marno & Csibra, 2015; Nielsen, 2006). Furthermore, infants and young children have an expectation for novel and generalisable information (L. P. Butler & Markman, 2012, 2013, 2014). This raises important questions about how infants use communicative signals to make predictions about other people's actions in order to learn from them.

2.1 Infants' expectations about others' actions

Infants have a basic understanding of actions in terms of goals and outcomes, and quickly learn to anticipate the actions of the people around them (Gredebäck & Melinder, 2010; Henrichs et al., 2012; Kochukhova & Gredebäck, 2010; von Hofsten & Rönnqvist, 1988). Previous research has used anticipatory looking (Hunnius & Bekkering, 2010), pupil dilation (Gredebäck & Melinder, 2011), desynchronisation of the μ-rhythm (a neural marker of motor activation) in the EEG (Stapel et al., 2010), and violation of semantic expectations (Reid et al., 2009) to investigate whether infants understand and predict everyday actions. Many of these studies have investigated conventionalised actions with clear goals, such as drinking from a cup, feeding actions, and similar.

Pupil dilation and anticipatory looking studies (Gredebäck & Melinder, 2011, 2010) suggest that infants show larger pupil dilation for surprising actions, such as observing other people being fed with a spoon when these actions were directed towards the hands instead of the mouth. These observations were moderated by cultural experience, for example using forks in Western European, and chopsticks in Asian countries (Green et al., 2016), age (Gredebäck & Melinder, 2010, in 6-month-olds), and whether feeding actions are rational by bringing food straight to the mouth, or placing the food on the receiver's hand first (Gredebäck & Melinder, 2010, 2011, with 6- and 4-month-old children respectively). However, infants did not show increased pupil dilations if the feeding action was obstructed by an object (Gredebäck & Melinder, 2011). Hunnius and Bekkering (2010) investigated whether 6–16-month-old infants and adults anticipate goal-directed actions, involving different objects—a phone (to the ear), a brush (to the hair) and a cup (to the mouth). After the first trial, infants only reliably anticipated the target of the cup. However, over the course of the experiment, all age groups started to reliably predict the other semantically congruent actions (e.g. brush–hair), but not incongruent ones (e.g. brush–mouth). Only the adult group quickly adjusted to new, incongruent goal locations. These results suggest that infants take into account semantic congruence from at least six months onwards and require multiple exposures to reliably predict congruent action outcomes. However, they find it difficult to override previous knowledge and predict incongruent action outcomes.

2.2 Communicative signals modify expectations about actions

Although infants are able to form predictions about actions through observation alone, many actions remain cognitively opaque to the observer. Csibra and Gergely (2009, 2011) propose that infants are especially attuned to a specific set of communicative signals that allow them to engage in fast social learning and copy actions even if they do not fully understand their purpose. Importantly, infants do not simply pay more attention to social partners who ostensively communicate with them, they also expect that the information presented to them is relevant to them and that it conveys novel, generalisable knowledge (Csibra & Gergely, 2009). Many studies have shown that the presence of communicative signals can alter children's understanding and imitation of actions. For example, 18- and 24-month-old infants were more likely to copy actions in a social-communicative context, compared to one where the demonstrator acted aloof and uninterested in the child (Nielsen, 2006). Fourteen-month-old children are more likely to imitate an adult turning on a lamp with their head in an ostensive context, but prefer using their hands after merely observing the adult in a non-communicative setting. However, they only do this for salient action goals, but not when the action has no clear effect, i.e. the head touch does not turn on the light (Király et al., 2013).

Children also make different inferences about the meaning of actions in different communicative contexts: Eighteen-month-olds only copied the manner of the action when they had been informed about the action's goal prior to the action's demonstration, but not when they received no prior information about the goal (Southgate et al., 2009). A control group that explored the action outcome on their own did not increase their imitation of the action manner. Therefore, infants interpret the manner of the action as relevant when the goal has already been communicated, but focus on the goal when they received no prior information. This suggests that they already have an understanding of communicative relevance. In summary, understanding goals *and* communicative signals are both important in social learning. Infants are more likely to imitate actions with clear goals and that are presented communicatively (Adam et al., 2016; Király et al., 2013; Nielsen, 2006; Southgate et al., 2009).

Alternative accounts to Natural Pedagogy reject the claim that infants are sensitive to communicative signals in early infancy (Gredebäck et al., 2018; Heyes, 2012, 2016a; Szufnarowska et al., 2014). They argue increased rates of gaze following and learning are better explained by general mechanisms of arousal and attention, and that communication is simply one way of eliciting attention and arousal in infants. Therefore, infants' increased gaze following after encountering communicative signals could also be based on a more general mechanism of arousal and attention. According to this account, infants are more likely to follow gaze after arousing or attention-getting events, simply because communicative signals are more arousing (c.f. Szufnarowska et al., 2014; Gredebäck et al., 2018). However, Marno et al. (2015) found no increase in four-month-olds' pupil dilation when comparing normal speech, backwards speech and a no-speech control condition, indicating that the presence of communication may not lead to an increase in arousal on its own. Furthermore, there is also evidence of a shared neural signature of communicative signals, such as infant-directed speech and direct gaze (Parise & Csibra, 2013), suggesting distinct processing of ostensive signals from at least as early as five-months onwards.

2.3 Electrophysiological correlates of action understanding and communication

Although studies have shown that the presence of communicative signals increases gaze following, and affects the imitation of actions and the interpretation, we currently know little about the neural mechanisms of how communication affects the interpretation of actions, and thereby infants' learning about and the imitation of other people's behaviour. The study of event-related potentials (ERP) can help to identify the underlying cognitive processes of infants' understanding of actions and communication. There have been several ERP components that have been linked to action understanding, communication and general cognitive processing, and three ERP components are of particular interest:

- The Pb, an infant-specific ERP component (Webb, Long, & Nelson, 2005) that has been reported in research on joint attention and recognition (Kopp & Lindenberger, 2011, 2012). A similar component has also been found in infants' processing and integration of ostensive signals (Parise & Csibra, 2013),
- The Nc, an infant-specific marker of attention (Courchesne, Ganz, & Norcia, 1981; Reynolds & Richards, 2017; Richards, 2003; Webb et al., 2005)
- The N400, a marker of semantic expectancy violation (Amoruso et al., 2013; Kutas & Federmeier, 2000, 2011; Reid et al., 2009)

In the following two experiments, we measured these ERP components to study how communication changes the interpretation of goal-directed actions. We presented infants and adults with videos and images in which participants were either directly addressed through direct gaze and infant-directed speech, or observed an actor talking to themselves avoiding direct gaze and using adult-directed speech (c.f. Yoon et al., 2008). These videos were followed by a series of images that depicted everyday actions consisting of a picture priming an action (e.g. eating with a spoon), followed by an outcome picture that either fits the semantic context (e.g. spoon going into mouth) or violates it (e.g. spoon going to ear). According to previous research (Reid et al., 2009; Hunnius & Bekkering, 2010), 9-month-old infants are familiar with these actions. Whereas the first experiment in this paper does not show the actors using referential cues towards the object, the actors in the second video provide referential signals towards the objects. ERPs can provide invaluable information on underlying cognitive processes of how infants understand these images. In the current study, we will be looking at the ERP response towards the outcome of such familiar actions. In the following section, we will discuss these three ERP components in more detail and draw competing hypotheses based on previous research.

The Pb component

The Positive before (Pb) is an early infant-specific ERP preceding the Negative Central (Nc) component at around 200–400 ms (Kopp & Lindenberger, 2011; Karrer, Karrer, Bloom, Chaney, & Davis, 1998; Webb et al., 2005) and has been linked to joint attention and memory (Kopp & Lindenberger, 2011, 2012) and conceptual interpretation (Karrer et al., 1998). Webb et al. (2005) report a more positive Pb amplitude for unfamiliar over familiar faces, but the opposite effect for familiar over unfamiliar objects. Furthermore, 5-month-old infants show an ERP central component with selective sensitivity for signals indicating the presence of ostensive communication, such as direct gaze and infant-directed speech (Parise & Csibra, 2013), similar in morphology and scalp distribution to the Pb.

Kopp and Lindenberger (2011, 2012) have found more positive deflections for the Pb in instances of low joint attention towards objects. In their studies, four- (Kopp & Lindenberger, 2011) and nine-month-old (Kopp & Lindenberger, 2011) infants were habituated towards a set of objects in the presence of an adult who either engaged with the infant and the object (high joint attention) or only the object (low joint attention). The high joint attention training the model pointed at the object and looked at the infant and spoke in infant-directed speech. In the control condition, direct gaze was avoided, actors only looked at the object and the speech was a recording taken from another session. Therefore, although both conditions used infant-directed speech, the actor in the low joint attention condition did not address the infant or engaged in eye contact or referential signals. Afterwards, infants were presented with the familiar and a novel set of objects and had their EEG recorded. In a second session, a week later, infants were presented with the same set of objects again and a new, third set of objects. Differences in the Pb component only appeared during the second sessions. Four-month-olds showed an enhanced positive Pb deflection for the low joint attention condition, and the nine-month-olds only displayed the more positive Pb for familiar objects in the low joint attention condition.

Due to its latency, the presence of a Pb would indicate an early sensitivity towards the presence of communication. The findings by Parise and Csibra (2013) suggest that the Pb response linked to the main effect of communication may indicate a preparedness-to-learn, in line with Natural Pedagogy (Csibra, 2010). The results by Kopp and Lindenberger (2011, 2012) and Karrer et al. (1998) suggest that the Pb may also be linked to object processing, *after* communication, and potentially reflect a process of knowledge contextualisation.

Based on these findings, we predict that communicatively presented action outcomes will lead to a more positive deflection in the time windows and scalp locations associated with the Pb component. However, we may also find that addressing children leads to differentiated processing of the target of the communication, i.e. the demonstrated actions and their outcomes.

The Nc component as a measure of attention and arousal

The Nc is an infant-specific component sensitive to attention and arousal (Ackles & Cook, 1998, 2007; Ackles, 2008; Courchesne et al., 1981). The Nc component is distributed fronto-centrally on the scalp and is expressed as a negative-ongoing stretched peak between 400 and 800ms (Ackles, 2008; Courchesne et al., 1981). The Nc is a relatively robust ERP component and has been observed in many paradigms, with increased responses towards oddball stimuli (Ackles & Cook, 1998, 2007; Ackles, 2008; Courchesne et al., 1981) as well as familiar or novel items (Hoehl et al., 2008; Reid et al., 2009). The Nc is not just sensitive to oddballs, and no increase in the Nc response is found if infants are already familiar with the oddballs (Nelson & Collins, 1991, 1992). The Nc is also linked to a deceleration of heart rate that correlates with infants' attendance to the stimuli (Richards, 2003). Additionally, infants show an increased Nc-response towards familiar eating actions compared to a potentially novel non-eating action (e.g. putting spoon to forehead), either because they are more familiar or because of their interest in food (Reid et al., 2009). Due to this response pattern, it has been argued that the Nc reflects a general measure of attention and/or arousal towards stimuli (Richards, 2003).

It is worth noting that the Nc is also sensitive to ostensive signals, and increased Nc amplitudes have been observed in 5- (Parise, Reid, Stets, & Striano, 2008) and 9-month-old (Striano, Reid, & Hoehl, 2006) infants for objects cued by gaze. However, infants also show a *de*creased Nc-response towards objects that were previously gaze-cued (Hoehl et al., 2008). Therefore, an increase in the negative deflection for the Nc for communicatively presented outcomes may indicate that ostensive communication facilitates learning through attention and arousal towards the stimuli. This may lend support to theories that emphasise the role of attention and arousal in learning (as argued by Gredebäck et al., 2018; Szufnarowska et al., 2014, but see: Csibra et al., 2018). Such a modulation of the Nc can provide valuable information on the role that attention and arousal during the processing of event sequences. However, the mere presence of differentiated attention and arousal towards communicative contexts does not exclude the possibility of a specialised system to detect communication and create a referential expectation, as proposed by Natural Pedagogy (Csibra, 2010).

Given these previous findings, we may observe an increased Nc response for completed eating actions, replicating Reid et al. (2009). Furthermore, we can expect an increased Nc for communicatively presented actions if communication leads to increased attention and arousal towards the action sequence. At the same time, the Nc may also *decrease* if infants habituate to communicatively presented actions faster (cf. object encoding in Hoehl et al., 2008).

The N400 as a marker of semantic expectancy violations

The N400 component is argued to reflect the activation of semantic predictions. It is commonly found in priming paradigms, where semantically incongruent items following a prime show a more negative response compared to items that are semantically congruent to the prime (Kutas & Federmeier, 2000, 2011). Originally, the N400 was found in studies on language comprehension when a sentence primed the listener for a specific word, but a different, unrelated word was delivered. The N400 is not only related to language, but also other kinds of semantic information. It has been found in action observation, but also line drawings, photographs, faces (Kutas & Federmeier, 2000) and actions sequences (Amoruso et al., 2013).

The shape and morphology of the N400 varies with the stimuli content and task, for example tasks involving visual stimuli show a stronger N400 in areas associated with the processing of visual information. Furthermore, the action N400 is typically associated with a positive deflection for the unexpected outcome, rather than the negative deflection found in the linguistic N400 (Amoruso et al., 2013; Kutas & Federmeier, 2000). Some authors also describe the N400 as a negative peak within a larger positive deflection for the unexpected condition, compared to the expected baseline that shows no peak (e.g. Reid et al., 2009).

The interpretation of the action N400 is strongly linked to its interpretation in linguistic research (Amoruso et al., 2013). The linguistic N400 and action N400 do not only share characteristics in morphology, timing, and the paradigms used to elicit them, there are also developmental links between action N400 and linguistic N400: Infants who show a larger action-N400 at 9 months also show a greater vocabulary scores at 18 months (Kaduk et al., 2016).

The linguistic N400 has been shown to be sensitive to pragmatic aspects during communication, such as the listener's knowledge about the speaker and instances of false beliefs (Kulakova & Nieuwland, 2016; H. J. Ferguson, Cane, Douchkov, & Wright, 2014; Hagoort, 2004). The N400 has also been found for gestures (Amoruso et al., 2013). This indicates that the N400 is tightly linked to the communicative context, but to our knowledge, there are no studies that have investigated whether the interpretation of everyday actions is influenced by the communicative context.

The stimuli used to investigate the linguistic N400 and the gesture N400 are by definition communicatively presented, however, in the action N400 studies the presentation is observational only. Although there is some crossover in studies on gestures, gestures themselves are often conventionalised and communicative. In the following study, we would like to investigate the effect of modifying the communicative context on the understanding of everyday actions. Depending on the interpretation of the N400 effect within the Natural Pedagogy Framework, there are two alternative hypotheses:

- Since the N400 is linked to semantic processing, and the N400 is commonly observed in communicative contexts, it is possible that the mean amplitude between expected and unexpected actions is increased after being addressed.

- However, communicative contexts may prime infants towards *novel* information (Csibra & Gergely, 2009; Tatone & Csibra, 2015). Consequently, they may show a decreased difference between the expected and unexpected outcomes after being addressed communicatively.

Because of the different predictions about whether communication primes infants' expectation towards novel or semantically familiar action outcomes, it is important to also study the effect of communication on action understanding in adults to establish a baseline response and identify key areas for analysis and we will investigate the same hypotheses.

For the current study, we decided to investigate 9-month-old infants. Since we predict that the presence of communicative signals prior to the action demonstration potentially modulates the N400 and Nc components, we decided to investigate an age group that shows a reliable response in these ERP components. At the time of writing, the earliest evidence of an action understanding on the N400 and Nc components has been found in 9-month-old infants (Kaduk et al., 2016; Reid et al., 2009), but not in younger infants (Michel, Kaduk, et al., 2017; Reid et al., 2009). Meanwhile, already younger children already have demonstrated sensitivity towards communication on the Pb component. Therefore, by the time infants reach 9 months, they should show evidence of all three ERP components of interest.

2.4 Experiment 1: Ostensive communication and action semantics

Method

Participants

Infants: Sixteen 9-month-old infants were included in the final sample (average age: 278 days; range: 265–296 days; 9 females). They all matched the minimum criterion for inclusion of 8 usable trials per condition. An additional 19 infants were excluded because they did not have enough artefact-free trials ($N = 18$) or refused to wear the EEG cap ($N = 1$). This drop out rate is comparable to similar research using EEG data with this age group (Hoehl & Wahl, 2012; Stets, Stahl, & Reid, 2012). Infants were recruited through the Lancaster Babylab database and received a book for their participation. The parents received £10.00 for their travel expenses.

A further 12 infants participated in a pilot study to establish the optimal ratio between the trial length and attrition rate and were not included in the final sample.

Adults: Sixteen adults (average age: 21 years, range: 18–31 years, 6 females) contributed usable data of more than eight usable trials per condition. An additional 4 adults were tested, but excluded because they provided less than 8 artefact free trials per condition due to contamination in the alpha frequency band. Participants were recruited through advertisements on the Lancaster University campus and through the university's online participant recruitment system. Participants did not know any of the actors in the movies. They received £10 for their participation.

The study was approved by the Lancaster University Research Ethics Committee. All participants gave their consent before to start the experiment.

Materials

The stimuli consisted of a video with an actor greeting the participant, followed by six pairs of still images depicting everyday eating actions (c.f. Reid et al., 2009). In the video, the actor greeted the participant either greeted the participants (ostensive condition) or did not greet them (non-ostensive control condition). In the ostensive condition, the actor looked straight, smiled, waved and greeted the participant in infant-directed speech, saying: “Hello baby! Look!” (similar to Yoon et al., 2008). In the control condition, the actor adopted a neutral facial expression, looked slightly below the line of sight without establishing eye contact with the participant and speaking in a neutral, adult-directed speech “Oh, what’s that.” (no rising intonation at the end, cf. Yoon et al., 2008).

Each series of images following the video included the action prime (e.g. holding a spoon, consistent across all conditions), one picture for the anticipated outcome (moving the spoon to the mouth) and one picture for the unanticipated action outcome (moving the spoon to the ear). The objects used to prime the actions were a spoon, an apple, and a cup (all anticipated target: mouth, unanticipated target: hair/ear). We focussed on eating/drinking actions as these are the actions infants are typically most familiar with (Domínguez-Martínez, Parise, Strandvall, & Reid, 2015; Gredebäck & Melinder, 2010; Hunnius & Bekkering, 2010; Kaduk et al., 2016; Reid & Striano, 2008; Reid et al., 2009). The total height of the stimuli was approximately 24cm, which at a distance of 80cm from the screen results in a visual angle of 17°. The distance between the two goal locations of the target picture was approximately 5 cm, which resulted in a visual angle of 3.6°. To minimise eye movements (Hoehl & Wahl, 2012) that potentially reduce the N400 in this paradigm (Domínguez-Martínez et al., 2015), we used varying fixation points in the upper centre of the image on the actor’s head before the target image. The fixation points consisted of 200ms of different rotating or pulsing images of approximately 0.5°in height. To ensure a clean baseline, the movement/pulsing was frozen with a varying jitter between 200-400ms before the onset of the outcome picture. An overview of the procedures and timings is provided in Figure 2.1. Adults were presented with the same stimuli as infants.

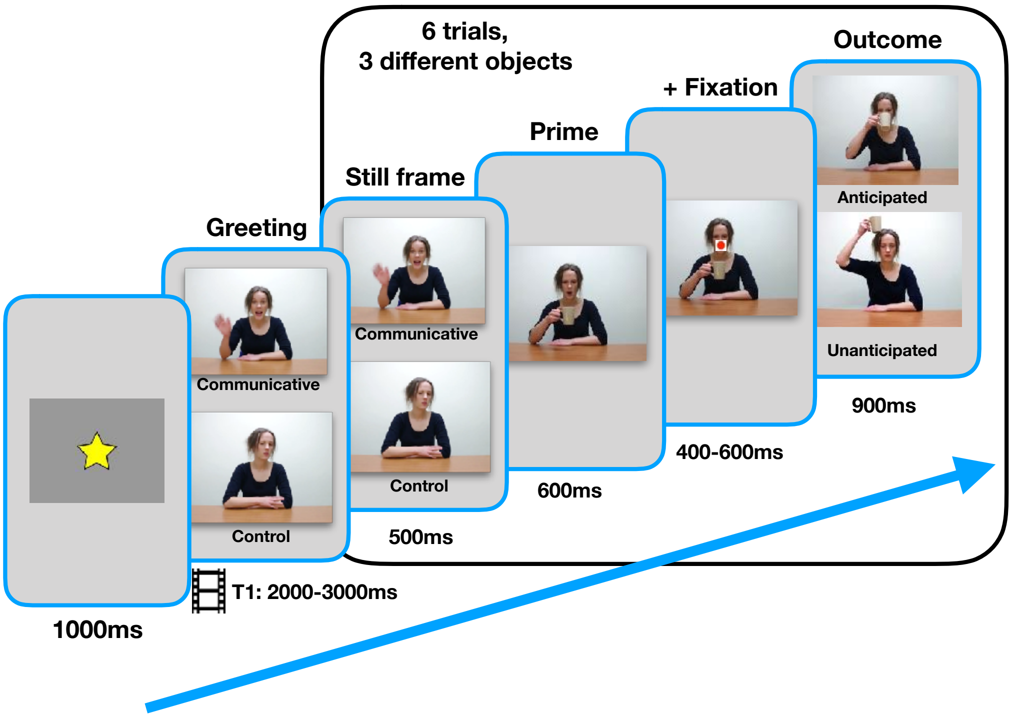

Figure 2.1: Running order of a block for Experiment 1. During the first trial of a block, the actor looked at the object. During trials 2–6, children saw a still frame of the video. Within a block, six trials were presented. All trials of a block showed different object-outcome combinations.

Procedure

The procedure is based on the study by Reid et al. (2009), with the addition of an explicit ostensive greeting and the non-ostensive control condition. The study used a mixed design, in which all participants were exposed to ostensive and control conditions, and both outcomes, anticipated and unanticipated. Furthermore, participants were presented with all actors and all action types. However, within a particular combination of actor and action, participants only saw either the ostensive *or* the control condition to avoid spill-over effects from the ostensive conditions. To keep the presentation time brief and within the typical attention span of infants, the stimuli were presented in blocks of six actions per greeting. Each block started with a yellow star being shown on screen and a pling noise. This was followed by the greeting and six-picture sequences of each of the three actions in a random order. The order of blocks was randomised.

Infants were sitting on the lap of their caregiver in front of a CRT screen at a distance of approximately 80cm. They were wearing a 124-channel Geodesic Sensor Net (HCGSN 130; EGI, Eugene, OR). A video camera recorded the infant's face, and we used the recordings to offline-reject those trials where the infant was not attending the presentation screen. Caregivers were instructed to watch their infant and not to talk or point during the experiment. A loop of a black spiral moving on a grey screen was used as an attention getter if the infants disengaged between trials. If the infant disengaged for longer periods, the experiment would be paused and the experimenter entertained the infant by blowing bubbles. The presentation ended if the infant became fussy or all blocks were presented. On average, each infant watched 38 trials per condition of which 14 were usable (Communicative anticipated: 15/38, Communicative unanticipated: 15/38, Control anticipated: 12/38, Control unanticipated: 12/38).

The procedure for the adults was the same as in the infant study, apart from some minor modifications: We used 128-channel Geodesic Sensor Nets, which have additional electrodes in the eye region to record eye movements. Participants were instructed to sit still and blink on the star image between blocks. On average adults watched 41 trials per condition. Due to high levels of alpha contamination and eye blinks, only 22 were usable on average (Communicative anticipated: 21/41, Communicative unanticipated: 23/41, Control anticipated: 20/41, Control unanticipated: 23/41).

EEG processing

The EEG signal was recorded using the Net Station Amplifier (Electrical Geodesics Inc., Eugene, OR, USA) with a high-density EEG net at 500 Hz sampling rate and a low pass filter of 200 Hz. The reference was on the vertex (Cz), the ground electrode was placed between Cz and Pz.

Data was offline-filtered using a 0.3-30 Hz bandpass filter and segmented into epochs of 1100 ms based on the onset of the outcome picture. The first 200 ms of each epoch analysed was used for baseline correction. After stimuli onset the target period for the ERP analysis is 900 ms (see Figure 2.1). Infants were only included in the analysis if they attended at least 8 artefact-free trials per condition.

The segments were extracted with a baseline of 200 ms and a length of 900 ms. Net Station's (Electrical Geodesics Inc., Eugene, OR, USA) artefact detection (*Infants:* Data were rejected for body and eyes movements when the average amplitude of a 640 ms gliding window exceeded $55\mu V$ at horizontal EOG channels, $140\mu V$ at vertical EOG channels and $200\mu V$ at any other channel, *Adults:* Data were rejected when average amplitude of an 80 ms gliding window exceeded $80\mu V$ at EOG channels and $50\mu V$ at any other channel) was used to filter out bad trials and channels. Data were also visually edited offline for artefacts and to ensure that included trials were those where the infant was attending to the screen. Bad channels of accepted trials were replaced using Net Station's bad channel replacement spline interpolation and all trials were baseline corrected. Segments containing more than 13 bad channels were excluded. All trials were averaged per condition and exported to R statistics software, version 3.4.1 (R Core Team, 2017).

Statistical analyses

Time windows and EEG channels for each component were analysed based on previous research (Ackles, 2008; Ackles & Cook, 2007; Kopp & Lindenberger, 2011, 2012; Parise & Csibra, 2013; Reynolds, 2015) and visual inspection of the data.

We investigated the Pb and Nc component in the same fronto-central area (electrode sites 5, 4, 6, 7, 11, 12, 13, 19, 20, 24, 106, 112, 118, 124, corresponding to the area between F3, Fz, F4 and Cz in the 10-20 system). The time window for the Pb was 200–350 ms, and 350-700 ms for the Nc, and we analysed the average deflection within these time windows.

The N400 was similar location to previous research (Reid et al., 2009; Kaduk et al., 2016; Domínguez-Martínez et al., 2015) on the electrodes 60, 61, 62, 66, 67, 71, 72, 76, 77, 78, 84, 85, corresponding to the area around Pz in the 10-20 system. The N400 in previous research (Reid et al., 2009; Kaduk et al., 2016; Domínguez-Martínez et al., 2015) was expressed as a negative peak in the unexpected condition, but no peak in the expected condition. In order to analyse this effect, these studies used the window analysis technique of Hoormann, Falkenstein, Schwarzenau, and Hohnsbein (1998), as it is suitable for analyses that contain a peak in one but not the other conditions. For this analysis, the ANOVA includes time as an additional within-subjects variable, with 11 samples of 12ms length across the time window of interest and allows to establish whether the difference between the ERPs changes over time. However, in our data, there was no discernible peak apparent in the unexpected conditions that would warrant the use of this analysis technique and we analysed the averaged voltages for each condition.

We conducted 2×2 repeated measures ANOVAs with Communication (ostensive vs. control) and Outcome (expected vs. unexpected) as within-subject factors for all components using the `aov` and the ezANOVA package. Effect sizes are reported using Generalised Eta Squared (η^2_G, see Bakeman, 2005, for details). Contrast codings were calculated with the lsmeans package by Lenth (2016).

In addition to the ANOVA, we also used Bayesian Factor analyses. Bayes Factors allow us to evaluate whether the evidence *supports* the null hypothesis (Dienes, 2008, 2014, 2016; Dienes & Mclatchie, 2018; Jarosz & Wiley, 2014). Bayes Factors can be interpreted like null hypothesis testing with a cut-off of $p < .05$: A Bayes Factor of less than 1/3 can be interpreted as evidence in support of the null hypothesis, a Bayes Factor of 3 or larger can be interpreted as evidence in favour of the alternative hypotheses. Values between 1/3 and 3 can be interpreted as insufficient evidence for either hypothesis (Dienes, 2016). Bayes Factors also have an intuitive interpretation of denoting the likelihood of one hypothesis over an alternative hypothesis. For example, a Bayes Factor $B_{(H1|H0)} = 10$ indicates that H1 is ten times more likely than H0. Jeffreys (1961) offers a scale to interpret the strength of evidence. According to this scale, Bayes Factors between 1–3 offer only anecdotal evidence, between 3–10 Bayes Factors offer substantial, between 10–30 strong and between 30–100 very strong evidence. Bayes Factors of 100 or larger show decisive evidence in favour of the hypothesis (Jarosz & Wiley, 2014).

We calculated Bayes Factors to identify whether theoretically motivated differences observed between ERP components were *meaningfully* different. These analyses were carried out using a uniform distribution ($B_{U(H1|H0)}$), specifying the lower and upper boundaries of an expected ERP effect. To set these boundaries, we surveyed the literature. Fu, Bin, Dienes, Fu, and Gao (2013) have used $1\mu V$ as the smallest difference in an ERP component between conditions. Previous studies investigating similar components (Reid et al., 2009; Kaduk et al., 2016) typically revealed differences of up to $7.5\mu V$ and we set $10\mu V$ as a cautious upper limit on any predicted effect.

For the analysis of the N400, we also had specific predictions about the relation of the N400 between communicative and control conditions. We conducted a series of follow up tests using the difference between anticipated and unanticipated outcomes in the control condition to predict the differences in the communicative condition. Bayes Factors ($B_{N(H1|H0)}$) were calculated assuming two-tailed normally distributed mean differences between anticipated and unanticipated outcomes in the control condition to predict whether the presence of communication: (1) does not affect the N400 deflection (2) enhances the N400 deflection or (3) attenuates the N400 deflection. These hypotheses predicted the difference in the communicative condition by taking (1) the mean of the control condition (2) doubling the mean or (3) halving the mean.

Results

Pb component

A 2 × 2 ANOVA shows no significant effects in the Pb-response (all $ps > .26$, see Table A.1 for details and Figure 2.2 for the ERP plot).

For the Bayes Factor analysis, we investigated the main effect of Communication using a uniform distribution. We predicted a difference between the communicative and control condition of 1 to $10\mu V$ and find evidence of an absence of a main effect for Communication ($\Delta M_{COM-CTL} = 0.07\mu V, SE = 0.93, B_{U(1,10)} = 0.04$).

Nc Component

The 2 × 2 ANOVA showed no significant main effects or interaction on the PB response between Communication and Outcome (all $ps > .49$, see Table A.2 for details and Figure 2.2 for the ERP plot).

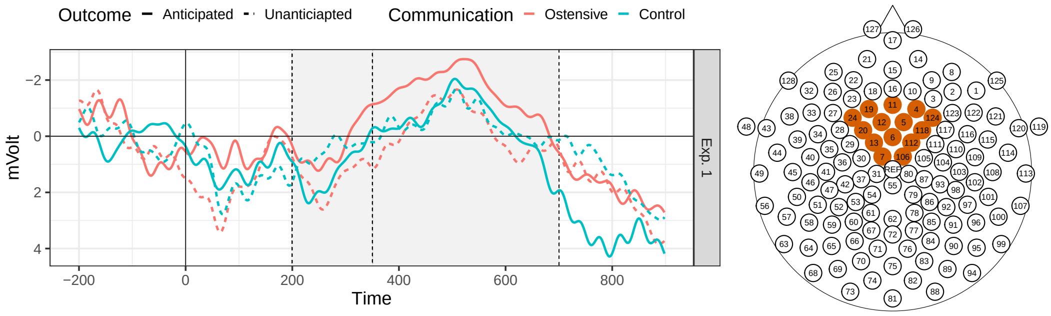

Figure 2.2: ERP waveforms for the Pb (200-400) and Nc (350–700 ms) of the infant data in Experiment 1.

Furthermore, the analysis of the main effect of Communication ($\Delta M = -0.44, SE = 0.91$) found evidence against the hypotheses that communicatively presented action outcomes are more positive ($B_{U(-1,-10)} = 0.08$) or more more negative than ($B_{U(1,10)} = 0.02$) compared to the control stimuli. The Bayes Factor analysis for Outcome showed evidence against a more negative Nc response compared for anticipated action outcomes ($B_{U(1,10)} = 0.01$). Finally, investigating potential interaction effects, we found insufficient evidence to suggest that the difference between anticipated and unanticipated Outcomes is the same in the communicative condition ($\Delta M = -1.34, SE = 1.42$) and the control condition ($\Delta M = -0.01, SE = 1.42, B_{N(-0.01,-1.34)} = 1.0$).

N400 component

Infants: The ANOVA showed a significant main effect for *Outcome* ($F(1,15) = 10.03, p = .006, \eta^2_G = 0.20$). This effect is driven by a more negative deflection for anticipated ($M = -3.29\mu V, SE = 1.28$) compared to unanticipated ($M = 1.13\mu V, SE = 1.28$) outcomes. All other effects did not reach significance (all $ps > .25$, see Table A.3 for details).

The Bayes Factor analysis supports these results by indicating strong support for a statistically meaningful main effect of $Outcome$ ($\Delta M = -4.43\mu V, SE = 1.40, B_{U(-1,-10)} = 58$). For the planned contrasts, we find decisive evidence in support of a meaningful outcome effect as expressed through the difference between anticipated and unanticipated outcomes in the communicative condition ($\Delta M = -5.50\mu V, SE = 1.65, B_{U(-1,-10)} = 110$) and moderate evidence in the control condition ($\Delta M = -3.36\mu V, SE = 1.65, B_{U(-1,-10)} = 3.3$).

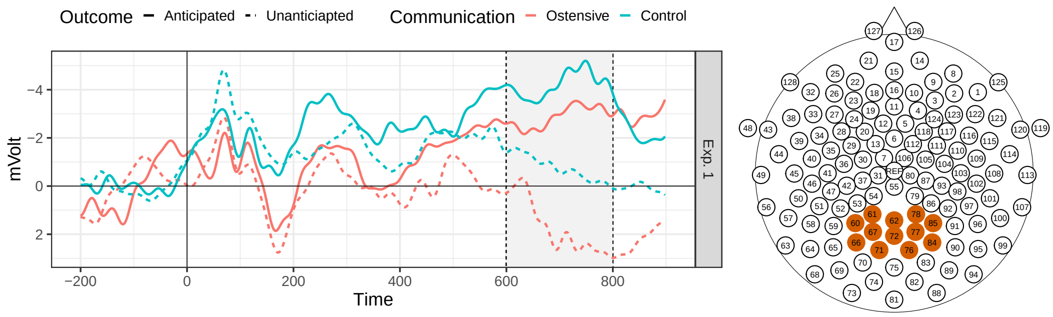

Figure 2.3: ERP waveforms for the N400 component (600-800 ms) of the infant sample in Experiment 1

In a follow-up analysis, we investigated the effects in more detail, as there are three potential hypotheses: (1) Communication and Control show the same difference between anticipated and unanticipated outcomes ($B_{N(-3.3|-5.50)} = 112$) (2) Communication enhances the N400 response and infants show *twice* the difference between anticipated and unanticipated in the communicative condition ($B_{N(-6.6|-5.50)} = 147$) (3) Communication attenuates the N400 response, and infants only show *half* the difference between anticipated and unanticipated in the communicative condition ($B_{N(-1.7|-5.50)} = 46$). The Bayesian analysis also allows us to directly compare these hypotheses, suggesting that Hypothesis 2 that infants show an enhanced N400 response has the strongest support. It is 1.3 times more likely than Hypothesis 1, and 3.2 times more likely than Hypothesis 3.

Adults: There was a significant interaction between action $Communication$ and $Outcome$ ($F(1,15) = 15.06, p = .001, \eta^2_G = 0.12$) and a main effect of $Outcome$ ($F(1,15) = 7.17, p = .002, \eta^2_G = 0.23$) that was driven by the difference between anticipated ($M = 0.88\mu V, SE = 0.38$) and unanticipated ($M = 1.88\mu V, SE = 0.38$) action outcomes. The main effect of Communication did not reach significance ($p = .83$, see Table A.4 for details, Figure 2.4 for the ERP plot).

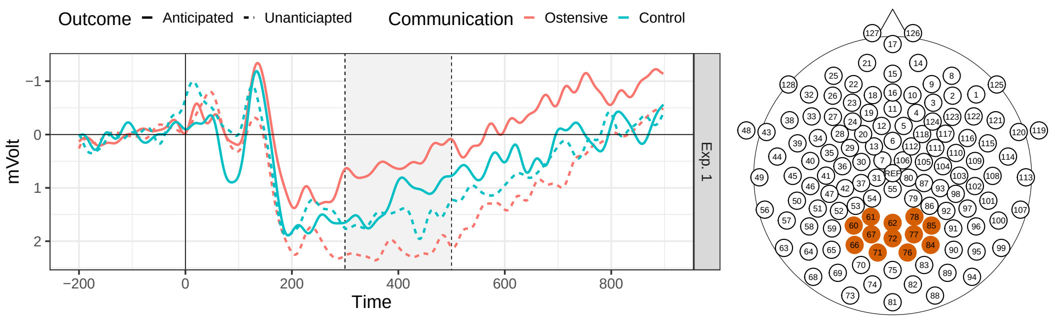

Figure 2.4: ERP waveforms for the N400 component (300–500 ms) of the adult sample in Experiment 1

We conducted t-tests on the contrasts of each level of Communication to analyse the interaction. In the communicative condition, unanticipated actions were more positive ($M = 2.18\mu V$, $SE = 0.41$) compared to anticipated ones ($M = 0.53\mu V$, $SE = 0.41$) and this difference is statistically significant ($t(20.83) = -4.034, p = .0006$). However, in the control condition, anticipated outcomes ($M = 1.23\mu V$, $SE = 0.41$) were not significantly different to unanticipated outcomes ($M = 1.58\mu V$, $SE = 0.41$, $t(20.83) = -0.85, p = .40$).

The Bayes Factor shows only anecdotal evidence for a potentially meaningful effect of Outcome ($B_{U(-1,-10)} = 1.9$). Further analyses on subsets of communicative and control condition reveal strong evidence support of the hypothesis of a statistically meaningful difference between anticipated and unanticipated outcomes in the communicative condition ($\Delta M = -1.66\mu V, SE = 0.41, B_{U(-1,-10)} = 369$. However, there is evidence *against* this effect in the control condition ($\Delta M = -0.35\mu V, SE = 0.41, B_{U(-1,-10)} = 0.009$).

We conducted the same follow-up analysis as we did for the infant sample, to investigate the effect of $Communication$ on the N400 ERP component. (1) Communication and Control show *no difference* in their N400 response ($B_{N(-0.35|-1.66)} = 43$) (2) Communication doubles the N400 response as measured by the difference between anticipated and unanticipated outcomes ($B_{N(-0.70|-1.66)} = 315$) (3) Communication attenuates the N400 response, and infants only show *half* the difference between anticipated and unanticipated in the communicative condition ($B_{N(-0.17|-1.66)} = 12.7$). The Bayes Factor analysis suggests that once again that Hypothesis 2, predicting that the presence of communication increases the N400, receives the strongest support. It is 7 times more likely than Hypothesis 1 suggesting that both values are the same and 24 times more likely than Hypothesis 3 predicting an attenuating effect of Communication on the N400.

Discussion: Experiment 1

Infants in Experiment 1 did not show any evidence that the presence of communication or unexpected outcomes modulates their Pb or Nc components. Even though an interaction effect of Communication and Outcome on the N400 is not detected by traditional ANOVA in the infant sample, we were able to detect meaningful differences between anticipated and unanticipated Outcomes in the communicative and the control condition. By comparing specific hypotheses on the directions of the effect, we were able to establish that it is most likely that communication *enhances* the N400 response, whereas unanticipated action outcomes show a more negative deflection in the communicative condition, compared to the control. The adults in Experiment 1 show an interaction between Communication and Outcome on the N400. By looking at this effect in more detail, we were able to establish that adults, like the infants, appear to show a larger difference between anticipated and unanticipated outcomes for communicatively presented outcomes. But unlike the infants, there is evidence that adults did not show such a difference in the control condition.

2.5 Experiment 2: Ostensive-referential communication and action semantics

Experiment 1 investigated whether communication helps infants to interpret everyday actions, such as eating. The absence of an effect of communication may be explained by the absence of the object and/or referential signals that link the communication with the object-action the actor is about to perform. In particular, research with toddlers has shown that parents use more referential but fewer ostensive signals during sincere and pretence interactions, compared to humorous ones (Hoicka, 2016). It is possible that 9-month-old infants need a reference to the object in order to focus their attention during the action. Alternatively, a referential signal to the object might create a referential expectation of how that object will be used and that ostension has an effect only if it is followed by a referential signal to the object (Senju & Csibra, 2008; Senju, Csibra, & Johnson, 2008). To investigate this possibility, we conducted a second experiment and changed the procedure in the following ways: (1) the object is now present during the greeting and during the first block of the trial, the actor looks at the infant and at the object; (2) each block depicts only one action to retain the first referential look towards the object.

We were also concerned that the infants in our paradigm may be less likely to learn from actors that are doing something that they know is wrong. Numerous studies with toddlers and older children have shown that infants are less likely to imitate in such conditions (Harris & Corriveau, 2011; Poulin-Dubois, Brooker, & Polonia, 2011; Tummeltshammer et al., 2014; Zmyj, Buttelmann, Carpenter, & Daum, 2010). It is possible that observing the very same actor performing congruent and incongruent actions lead to the null result on the N400 component as a function of communication. In Experiment 2 each actor only presented either congruent or incongruent trials.

Method

Participants

Infants: The final sample contained 16 infants 9-month-old infants (average age = 270 days, range = 254–282 days, 7 female). An additional 18 infants did not provide 8 usable trials per condition.

Adults: The sample contained sixteen adults (average age = 35 years, range =19–62 years, 8 female). Two additional adults were tested but did not provide usable data because they did not provide the minimum number of usable trials due to contamination in the alpha frequency band (1) and due to technical problems with the experimental procedure (1).

Stimuli

As in Experiment 1, we recorded four new actors (four female) engaged in everyday actions, as well as the greetings clips. We also created a transparent image of the action-related objects, so that the object could be superimposed onto the greeting. Furthermore, during the first greeting of a block, after looking at the child (communicative condition) or looking below the child's line of sight (control condition), the actor always looked at the object. This required that the object is kept constant during each block, rather than cycling through different objects as in Experiment 1. Actors used short verbal greetings before each of the trials. An overview of the procedures and timings is provided in Figure 2.5. Apart from these changes, the stimuli were the same.

Procedure

We made the following changes to the procedure:

- Actors were consistently congruent or incongruent to make it easier for infants to follow the procedure. Once again, an actor was either ostensive or control. The way an actor communicates to the infant (ostensive/non-ostensive) was counterbalanced across participants
- Instead of showing a still frame from the greeting at the beginning of each trial, we showed a short video of the actor greeting the child with a single word (*Communicative:* “Hey”, “Look”, “Hello”, “Wow”, *Control:* “Ok”, “Well”, “Yeah.", “Hmm")

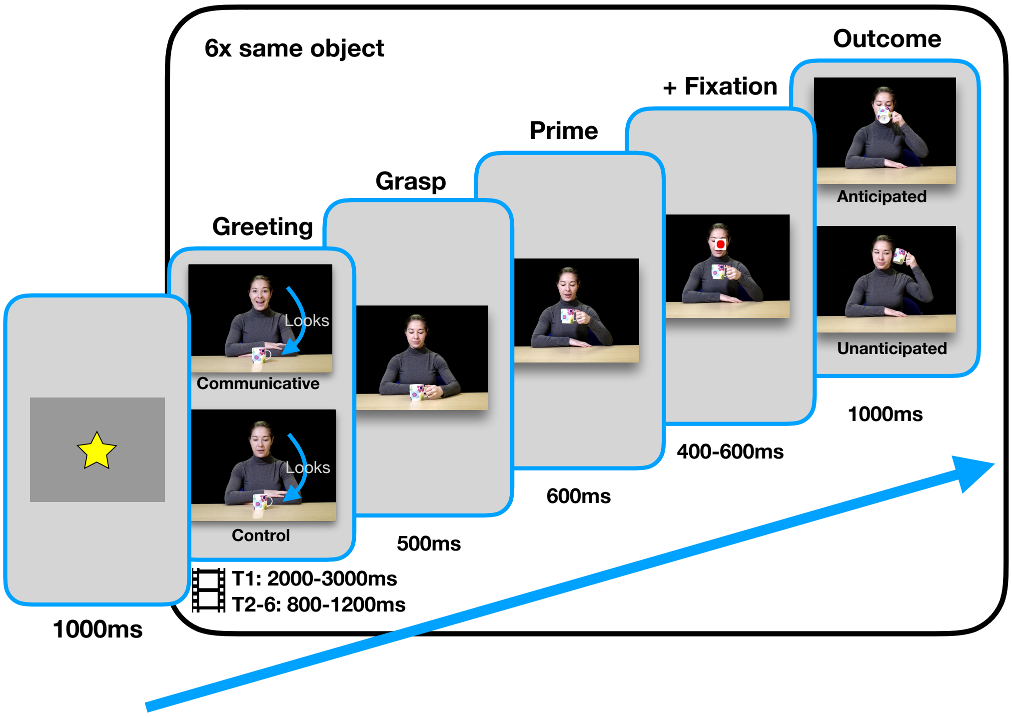

Figure 2.5: Running order of a block for Experiment 2. During the first trial of a block, the actor looked at the object. During trials 2–6, the actor only addressed the child with a short phrase. Within a block, six trials were presented. All trials of a block showed the same object-outcome.

Apart from these changes, the procedure, the processing of the EEG signals and the statistical analyses of the results were just as in Experiment 1.

On average, each infant watched 38 trials per condition of which 14 were usable (Communicative anticipated: 13/37, Communicative unanticipated: 12/37, Control anticipated: 11/37, Control unanticipated: 11/36).

Adults watched 83 trials per condition on average, of which 32 were usable (Communicative anticipated: 43/83, Communicative unanticipated: 43/83, Control anticipated: 39/83, Control unanticipated: 45/83).

Results

Pb

The infant-specific Pb effect in the second study showed a significant interaction between Communication and Outcome ($F(1,15) = 9.609, p = .007, \eta^2_G = 0.135$, see Figure 2.6). In the presence of infant-directed communication, anticipated outcomes ($M = 3.64\mu V, SE = 0.93$) lead to a more positive deflection compared to the unanticipated ($M = 1.43\mu V, SE = 0.93,\ t(29.10) = 1.88, p = .07$). In the control condition, this effect is reversed, and unanticipated outcomes ($M = 3.72\mu V, SE = 0.93$) show a more positive deflection compared to anticipated outcomes ($M = 1.26\mu V, SE = 0.93,\ t(29.10) = -2.10, p = .045$).

In the Bayes Factor analysis on the communicative of control conditions on each of the levels of Outcome, we found evidence against communicatively presented action outcomes being more positive than control ($\Delta M = 0.04\mu V, SE = 0.98, B_{U(1,10)} = 0.04$). This is due to the interaction that we also found in the traditional analysis: In the communicative condition, there is moderate evidence that anticipated outcomes are more positive than unanticipated outcomes ($\Delta M = 2.47\mu V, SE = 0.98, B_{U(1,10)} = 4.91$). In the control condition, there is moderate evidence for a reverse effect ($\Delta M = -2.29\mu V, SE = 0.98, B_{U(-1,-10)} = 3.82$). We directly contrasted both values by running an additional analysis by using the difference between Anticipated and Unanticipated Outcomes in the Communicative condition to predict the values in the Control condition. We found strong evidence against the hypothesis that these differences are the same $B_{N(2.47,-2.2)} = 0.10$), thereby supporting the presence of an interaction.

Nc Component

We found a marginally significant interaction of *Communication* and *Outcome* ($F(1,15) = 4.18, p = .06, \eta^2_G = 0.049$). There were no significant main effects (all $ps > 0.20$, see Table A.6 for details and Figure 2.6 for the ERP plot). In order to investigate this interaction, we conducted conducted t-tests on the contrasts of the two levels of *Communication*. In the communicative condition, there was no significant difference between anticipated ($M = 3.12\mu V, SE = 0.99$) and unanticipated outcomes ($M = 2.91\mu V, SE = 0.99$, $t(28.07) = 0.18, p = 0.86$). However, in the control condition anticipated outcomes showed a less positive response ($M = 1.90\mu V, SE = 0.99$), compared to unanticipated ones ($M = 4.51\mu V, SE = 0.99$, $t(28.07) = -2.30, p = 0.03$).

The Bayes Factor analysis found evidence against a main effect of Outcome, suggesting that there is no meaningful, more negative Nc response for anticipated compared to unanticipated outcomes ($\Delta M = -1.20, SE = 0.90$, $B_{U(1,10)} = 0.004$). Furthermore, the analysis of the main effect of communication ($\Delta M = -0.19, SE = 1.12$) found evidence against the hypotheses that communicatively presented action outcomes are more positive ($B_{U(1,10)} = 0.05$) or more more negative than ($B_{U(-1,-10)} = 0.07$) compared to the control stimuli.

By looking at each of the levels of communication, we found evidence against a meaningful difference between anticipated and unanticipated outcomes in the communicative condition ($\Delta M = 0.20, SE = 1.13, B_{U(-1,-10)} = 0.046$). However, in the control condition, anticipated outcomes are less positive than unanticipated outcomes ($\Delta M = -2.61, SE = 1.13, B_{U(-1,-10)} = 4.13$). Furthermore, there is evidence against the hypothesis that the difference between anticipated and unanticipated outcomes in the communicative is the same as in the control condition ($B_{N(-2.61,0.20)} = 0.17$).

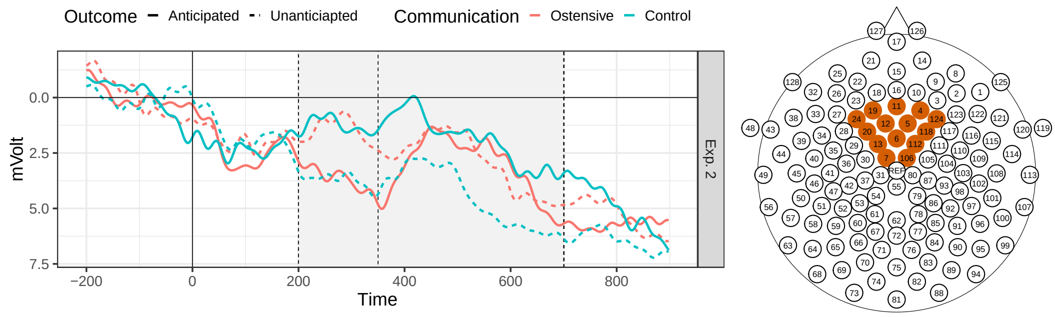

Figure 2.6: ERP waveforms for the Pb (200-400) and Nc (350–700 ms) of the infant data in Experiment 2.

N400

Infants: The ANOVA revealed a main effect of *Outcome* ($F(1,15) = 7.09, p = 0.02, \eta^2_G = 0.15$) with anticipated action outcomes ($M = -4.09, SE = 1.14$) eliciting a more negative deflection compared to unanticipated action outcomes ($M = -0.04, SE = 1.14$, see Figure 2.7). We did not find a main effect of *Communication* and the *Communication* × *Outcome* interaction (all $ps > .15$, see Table A.7 and Figure 2.7) for details.

For the Bayes Factor analyses, we found some evidence for an effect of outcome ($\Delta M = -4.05\mu V, SE = 1.52$, $B_{U(-1,-10)} = 14$). Analyses of the contrasts showed moderate evidence that communicatively presented images had a greater difference between anticipated and unanticipated outcomes ($\Delta M = -5.06\mu V, SE = 2.16$, $B_{U(-1,-10)} = 9$), but only anecdotal evidence of such an N400 effect for the control stimuli ($\Delta M = -3.03\mu V, SE = 2.16$, $B_{U(-1,-10)} = 1.33$)

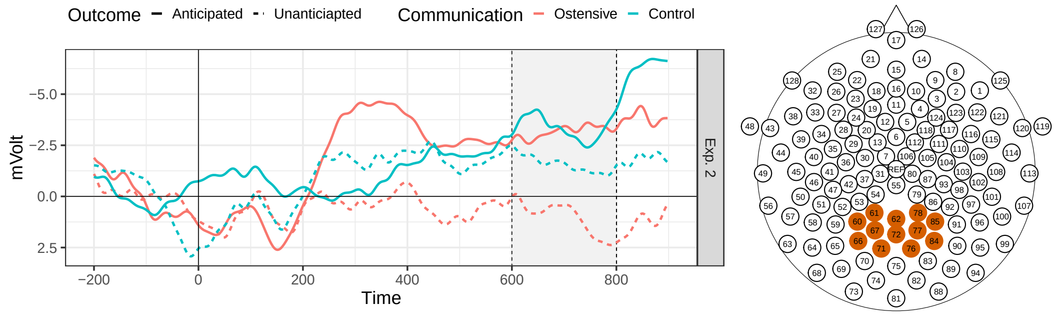

Figure 2.7: ERP waveforms for the N400 component (600-800 ms) of the infant sample in Experiment 2

To test the specific hypotheses on the modulation of communication on the N400, we ran a Bayesian analysis and one sample t-tests for the communicative condition using the mean of the control condition to predict the mean of the communicative condition. All models show moderate evidence by the data. The best model is once again Hypothesis 2 predicting an increased N400 response in the presence of communication ($B_{N(-6.08,-5.06)} = 11.7$). This is followed by Hypothesis 2 predicting that the mean amplitude in the communicative condition is the same as the control condition ($B_{N(-3.03,-5.06)} = 9.4$). Hypothesis 3, predicting an attenuated N400 response, is the lowest-performing model ($B_{N(-1.51,-5.06)} = 5.1$). However, these effects are small and Hypothesis 2 has only anecdotal evidence in favour of an enhanced over Hypothesis 3 predicting an attenuated N400 response ($B_{(H2,H3)} = 1.24$) and Hypothesis 1, predicting no difference between conditions ($B_{(H2,H1)} = 2.29$).

Adults: No main effect or interaction was significant (all $p > .16$, see Table A.8 and Figure 2.8 for details, Figure 2.8 for the ERP plot).

The Bayesian analysis supports this conclusion: There is evidence against a main effect of outcome ($\Delta M = -0.33\mu V, SE = 0.22, B_{U(-1,-10)} = 0.0002$) and there is evidence against a difference between anticipated and unanticipated

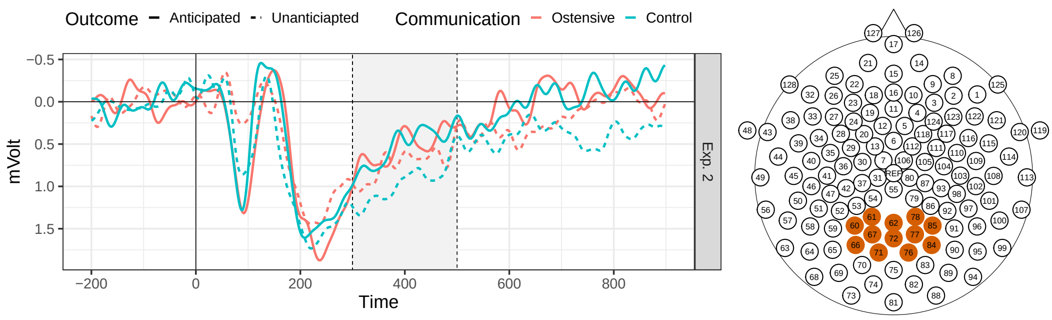

Figure 2.8: ERP waveforms for the N400 component (300–500 ms) of the adult sample in Experiment 2.

outcomes in the communicative ($\Delta M = -0.20\mu V, SE = 0.30, B_{U(-1,-10)} = 0.008$) and the control condition ($\Delta M = -0.44\mu V, SE = 0.30,\ B_{U(-1,-10)} = 0.0003$). Because of the absence of a meaningful N400 effect altogether and for both conditions, no further analyses have been conducted.

Additional analyses

Cross experiment comparison—Pb: To investigate whether the different results in Experiment 1 and Experiment 2 on the Pb component reflect a difference between the two experiments, we conducted a three-way ANOVA with Experiment as a between-subject factor, and Outcome and Communication as within-subjects factors. We found a significant interaction of $Experiment \times Outcome \times Communication$ as within-subjects factors ($F(1,30) = 8.86, p = .006, \eta^2_G = 4.83$, see Table A.9) in addition to a main effect of Experiment ($F(1,30) = 4.20, p = .05, \eta^2_G = 4.58$).

Cross experiment comparison—Nc: To investigate whether the different results in Experiment 1 and Experiment 2 on the Nc component reflect different ERP responses, we also conducted a three-way ANOVA with $Experiment$ as a between, and $Outcome$ and $Communication$ as within-subjects factors. The only significant main effect was of Experiment ($F(1,30) = 15.16, p = .0005, \eta^2_G = 0.17$), with Experiment 1 giving a more negative Nc response overall ($\Delta M_{Exp.1-Exp.2} = -3.80, SE = 0.97, t(30) = 5.218, p = .0005$).

Cross experiment comparison—N400 Infants: We found main effects of Outcome for Experiment 1 and Experiment 2 on the parietal N400 component. However, the Bayesian analysis showed that there is a potential interaction with Communication, whereas communicatively presented action outcomes lead to an increased N400 effect (as measured by the difference between anticipated and unanticipated outcomes), compared to the non-communicative control condition. It is possible that this interaction might reach significance when both data sets are pooled. Therefore, we conducted a three-way ANOVA $Experiment$ as a between, and $Outcome$ and $Communication$ as within-subjects factors. The analysis revealed no effect of Experiment as a main effect or interaction (See Table A.11 for details). Once again, the main effect of $Outcome$ is the only main effect reaching statistical significance ($F(1,30) = 11.95, p = .002, \eta^2_G = 0.086$), with unanticipated outcomes ($M = -3.41, SE = 0.86$) showing a more negative deflection than anticipated outcomes ($M = 0.10, SE = 0.86$).

Cross experiment comparison—N400 Adults: The adults in Experiment 1 demonstrated an interesting interaction between Communication and Outcome, whereas the adults in Experiment 2 did not show any effect of Communication and Outcome. We were interested whether this difference reflects a genuine, statistically reliable difference between both experimental groups and conducted a three-way ANOVA $Experiment$ as a between, and $Outcome$ and $Communication$ as within-subjects factors. This analysis showed a significant interaction of the highest order ($F(1,30) = 8.96, p = .005, \eta^2_G = 0.022$) in addition to the second-order interaction involving Communication and

Outcome ($F(1,30) = 4.19, p = .049, \eta^2_G = 0.01$) and the main effect of Outcome ($F(1,30) = 9.32, p = .005, \eta^2_G = 0.062$), See Table A.12 for details).

Discussion Experiment 2

One of the key findings of Experiment 2 is the interaction effect at the Pb. We found a more positive deflection towards communicatively presented outcomes in the anticipated condition. However, for the unanticipated condition, this effect was reversed. Assuming that this component is related to the one observed by (Parise & Csibra, 2013), the presence of this component may reflect a process of information seeking and already by 9 months, infants potentially take into account both, communication and action outcomes. Furthermore, our cross-experiment analysis has shown that this effect differs between Experiment 1, and Experiment 2.

The findings on the Nc tentatively replicate and extend previous findings by Reid et al. (2009) as they indicate that in non-communicative contexts, infants show greater arousal towards familiar or eating actions when infants are not directly addressed, but in the presence of communication this difference disappears. Notably, the cross-experiment comparison cannot rule out that this effect is limited to Experiment 2 only.

We have been able to replicate the results of the N400 effect of Outcome for the infant sample. Once again, we found a main effect of Outcome using traditional analyses. Additionally, the Bayes Factor analysis revealed a similar pattern in Experiment 2 that we already found in Experiment 1, supporting the hypothesis that communication leads to an enhanced N400 effect as expressed through a larger difference between anticipated and unanticipated outcomes in the communicative compared to the control condition. We have found this pattern in three of the four data sets, with the exception of the adults in Experiment 2. The adults in Experiment 2 did not show any evidence in support of an N400. It is likely that the revised, predictable relationship between actors and action outcomes allowed adults to predict even the unanticipated action conclusions and attribute meaning to them.

2.6 General discussion

In the current study, we investigated three ERP components that are known to be associated with infants' semantic understanding of events (N400), allocation of attention and arousal (Nc) and the presence of communicative signals and/or contextual interpretation (Pb). The ERP components in this study showed a complex pattern in infants' response towards congruent and incongruent action outcomes in communicative and non-communicative contexts. Infants in both experiments showed a clear effect of action outcome on the N400, replicating previous research on the N400 ERP in infants (Kaduk et al., 2016; Reid et al., 2009) and adults (Amoruso et al., 2013; Domínguez-Martínez et al., 2015). Furthermore, we observed a potentially enhanced response towards communicatively presented action outcomes. Effects on the Pb and the Nc components were only visible in Experiment 2, when ostensive signals were combined with referential signals and action outcomes were more predictable.

The results of the Nc component are important in assessing whether communication helps to facilitate processing by allocating more attention or arousal towards the processing of action outcomes. In Experiment 1 we did not replicate previous findings that congruent eating actions lead to an increased Nc response and we used Bayesian Factors to establish the absence of an effect. In Experiment 2, we also did not find a reliable Nc effect of Communication for either Communication or Outcome. However, the interaction term only marginally missed significance. Planned comparisons using Bayes Factors indicated a differentiated response between communicatively and non-communicatively presented actions. For the communicatively presented action outcomes, no difference is detectable. However, non-communicatively presented action outcomes elicited a more negative deflection for anticipated action outcomes. These results provide an indication that infants may only show heightened arousal towards completed eating actions in non-communicative conditions, replicating previous research by Reid et al. (2009). However in the presence of communication show similar levels of arousal and attention. Importantly, this difference only came into play when the stimuli were sufficiently predictable and or actors used referential signals to establish a link between the communication and the object-action relationship. Since the Nc reflects novelty or arousal and decreases with repeated stimuli presentation (Nikkel & Karrer, 1994; Wiebe et al., 2006), it is possible that the communicative presentation lead to increased habituation towards unexpected action outcomes, however in the non-communicative control habituation is slowed down. Similar effects have been observed by Hoehl et al. (2008) for objects cued by gaze, compared to those that were not cued. Such an effect would be indicative of communication modulating arousal across a number of trials, rather than arousal modulating learning. Further research will be needed to tease apart the specific effects of referential signals and action structure. Furthermore, a trial-level analysis of the progression of Pb and Nc components could potentially shed light on processes of learning and novelty detection that may have been masked by the averaging of ERP components.

Previous studies on the Nc component have found effects of communication on infants' object processing (Hoehl et al., 2008; Parise et al., 2008). However, in these studies infants received a live training with an actor that was either communicative or non-communicative. It is possible that only real life communication is sufficient in boosting infants' arousal to support learning. However, previous research using screen-based paradigms has demonstrated that infants use communicatively presented information differently to non-communicatively presented information (eg. Hernik & Csibra, 2015). Furthermore, neither of the studies revealed a main effect of communication in the Nc component. Therefore, they provide evidence *against* a purely attention-driven account of infants' understanding of everyday actions during communication.

On the N400 ERP component, both infant samples show a clear main effect of outcome. The findings on the N400 component show a complex response pattern for infants. Both infant groups show main effects of outcome in the ANOVA. This replicates previous research on infants' action understanding that found a sensitivity towards incongruent action outcomes from at least 9 months onwards (Reid et al., 2009), or possibly even at the age of 5 months with simplified stimuli that only showed the outcome of the action (Michel, Kaduk, et al., 2017).

The results of the adult N400 ERPs show a complex pattern: The ANOVA in Experiment 1 indicated a main effect of outcome. However, the planned contrasts using Bayes Factors indicated a meaningful difference between anticipated and unanticipated conditions in the communicative condition only. In the control condition, the difference between both conditions was smaller than the 1–10μV difference. These divergent results are due to both analyses asking different questions: Whereas the ANOVA is testing for an overall effect of each of the factors and the interaction term, the Bayes Factor analysis looks at the difference between anticipated and unanticipated outcomes on each level of communication individually, testing whether the difference between these conditions is within the parameters typically expected for ERP effects. But what about adults in Experiment 2 who showed no evidence of an N400 effect overall? It is likely that the more predictable design, in particular actors having clear, distinct roles either anticipated or unanticipated outcomes, allowed participants to anticipate the incongruent action outcomes. This effect mirrors previous research that found adults quickly learn to anticipate unexpected action outcomes, but children between 6 to 16 months do not (Hunnius & Bekkering, 2010). It is possible that adults find it easier to process a change in the goal outcome. In fact, adults are aware of the experimental context and may perceive the incongruent action outcomes as being meaningful *within the experimental context* (Watzlawick, Bavelas, & Jackson, 1967).

Another key finding of the N400 is related to the predictions that we can derive from Natural Pedagogy. As we discussed in the introduction, we can derive two distinct predictions of the effect of communication on the N400 ERP. The presence of communication might prime meaningful information, and children are even more likely to anticipate the congruent action outcomes. This is also the interpretation that is most closely linked to the linguistic N400, since it appears in communicative contexts. Alternatively, infants may expect adults to provide novel information that they can learn and generalise from. Of course, it is also possible that the presence of communicative signals does not influence the N400 ERP, either because children do not process pedagogically presented actions differently to non-pedagogically presented ones, or Natural Pedagogy uses a different neural mechanism to alter infants' learning. However, three of the four data sets provide evidence that the presence of communication enhances the N400 response. Furthermore, the overall pattern of results in the adult sample of Experiment 1 mirrors the results we found in the infant samples, and the hypothesis that the presence of communication enhances the N400 response was more likely than the hypothesis that both differences are the same for control or communicative conditions, or that communication attenuates the N400 response. In summary, we have found some evidence of an enhanced N400 effect for communicatively presented action outcomes, strengthening accounts that support enhanced semantic processing in the presence of communicative signals.

The results of the Pb indicate that this component is responsive to the presence of communication *and* action outcomes, which suggests it is not a direct index of pedagogical or domain-general learning mechanisms. We did not observe a Pb effect in Experiment 1, and, using Bayes Factors, were able to establish its absence for this sample. However, in Experiment 2 we found evidence of a Pb component preceding the Nc. The location and timing are similar to a component identified in previous research on infants' understanding of multimodal communicative signals (Parise & Csibra, 2013) and object memory in low and high joint attention contexts (Kopp & Lindenberger, 2011, 2012). However, the ERPs investigated in our study are time-locked to the outcome of the action, after the infant has been, or not been, ostensively addressed. Therefore the paradigm is different from previous research on Pb and Pb-like components (Parise & Csibra, 2013; Kopp & Lindenberger, 2011, 2012).

The Pb has been linked to to the contextual interpretation of events (Karrer et al., 1998). In our study, the Pb shows sensitivity towards action outcomes, beyond the sensitivity towards the presence of communication. The latency of the Pb indicates that this process precedes the semantic understanding indexed by the N400. It is possible that the Pb reflects a general information-seeking process that takes into account familiarity (of the action), and the presence of communication.

It is possible that the reduced complexity and higher predictability in Experiment 2 poised infants to process take into account both sources of information accordingly. We may have observed the interaction in the Pb component only because the presentation in Experiment 2 is more predictable and allowed infants to link actors and outcomes to learn about their reliability. Prior research indicates that the Pb increases over repeated presentations (Nikkel & Karrer, 1994). Any such effect would disappear in Experiment 1, where actors were engaged in expected and unexpected action outcomes within one experimental session.

The other key manipulation in Experiment 2 was the addition of referential signals before each block of action presentations, and may have had an effect on the Pb component. Parents use more referential signals in instances of generalisable interactions with their children, such as sincere demonstrations and pretence, but they use more ostensive signals when engaging in non-generalisable demonstrations, such as joking (Hoicka, 2016; Hoicka, Butcher, Malla, & Harris, 2017). Therefore, the presentation in Experiment 1 might have primed children to expect a non-generalisable joking context, and show a non-differentiated response towards actions and communication. However, the addition of referential signals in Experiment 2 might have initialised infants' expectation that the presentations are sincere, and the resulting pedagogical context may have lead to the differentiated response on the Pb. So far, studies with older children of 3 to 4-years have shown that children avoid trusting informants with humorous intentions, but are willing to trust a previously humorous informant in a sincere context(Hoicka et al., 2017).

If the actor is communicative and engages in a familiar action, infants may be looking for novel, relevant information to interpret the meaning of the communication. If they are then presented with the unexpected action outcome, they may perceive this outcome as the resolution of the informative intention. However, seeing the familiar action may be insufficient to resolve the communicative intention, and infants continue looking for the meaning of the shown action.

An alternative explanation of the reduced Pb response in the communicative condition reflects is an early marker of epistemic vigilance (Mascaro & Sperber, 2009; Mascaro, Morin, & Sperber, 2017). According to this interpretation, infants are less interested in learning from people that they know to be wrong, mirroring research in 9-month-olds (Tummeltshammer et al., 2014) older children (Poulin-Dubois et al., 2011; Zmyj et al., 2010), in order to avoid being manipulated by others. However, if the actor makes no effort to address the infants, their unexpected actions are unlikely to reflect attempted manipulations and potentially worth contextualising.

In addition to an enhanced Pb for anticipated action outcomes in the communicative condition, we observed the reverse effect in the control condition. This suggests that Pb response is not indexing an understanding of communicative relevance on its own. In the control condition, infants may not be looking to integrate the anticipated action outcomes into the wider context. By the age of 9 months, infants are already highly familiar with eating actions (Green et al., 2016), and observing actors eat is unlikely to require a contextual (re-)interpretation of the event. However, the opposite may be true for actors' repeated and consistent presentations of the unanticipated action outcomes, in line with proposals on the importance of prediction errors in learning (Niv & Schoenbaum, 2008; Stahl & Feigenson, 2015, 2017). General cognitive theories have argued that an organism continuously attempts to predict regularities in the environment (A. Clark, 2013). Learning is facilitated in contexts where predictions and inputs do not match, and the predictions have to be revised (Niv & Schoenbaum, 2008; Stahl & Feigenson, 2015, 2017). Because the stimuli consisted of familiar actions with unexpected action outcomes, an enhanced processing of unexpected action outcomes is also compatible with accounts of curiosity learning (Gottlieb et al., 2013; Twomey & Westermann, 2015, 2017). These theories predict that infants actively look for information that is sufficiently similar to integrate, but sufficiently different to extend it into existing knowledge. If this is the case, infants may show an enhanced Pb towards the unexpected outcomes because they are different enough to warrant curiosity. However, the anticipated outcomes are already too predictable to be interesting. Although this is a potentially powerful learning mechanism (Oudeyer & Smith, 2016), on its own, it cannot explain why infants in the communicative condition showed the reversed pattern, without appealing to prior experience that primes infants to process communicatively presented information differently. By the age of 9 months, infants already combine information from communicative signals with object knowledge (Pauen, Birgit, Hoehl, & Bechtel, 2015).

In our study, we investigated action sequences that either concluded with an outcome congruent to the preceding prime picture, or that depicted an incongruent action outcome. Some studies have manipulated the prime with regards to its fitness for purpose, but kept the outcome image constant. Reid and Striano (2008) used action sequences of objects that either warranted a use or not (e.g. putting an empty vs. a full spoon to the mouth, putting on only one shoe before walking). However, using this paradigm adults only showed an N400 ERP effect for a subset of the actions, the eating actions. Such paradigms are perceptually complex and it remains an open question whether and how infants would understand such violations.

Another important question relating to the processing of outcomes in the current study relates to infants' understanding of the unexpected outcomes themselves. The unanticipated outcomes shown in our study were largely devoid of meaning, with the actor simply putting the objects to their forehead. It is possible that infants have a different understanding about of novel but meaningful action outcomes, for example, when a spoon is used to turn on a light. Such a use would be meaningful on its own (albeit different from the associated use for the object), but would also be more salient Prior research has shown that the saliency of a goal is important in helping infants to anticipate action outcomes (Adam et al., 2016) and that older children only imitate otherwise irrational actions if they have clear effects (Biro, Verschoor, Coalter, & Leslie, 2014; Király et al., 2013). Both points are similar in their conceptualisation, but future research should aim to further disambiguate such differences goal processing in the context of communication.

One of the disadvantages of such a paradigm is that parts of the analysis require the comparison of perceptually different outcome pictures in order to elicit the semantic violation we were interested in. Because of this, the effects observed could also be attributed to a perceptual difference between the two pictures (Luck, 2014). However, despite this, our study also revealed differences in the processing of all three components based on the presence of communicative signals prior to the outcome picture. Because between both communicative conditions, the analysed images are exactly the same, any differences in the results cannot be explained by perceptual differences for the pictures alone.

Conclusion

Although the underlying motivation behind infants' differentiated processing of expected and unexpected action outcomes in communicative contexts remains unclear, the results on the Pb provide further evidence that by the age of 9 to 12 months, infants can integrate social signals and object knowledge to direct their attention (Pauen et al., 2015). By comparing specific ERP components associated with different mechanisms of perception and learning, we aimed to shed light on infants' understanding of everyday actions, and how it is influenced by communicative signals. The two experiments have revealed the importance of referential signals and/or the structure of information in children's understanding of actions. Most importantly, key modulations associated with signals indicating the presence of communication occurred comparatively early in processing at 200-350 ms after stimulus onset. It is likely that at this point in time, the information is being contextualised for further interpretation. However, there was no evidence for a direct modulation of attention in the presence of communication. Both studies revealed evidence against an increased Nc response for communicative conditions. If communication does not increase markers of arousal, we can exclude purely attentional and arousal driven accounts as explanations for infants' learning in social contexts with some degree of confidence. Likewise, we only found limited evidence that communication modifies the meaning of actions as indexed by the N400 ERP component. Furthermore, even if communication increases the semantic understanding of actions, the analyses showed meaningful effects for the N400 component even in the absence of communicative signals. Taken together, the current set of studies revealed a complex processing of actions.

Chapter 3

Paper Two: The effect of communicative signals on the anticipation of familiar, novel and unexpected action outcomes in 7-month old infants: Evidence from anticipatory looking and pupil dilation

Infants are apt social learners and learn about other people's actions through own experience, observational learning and pedagogical demonstrations. The ability to predict actions and anticipate their outcomes is an integral part of communication (Pickering & Garrod, 2009, 2011, 2013) and joint action (Sebanz & Knoblich, 2009). Therefore, anticipatory looking is not only an important measure of infants' understanding of actions, but is also an important marker of their ability to engage with others.

Previous studies have shown that infants are already able to anticipate a wide range of everyday actions (e.g. Green et al., 2016; Hunnius & Bekkering, 2010; Kochukhova & Gredebäck, 2010). Furthermore, infants are skilled social learners and are sensitive to communicatively presented information. They prioritise (Marno & Csibra, 2015) and are more likely to learn enduring information in the presence of communicative signals (Hernik & Csibra, 2015), such as direct gaze and infant-directed speech. According to Natural Pedagogy theory (Csibra & Gergely, 2009, 2011), this is because communicative signals create a learning context in which infants expect novel, generalisable information. In the previous chapter, we investigated whether the presence of communicative signals influences the neural correlates of infants' (and adults') understanding of action outcomes. Following on from this, we turn our attention to another measure of learning and investigate whether ostensive signals help infants to anticipate action outcomes. In the following study, we investigated whether addressing infants in a communicative way can help them to anticipate familiar congruent actions on the one hand and on the other hand, can help them to change their predictions about already familiar actions and learn novel actions. We also investigated whether ostensive signals increase arousal as measured through the pupillary light reflex.

The ability to anticipate the outcome of an action before its conclusion is an important marker of action understanding (Flanagan & Johansson, 2003). A number of factors play a role in infants' ability to predict the outcome of an action: Infants show an early understanding of teleological actions and they expect actions to be carried out in an efficient manner (Csibra et al., 1999; Gredebäck & Melinder, 2011; Sommerville, Woodward, & Needham, 2005, but see Paulus et al., 2011 for a statistical learning account). Furthermore, they are more likely to predict actions that they have previously carried out themselves (Ambrosini et al., 2013; Cannon, Woodward, Gredebäck, von Hofsten, & Turek, 2012; Gerson &

Woodward, 2014). However, through observational learning, they also learn to predict a wide range of actions that they are beyond their own abilities.

In their daily life, infants show an understanding of a wide range of actions and their associated outcomes. Eating actions are some of the earliest actions predicted by infants (e.g. Green et al., 2016; Hunnius & Bekkering, 2010; Reid et al., 2007, 2009) and infants get their own motor experience with spoons and food items, for example by holding, banging and moving them. From 3 months onwards, infants understand movements of abstract agents as goal-directed. Once they have performed a reaching action themselves, they are able to anticipate other people's reaching actions (Sommerville et al., 2005). Furthermore, they predict the use of cutlery, hands or chopsticks to bring food to their mouth depending on their cultural experience (Green et al., 2016). Already by the age of four months, infants can track the use of simple tools after having observed their use (Stavans & Baillargeon, 2016). Infants from 6 months onwards are able to anticipate everyday actions such as eating or drinking after a few repetitions (Hunnius & Bekkering, 2010).

There is evidence that infants can predict adults putting spoons to their mouth from 6 months onwards (Kochukhova & Gredebäck, 2010). However, only by the age of 10-months do infants predict self-propelled spoons, suggesting that at least during the early months, seeing a human agent is an important clue in the prediction of goal-directed actions (see also Biro & Leslie, 2007). Meanwhile, 6- and 10-month-olds do not predict spoons going to the top of the head, suggesting that they have tool-specific knowledge (Kochukhova & Gredebäck, 2010).

Around this age, there is also some tentative evidence that infants have the first expectations about eating actions coming from ERP studies. Michel, Kaduk, et al. (2017) found evidence that already 5-month-olds distinguish between expected and unexpected actions when looking at pictures of action outcomes only. However, Reid et al. (2009) have found an N400 ERP towards unexpected action outcomes for 9-month-olds and adults, but no such evidence was found for 7-month-olds.

There is also tentative evidence for tool specific knowledge for other actions, too. Hunnius and Bekkering (2010) investigated whether 6, 8, 12, 14, and 16 month-old infants and adults understand the use of a variety of goal-directed actions, involving different objects—a phone (ear), a brush (hair) and a cup (mouth). After the first trial, infants only anticipated the target of the cup; the other two items were not reliably predicted. Over the course of the experiment however, all age groups started to reliably predict semantically congruent actions (e.g. brush–hair), but not those that were semantically incongruent (e.g. brush–mouth). Only the adults quickly adjusted to new outcomes (see also Paulus et al., 2011, for similar results in a different paradigm). By the age of 12 months, infants show more evidence of tool-specific knowledge. For example, they are able to categorise objects according to their function, rather than visual similarity (Träuble & Pauen, 2011). Infants also expect that each tool has only one single purpose (Casler, 2013; Casler & Kelemen, 2005) and persist in anticipating frequently observed actions even if the circumstances have changed (Paulus et al., 2011). Twelve and 18-month old infants also insist to hold a spoon by the ladle, even when it prevents them from successfully using the spoon to activate a lamp by putting the ladle through a hole. However, they made no such inference when they used a novel tool (Barrett, Davis, & Needham, 2007). Therefore, infants' expectations about familiar action outcomes may be resilient towards counter evidence and they are not able to learn the novel, alternative outcomes very easily.

Natural Pedagogy Theory (Csibra & Gergely, 2009, 2011) proposes that infants are attuned to a specific set of communicative signals that allow them to engage in fast social learning. Natural Pedagogy argues that infants respond to specific social cues by giving their sources preferential attention and expecting generalisable knowledge in their presence Csibra+Gergely:2009. By the age of 18 months, children take into account information that is relevant in the communicative knowledge between the caregiver and the infant, rather than engaging in individual learning only (Southgate et al., 2009). This ability allows infants to quickly acquire and generalise skills and behaviours (Csibra & Shamsudheen, 2015).

To this point, only few studies have investigated the effect of communication on infants' learning of actions (e.g. Hernik & Csibra, 2015; Király et al., 2013). Infants are able to learn about actions through observational learning, but the presence of communicative signals can lead to more enduring expectations about the tools and actions that infants observe. For example, 13.5-month-old infants presented with a box that peeled or unpeeled bananas were more likely to learn the function of the box when hearing infant-directed speech (Hernik & Csibra, 2015). More importantly, they were also more likely to adhere to communicatively presented information when they observed multiple trials of that contradicted the communicatively presented function of the object.

Most research on action understanding in infancy has looked at actions in isolation. For example, in the study by Hunnius and Bekkering (2010), infants observed the actions incidentally. The actors in these stimuli did not engage in any communicative behaviour, the movies did not have sound and the actor avoided looking directly into the camera. The adult control group was fully aware of the experimental context and came into the study knowing that the stimuli are potentially meaningful. Therefore, their awareness of the experimental context may have given meaning to otherwise non-meaningful action outcomes by creating a communicative context (c.f. Watzlawick et al., 1967). Because adults were able to assign meaning to the actions, they might have been able to anticipate even the incongruent action outcomes. The same may not be true for the infants and toddlers taking part in the Hunnius and Bekkering (2010) study. However, if communicative signals create a referential expectation about an action by marking the following demonstration as meaningful, infants may be more likely to anticipate action outcomes. It is possible that the presence of communicative signals poises infants to actively retrieve primed action representations and anticipate action outcomes beyond what they would do in observational contexts.

In the following study, we were interested in whether infants can learn to anticipate congruent and incongruent action outcomes if they are addressed communicatively before being shown the action demonstration. However, infants' expectations about familiar actions may be too ingrained, even in the presence of communication. It is also possible that they perceive communicatively presented actions with unexpected outcomes as joking interactions (cf. Hoicka & Gattis, 2008; Hoicka & Martin, 2016; Hoicka & Wang, 2011) or show epistemic vigilance towards adults that present information they know to be false (see Mascaro & Sperber, 2009; Poulin-Dubois et al., 2011; Zmyj et al., 2010, for older children and the previous Chapter for 9-month-olds). Therefore, we included additional, novel action-object relations that were used in the same way as the familiar and unexpected goal locations.

In addition to tracking infants' gaze, we also investigated their Pupillary Light Response (PLR, Hepach et al., 2012; Hepach, Vaish, & Tomasello, 2015; Hepach & Westermann, 2016; Hepach et al., 2017). The PLR is a slower and more persistent response towards differences in arousal that spans over several seconds and measures a baseline arousal state (Hepach et al., 2015; Hepach & Westermann, 2016). The PLR is evoked in response to a bright stimulus on a dark background. An initial pupillary constriction is followed by pupillary redilation, lasting approximately 5 s (Hepach & Westermann, 2016). Although the pupil mainly responds to the brightness of the surrounding, it is also sensitive to emotional and cognitive processes. This includes immediate on-line responses to unexpected events, but also longer-term changes in arousal (Hepach et al., 2015).

Pupillary measures have not commonly been used in the study of communicative signals, with a few exceptions (Marno et al., 2015; Rigato, Rieger, & Romei, 2016). Alternative accounts to Natural Pedagogy (Gredebäck et al., 2018; Szufnarowska et al., 2014) argue that the effect of communicative signals on infants' action learning is due to an increase of arousal. Previous research on four-month-olds presented with different types of speech did not find any evidence that (infant-directed) speech increases their pupil dilation on-line (Marno et al., 2015), compared to reverse speech or no speech at all. However, it is not clear whether the presence of communicative signals influences the immediate response indicated by on-line pupillary measurements, or whether it affects the tonic pupillary response indicating a long-term response in arousal. Therefore, it is interesting to look at the effects of the slower pupillary light reflex (Hepach et al., 2015) to investigate whether the presence of communicative signals influences infants' arousal.

Pupillary responses have also been involved in a variety of violation of expectancy paradigms to investigate action understanding (e.g. Gredebäck & Melinder, 2011) and object permanence (Sirois & Jackson, 2012; Jackson & Sirois, 2009) and the congruence between actions and emotions (Hepach & Westermann, 2013). However, currently only Hepach and Westermann (2013) have used the PLR to study expectancy violations, whereas the other studies have used on-line measures.

For the current study, we were interested in the effect of communication on early action understanding in seven-month-olds, as previous research has shown that between 5–9 months of age infants show evidence of being able to anticipate action outcomes, but do not yet show a full semantic understanding of these actions. Five-month-olds show evidence of increased familiarity for congruent actions, such as bringing food to the mouth (Michel, Kaduk, et al., 2017) and infants from 6 months onwards are able to anticipate a number of other object-related actions (Hunnius & Bekkering, 2010; Kochukhova & Gredebäck, 2010). Other studies have found no evidence of *semantic* processing of these action sequences and Reid et al. (2009) have found an N400 ERP component for unexpected actions at nine months but not seven months of age. Likewise, Michel, Kaduk, et al. (2017) have also failed to find evidence of an N400 ERP in five-month-olds. Therefore, it appears that before nine months, infants are able to anticipate familiar actions, but do not yet have a fully semantic representation of the actions.

Hypotheses

Anticipatory Looking

If the presence of communicative signals contributes to infants' learning of new actions, we can hypothesise that when infants are addressed communicatively, they either (1) show increased anticipatory looks towards the incongruent action outcomes and the novel action outcomes, or (2) show increased anticipatory looks towards novel action outcomes only, but not incongruent action outcomes, since their previous knowledge of these action outcomes is still strong.

Pupil Dilation

If communication facilitates learning through arousal we should observe an increased pupillary light reflex after infants have observed a communicative actor. In addition, incongruent and novel actions may lead to greater arousal as measured by the pupillary light reflex, too. We may also observe an interaction of both factors. For example, communicatively presented actions may lead to greater arousal, when they show novel outcomes. Alternatively, infants may also show reduced arousal towards communicatively presented incongruent action outcomes.

3.1 Method

Participants

We included 43 7-month-old infants (average age: 214 days; range: 191–230 days; 20 females) in the anticipatory looking analysis. Infants were included in the analysis if they watched at least two experimental blocks and showed reliable tracking during calibration and in response to fixation points shown throughout the study. An additional 3 children were tested but excluded from the analysis, because of technical issues during the recording ($N = 1$), or unreliable calibration ($N = 2$). For the pupil dilation analysis, we investigated a subset of the previous sample and 34 infants were included in the final sample. Nine children were excluded due to abnormally large pupil measurements ($N = 2$), insufficient pupil size tracking during the pupil measurement ($N = 4$) or insufficient data during baseline measurement ($N = 3$).

A further 6 infants participated in a pilot study to establish the optimal length of the experiment.

Parents were recruited through the Lancaster Babylab database and received a book for their participation and £10.00 for their travel expenses. The study was approved by the Lancaster University Research Ethics Committee. Participants' parents gave their consent before to start the experiment.

Materials

The procedure of our study is based on Hunnius and Bekkering (2010). Each trial consisted of a video of an actor greeting the participant either communicatively (ostensive condition) or non-communicatively (control condition), before demonstrating an object-related action. The communicative actor looked straight ahead, smiled, waved and greeted the participant in infant-directed speech, with three longer greetings of approximately 2-3s: "Right, there we go!", "Oh, what's that!", "Hello there, look!" (similar to Yoon et al., 2008) and four short greetings of approximately 1s: "Wow!", "Hello!", "Look!", "Hey!". In the control condition, the actor adopted a neutral facial expression, looked slightly below the line of sight without establishing eye contact with the participant and speaking in a neutral, adult-directed speech "Oh! What's that.", "Right, there we go.", "Well then, look." (no rising intonation at the end, cf. Yoon et al., 2008). The short greetings were "Hmm", "Ok.", "Well.", "Yeah" (all approximately 1s). During the greeting, the object associated with the action was superimposed onto the video.

In the second part of the video (length: 6.1s), each actor presented the object by picking it up and putting it either to the mouth or their ear/hair. The objects consisted of two typically mouth-directed (spoon, cup), two head-directed (phone, hairbrush) and two novel objects (blue and green dog toys). An overview of the trial order is shown in Figure 3.2 and a selection of still frames from the videos is shown in Figure 3.1.

Figure 3.1: Example still frames of the stimuli, depicting the three different actors, the six different objects with one outcome. Note that for the study both outcomes were shown. Red and green areas show AOIs (red = head, green = mouth).

Procedure

Infants were sitting on their parents' lap, approximately 60 cm away from the screen. Parents were instructed to sit facing away from the screen by turning either to the left or right side. The direction that the parent was sitting was randomised. They were instructed to not look at the screen during the presentation.

Eye movements and pupil dilation were recorded at a sampling rate of 120 Hz and 0.4° accuracy using a Tobii X3-120 eye tracker (Tobii technology, Danderyd, Sweden). A custom Matlab (Mathworks, Natick, MA, USA) script was used for stimuli presentation using PsychToolBox version 3.0.12 and eye tracking data acquisition using Tobii SDK 3.0.

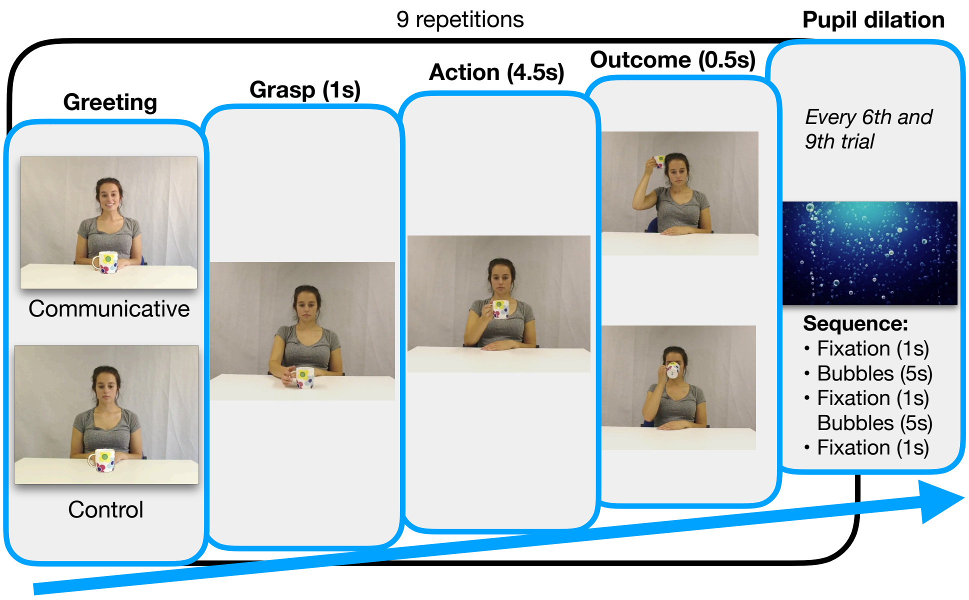

Figure 3.2: Trial order and order of one experimental block. The first, fourth and sixth greeting video used a longer greeting, the other greetings were short and consisted of one word only. Each block consisted of nine trials and PLR measurements were taken every 6th and 9th trial.

The stimuli presentation was initiated by a custom five-point calibration procedure of a blue dot moving across the screen. The dot made a sound at each calibration point, before moving to the next. The calibration was repeated until at least four of the five dots were successfully calibrated.

The videos described in *Materials* were shown in blocks of nine trials. The first, fourth and seventh greeting were long greetings and the greeting used for each trial was randomised. The action-object relationship during each block was kept constant. Between blocks, the study used a mixed design, during which the first actor presented two objects congruently, e.g. by picking up the spoon and putting it to their mouth. The second actor used the objects incongruently, e.g. put the spoon to the ear. The third actor used the novel objects. The order of presentation of each block was randomised and the combinations of actors/objects were counterbalanced. Therefore, infants were presented with all actors and all objects. However, within a particular combination of actor and action, infants only saw either the ostensive *or* the control condition to avoid spill-over effects from the ostensive conditions (c.f. Gliga & Csibra, 2009). Furthermore, each actor either presented the novel, congruent or incongruent conditions. Infants' looking behaviour was recorded continuously during the stimulus presentation.

Pupil dilation measurements were taken at the start of the presentation to establish a baseline measure and then every 6th and 9th trial within a block. During pupil measurements, an animation of blue bubbles interrupted by a black screen with a white fixation point was presented to ensure luminance was the same across all conditions (Hepach et al., 2012; Hepach & Westermann, 2016).

3.2 Data Preparation and Analysis

The data was imported and analysed using a custom script in R version 3.5.1 (R Core Team, 2018). The pupil dilation and gaze point data was filtered and interpolated using the scripts and procedures by Hepach et al. (2012). For the statistical analysis, we used linear mixed effects models using the `lme4` package version 1.1-17 (Bates, Mächler, Bolker, & Walker, 2015). Significance tests for model comparisons were carried out using the anova() function.

Anticipatory looking:

For each actor-object-outcome combination, Areas of Interest (AOI) were defined at the final destination of the object. The AOIs of all target areas were of the same size ($80 \times 50 px$ on a $600 \times 800 px$ upscaled image). Fixations were only analysed for the time after the onset of the grasp during the lifting phase, but before the object or the actor's hand reached the AOI (cf. Hunnius & Bekkering, 2010). Since we are not interested in the processing of the individual objects and to achieve greater consistency, the AOIs contrasted were only the head and mouth regions (See Figure 3.1)

Data was filtered and interpolated using the procedure described by (Hepach et al., 2012) and trials were removed if 50 % of the data was missing. The data was imported into the `EyetrackingR` package (Dink & Ferguson, 2015, `www.eyetracking-r.com`). Looks outside of the AOIs were included/excluded. The proportion variable was converted into the empirical logit (elog) to ensure a random distribution of the residuals vs. fits in the models (c.f. Dink & Ferguson, 2015).

We tested three mixed effects models predicting the proportion of looks towards the Target over the Competitor. The maximal model tested the interaction between $Communication$ (communicative, control), $Congruency$ (congruent, incongruent, novel) and the $TrialNumber$. $ActionTarget$ (head, mouth) was included as a control factor. We compared the maximal model to a model testing the $Congruency \times TrialNumber$ interaction to assess the effect of communication specifically and a null model that only contained $ActionTarget$ as a predictor (to control for the theoretically non-meaningful prediction that infants prefer to look at the mouth regions over the head regions). The full model specifications are shown in Table 3.1. This approach was chosen to reduce the overall number of comparisons and avoid multiple comparison problems of testing the significance of each factor separately (Forstmeier & Schielzeth, 2011; Mundry & Nunn, 2009).

All models contained the same random effects structure and Participant ID and Object were specified as random effect levels. Communication and Congruency were specified as slopes on the participant level, no slopes were specified on the Object level, corresponding to the maximally converging random effects structure (Barr, 2013; Barr, Levy, Scheepers, & Tily, 2013; Bell, Fairbrother, & Jones, 2018).

Pupil dilation

The baseline score of the pupil dilation measurement was taken at the beginning of the experiment, before any other stimuli were presented. Subsequent measurements were taken on the sixth and ninth trial for each block (c.f. Hepach et al., 2012, for details on the methodology). The data was averaged and a running baseline correction was applied by subtracting the baseline measure of each trial from each subsequent pupil measurement (Hepach et al., 2012), resulting in a measure of the *change* in pupil dilation. The averaged time series graph is shown in Figure B.7.

Pupil measurements were removed if there was less than 50 % tracking data available during the pupil dilation recording or the child did not watch at least five trials during the action presentation. The final sample contained 182 data points (see Table B.2 for a distribution of the original and the included data sets).

For the statistical analysis, we took the mean of the time series for each measurement and computed a mixed effects analysis using the lme4 package. We compared the full interaction term of the $Communication \times Congruency$ interaction to a null model that contained the intercept only. Subject ID and Actor were specified as random effects. Object was not specified as a random effect due to the high correlation with the intercept. Congruency and Communication were defined as slopes in the Subject ID effect, but not on the Actor level (full model specifications are shown in Table 3.2. This represented the maximal converging random effects structure (Barr, 2013; Barr et al., 2013; Bell et al., 2018). The model fit was assessed by using a χ-square test on the log-likelihood ratio values of both models.

3.3 Results

Anticipatory Looking

The analysis suggests that the null model containing only the Action Target is the best representation of the data. Neither the model containing the interaction with Communication, Congruency and the Trial number ($\chi^2(6) = 3.287, p = .772$, see Figure B.5), nor the model testing the interaction between Communication and Congruency ($\chi^2(5) = 3.442, p = .632$) were significantly better. Therefore, we did not find any evidence that infants are able to anticipate the action outcomes, or that communication affects the anticipation of action outcomes over time.

However, the Action Target term in the null model showed a significant effect ($\beta = 3.7592, SE = 0.4965, \chi^2(1) = 36.187, p < 0.0001$), suggesting that infants strongly prefer looking at the mouth over the upper head region (See Figure 3.3 for details).

Pupil Dilation

We found no evidence that the model containing the Outcome by Communication interaction was better than the null model ($\chi^2(5) = 4.93, p = 0.42$).

Table 3.1: Model comparison for the anticipatory looking analysis, comparing the null model controlling for the AOI with the models containing the interaction between Communication (communicative, control) and Congruency (congruent, incongruent, novel) and Trial Number (0–9), controlling for Action Target (head, mouth). The full model specification was: $Elog_{Prop(Target/Competitor)} \sim 1 + Communication \times Congruency \times TrialNumber + ActionTarget + (Communication + ActionTarget|ID) + (1|Object)$

	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
$ActionTarget$	10	5,871.585	5,923.454	-2,925.792	5,851.585			
$Congruency \times TrialN + Act.Target$	15	5,878.143	5,955.947	-2,924.072	5,848.143	3.442	5	0.632
$Com. \times Congr. \times TrialN + Act.Target$	21	5,886.856	5,995.781	-2,922.428	5,844.856	3.287	6	0.772

Table 3.2: Model comparison for the pupil dilation analysis, comparing the intercept-only model with the model containing the interaction between Communication (Communicative, Control) and Congruency (Congruent, Incongruent, Novel). The full model was specified as $PupilChange \sim 1 + Communication \times Congruency + (1 + Communication + Congruency|ID) + (1|Actor)$

	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
$Intercept$	13	-104.996	-63.344	65.498	-130.996			
$Communication \times Congruency$	18	-99.931	-42.259	67.965	-135.931	4.935	5	0.424

Figure 3.3: Predicted proportions based on the complex model for the ActionTarget main effect. Error bars represent confidence intervals.

3.4 Discussion

We were interested in how infants understand the use of everyday objects in communicative and non-communicative contexts. In particular, we were interested in whether the presence of communicative signals prior to an action demonstration can help anticipate familiar action outcomes by marking the shown action as potentially relevant. We were also interested in whether the presence of communicative signals can override prior action expectations for already familiar actions and can help infants to anticipate novel action outcomes. The results of the anticipation analysis show that infants may not be as proficient in anticipating action outcomes as indicated by previous research (Hunnius & Bekkering, 2010), as we found only little to no evidence for the anticipation of action outcomes. We did, however, replicate a general preference for the mouth, over the head.

There are multiple reasons why infants showed more fixations to the mouth, compared to the head. In standard face-scanning tasks, the mouth area draws considerably more looks compared to the ear and temple regions, albeit not as many as the eyes (Kato & Konishi, 2013; Senju, Vernetti, et al., 2013). Furthermore, the mouth area is perceptually more salient and infants' ability to predict actions also depends on the saliency of the goal (Adam et al., 2016; Biro, 2013; Elsner, 2007). For example, infants' anticipations of an action sequence declined when the goal location was a black square blending into the background, compared to a salient red dot that was clearly distinguishable from the background (Biro, 2013). The action of putting things to the mouth also has clear outcome effects (i.e. mouth opens). Previous research has highlighted the importance of action effects in infants' anticipation of outcomes (Elsner, 2007). For example, simply touching an object without causing any effect does not lead infants to anticipate a similar touching action in the future (Woodward, 1998). Only when the actor actually grasps the object or there are noticeable action effects do infants anticipate these actions in the future (Csibra & Gergely, 2007; Elsner, 2007) or imitate them (Király, Jovanovic, Prinz, Aschersleben, & Gergely, 2003).

Infants may have also shown an increase in looks towards the mouth area because putting an object to the mouth is a meaningful action on its own or because they have experience with oral exploration of objects themselves. The purpose of the head directed actions may have been less clear to the seven-month-old infants in our study and it is perceptually less salient, since there is no clearly-defined target for the action. Although Hunnius and Bekkering (2010) investigating children between the ages of 6–24 months found anticipatory effects even for actions like using a hairbrush, research on 3-year-olds has found that children struggle to imitate actions terminating at body parts correctly (Gleissner, Bekkering, & Meltzoff, 2000) and younger infants may find these actions more difficult to predict as well.

Furthermore, the effects of communication may be expressed in other ways than increased anticipations towards outcomes. The study by Hernik and Csibra

(2015) showing that children form enduring tool functions used external tools (the banana peeler/unpeeler) in teaching 13.5-month-old children and thereby avoided the use of body-directed actions. However, even in this study, infants did not show increased looking times after being addressed in infant-, rather than adult-directed communication. These studies suggest that the low levels of anticipations in our study may be due to too complex or opaque stimuli given the age group investigated. It is also possible that successful anticipations require a clear goal to be learned in such a relatively short time and that particularly our head-directed actions were not easily identifiable as potential action targets.

An important difference to the study by Hunnius and Bekkering (2010) is that our study manipulated congruency in a within-subjects design and that this presentation might have been confusing for infants and we may have not observed an effect of communication on infants' anticipation of action outcomes for the same reason. Overall, the actions were of similar configuration and timing to the actions presented by Hunnius and Bekkering (2010). Daum, Gampe, Wronski, and Attig (2016) found that infants were more likely to anticipate actions that were carried out over a greater distance or were presented slower. In our stimuli, we controlled the timing so that the movement to the head and the movement to the mouth took approximately the same time. Overall, the changes in the speed of the action may have balanced out the shorter distance of the mouth-directed action, however the editing of the videos may have made them appear less natural and led to a decrease of object-associated anticipations and the observed effects may have been due to the processes discussed in the previous paragraph.

Finally, infants may have shown relatively few anticipations during the movement of the actions since they may have already anticipated the outcome locations during the greeting and therefore did not need to anticipate the action again after the onset of the movement. Unfortunately, previous studies do not allow us to draw conclusions on the timing of the anticipations. To control these confounds, it may be possible to use still images of the actors during the greeting and only modify whether or not the speech is infant-directed. This would make the stimuli less naturalistic but allows a more controlled presentation and analysis of the anticipations during the greetings.

In addition to infants' anticipation of action outcomes, we were interested in their excitatory arousal as measured through their pupil dilation after seeing the action-outcome pairings and being addressed communicatively (c.f. Hepach et al., 2012; Hepach & Westermann, 2016). We hypothesised that infants would show greater arousal in communicative compared to non-communicative contexts and might also take into account their expectations about these actions by showing greater arousal towards unexpected or novel action outcomes. However, the infants in our sample did not show an increase in arousal when they were communicatively addressed. Previous research has shown that multimodal combinations of visual and auditory signals can lead to increased pupil dilation (Rigato et al., 2016) and that pupil dilation does not increase for infant-directed compared to reverse speech (Marno et al., 2015). In our study, both greetings included a multimodal presentation that included speech and therefore these differences may not have influenced infants' affective response. However, the pupil dilations found by Rigato et al. (2016) were in direct response to the stimulus and may not have have been sufficiently long-lasting to affect the slower pupillary light reflex (Hepach et al., 2015). Therefore, a promising route for future research might look at infants' online response to expected, unexpected and novel action outcomes. Such an analysis is not possible with our data since the brightness of each video is not controlled over time (except during the bubbles-presentation during the pupillary light reflex measurement) and therefore any changes observed may be related to the brightness of the images. This is further complicated by the different trajectories of head- and mouth-directed actions, which may lead to artefacts in the pupil dilation measurements of commonly used eye trackers (Brisson et al., 2013).

In the light of these challenges, it may be more appropriate to investigate abstract, novel actions and to teach infants new actions to create the expectations about actions (Kaduk, 2017). Furthermore, a wider age range may be necessary to determine whether seven-months-olds' failure to anticipate even familiar, congruent action outcomes is due to their age or stimuli specific.

Chapter 4

Paper Three: Communicative signals as action segmentation markers in 18-month-old children

When learning about actions, children do not only need to learn about the goals and outcomes of an action, but also its structural properties. Actions are hierarchically organised, with simpler action units nested in higher-order action plans (Elman, 1990; Maffongelli, Antognini, & Daum, 2018; Zacks & Tversky, 2001). To understand the meaning of actions, it is necessary to segment them into appropriately-sized units, so that they can be integrated into existing knowledge or generalised to create new predictions. Such a process shares many similarities with the segmentation and processing of linguistic information (cf. Christiansen & Chater, 2016).

There are many perceptual properties that provide natural boundaries and allow a learner to identify many action units and subunits. For example, goal-directed actions have distinct endpoints, when the goal state is achieved. Already from an early age, infants show an understanding of actions as goal-directed (Biro et al., 2014; Csibra, 2003; Verschoor, Spapé, Biro, & Hommel, 2013) and distinguish between actions that are carried out in an efficient and non-efficient manner (Gergely & Csibra, 2003; Gredebäck & Melinder, 2011). However, not all action units are relevant to any given task, whilst some relevant actions may be difficult to identify because they are not salient on their own.

During child-directed interactions, parents engage in a wide range of behaviours that can potentially help children to break up actions into smaller, meaningful units, and highlight those that are relevant to the task. For example, infant-directed actions are often presented in an exaggerated manner, highlighting event boundaries (Brand et al., 2002; Koterba & Iverson, 2009; Rutherford & Przednowek, 2012) and are also highly repetitive (Brand et al., 2009). Furthermore, parents are more likely to look and address children at action boundaries (Brand et al., 2007, 2013; Williamson & Brand, 2014). Because of this, communicative signals are a potentially valuable source of structural information that can be used to break up actions into smaller segments. Previous research has shown that young children prefer looking at infant-directed actions (Brand & Shallcross, 2008), and show different patterns of exploration (Koterba & Iverson, 2009) and higher rates of imitation for such actions (Williamson & Brand, 2014). However, we currently do not know whether the *position* of communicative signals within a continuous action sequence affects infants' understanding of actions. The following paper will investigate whether toddlers use the position of a social signal to segment actions and change which part of an action they imitate.

4.1 Teleology as a foundation of action units

Children show a basic understanding of goal-directed actions from early on, also called *Teleology*. Children attribute goals to i) actions with an equivalent outcome, ii) actions that have an effect, iii) if the agent shows signs of animacy (Biro & Leslie, 2007). According to some theoretical accounts (Biro & Leslie, 2007; Csibra et al., 1999; Csibra & Gergely, 2007; Gredebäck & Melinder, 2011) infants also expect that actions are carried out rationality. For example, they assume that an agent will take the shortest path to reach a goal, and only expect the agent to take a longer path when the shortest is blocked. For example, by the age of 9 months, infants show an understanding of rationality in understanding actions and expect that an abstract object takes the direct path when moving to a goal location (Csibra et al., 1999). Once infants have been able to attribute a goal, they are also able to generalise this to other actions (Biro, Verschoor, & Coenen, 2011; Biro et al., 2014). Although this ability has been argued to be an innate core principle (Csibra & Gergely, 2007), there is also evidence that it may be learned. If 9-month-old infants are repeatedly shown an agent taking a longer path because the shorter path has been blocked, they will keep anticipating that the agent takes the longer path even when the obstacle has been removed (Paulus et al., 2011). This suggests that their predictions may not be driven by rationality or are easily affected by frequency information. Irrespective of its origin, infants appear to be sensitive to basic relationships between actions and goals from at least 9 months.

Infants also interpret the behaviour of others according to the same principle. For example, by the age of four months, infants show different pupil dilation for rational and irrational feeding actions (Gredebäck & Melinder, 2011). When an actor feeds another actor, infants show greater pupil dilations (indicating arousal or expectancy violations) to the actor putting food into the others' hand, instead of feeding them directly. However, the pupil dilation is at baseline when an obstacle prevents the expected feeding action (Gredebäck & Melinder, 2011).

An interesting case of infants' attribution of goals is revealed in their imitation of an action's manner compared to its outcome (Carpenter et al., 2005; Southgate et al., 2009). Twelve- and 18-month-old toddlers are more likely to imitate the manner of an action in the absence of a clear outcome. When an experimenter moved a toy animal either in a hopping or sliding movement, toddlers were more likely to imitate the manner when they saw the action performed on its own, but not when they were shown the animal go into a house (Carpenter et al., 2005). If they observe the sliding/hopping action on its own, toddlers interpret the manner of movement is the goal of the action. However, when the action has another, clearer goal, toddlers see the manner as merely instrumental, but not essential in achieving the goal of putting the animal into the house.

4.2 Meaning through communication

Caregivers often use so-called *ostensive signals*, such as direct gaze and infant-directed speech, to transmit new and relevant information. According to Natural Pedagogy Theory (Csibra & Gergely, 2009, 2011), infants have an innate sensitivity towards the sources of these signals. In their presence, infants will learn and generalise information faster and will form enduring representations, even if presented with counter-evidence (Csibra, 2010; Hernik & Csibra, 2015; Marno & Csibra, 2015).

Numerous studies have found evidence that communicatively-presented information is perceived differently to the non-communicatively presented information. For instance, 18- and 24-month-old children are more likely to imitate unnecessary actions in a communicative context, compared to a non-social context (Nielsen, 2006). In a situation where an experimenter had their hands occupied (e.g. holding a blanket), Király et al. (2013) found that 14-month-old children would imitate a non-rational action such as using one's head to turn on a light if they had been ostensively addressed. Two-year-olds are more likely to demonstrate a pedagogically demonstrated action over a non-pedagogically demonstrated action to a stranger (Vredenburgh, Kushnir, & Casasola, 2015). Although five-year-olds do not only overimitate in pedagogical contexts, but also in non-pedagogical demonstrations (Hoehl, Zettersten, et al., 2014), they reduce their levels of overimitation only when they subsequently see a communicative model perform the more efficient action.

According to Natural Pedagogy, social signals act as a reference in time *when* an event might be relevant to the child. In the presence of social signals, they will actively look for the meaning of an action to learn and generalise its effects (Csibra & Shamsudheen, 2015). But how do they infer which parts of an action sequence presented to them in a pedagogical context are relevant?

4.3 Meaning through action segmentation

According to Event Segmentation Theory (Zacks & Swallow, 2007; Zacks et al., 2009; Zacks & Tversky, 2001; Kurby & Zacks, 2008) segmenting a stream of events plays an important role in the comprehension and anticipation of event sequences (Zacks, Tversky, & Iyer, 2001; Zacks et al., 2007, 2009; Sonne et al., 2016; Baldwin, Baird, Saylor, & Clark, 2001). Events can be segmented based on low-level features, such as motion cues, or prior, higher-order knowledge of the event (Zacks & Swallow, 2007). For example, the action *Paul is making tea* can be described in different ways:

a) *Paul makes tea,*

b) Paul puts water in kettle, boils the water, rinses the teapot with hot water, puts a tea leaves into the pot and pours boiling water over it, or

c) Paul's right hand grasps kettle, his right hand moves the kettle to sink, the left hand turns the tap, water is running, hand turns tap, the kettle is moved to the previous location, the right hand touches the button on kettle, Paul picks up a newspaper, holds the newspaper in front of his face. Then Paul gets up, his right hand picks up the teapot, pours water into the tea pot, pours water out of the tea pot. Paul's hand moves away from tea pot, his hand picks up a spoon, the hand scoops up tea with the spoon, the hand holding spoon moves tea, hand holding spoon drops tea into tea pot, tealeaves fall into the teacup, and so on...

Whereas (a) would usually not be a helpful description of how to make a cup of tea, (b) would provide a reasonable instruction for someone familiar with the use of a kitchen. The final option, (c) is confusing despite the detailed description. It provides too much information to be remembered and it does not indicate which steps are essential to the action. Therefore, in order to learn the meaning of complex actions, segmenting events into appropriately-sized chunks is essential. Already from 10-months onwards, infants demonstrate sensitivity to event structures. Ten to 11-month-old infants look longer at actions paused midstream, compared to those where the pause coincided with an event boundary, suggesting that they perceive these videos as more different to the ones they were familiarised (Baldwin et al., 2001).

Events can be segmented based on repetitions and structural properties (Swallow & Zacks, 2008), or salient event boundaries (Adam et al., 2016). Actions in pedagogical demonstrations share certain properties that make them particularly suitable for the segmentation of events, for example, exaggerated movements (Brand et al., 2002; Williamson & Brand, 2014), repetition and variation (Biro & Leslie, 2007; Brand et al., 2009; Goldstein et al., 2010) and the provision of direct gaze at event boundaries (Brand et al., 2007). Eye contact may be particularly suitable for breaking up events, as brief periods of direct gaze disrupt visual working memory (J. J. Wang & Apperly, 2016).

4.4 Chunks and bottlenecks

Chunk-based learning of actions is based on theoretical accounts of language acquisition, but its principles also apply to the understanding of actions (Christiansen & Chater, 2016). According to chunk-based learning, children continuously attempt to integrate novel information. This requires the input to be processed immediately, before it is overwritten by new information. This creates a limitation of how much input can be processed and passed on to the next higher level, the amount of information that can be processed at any time is restricted. To overcome this bottleneck, a learner needs to form basic abstractions (e.g. moving hand, filling kettle) that can then be used to build higher level representations. However, once the appropriate higher level action representations (e.g. 'making tea') are in place, they can be used to reconstruct the lower level information (Loucks & Meltzoff, 2013; Christiansen & Chater, 2016; Zacks & Swallow, 2007).

A crucial difference between the Natural Pedagogy and Chunk-based learning accounts is that Natural Pedagogy predicts that communicatively presented information receives privileged processing compared to non-social, observational learning (Csibra & Gergely, 2011). Infants and children see actions demonstrated in communicative contexts as symbolic and representing other actions of the same kind (Csibra & Shamsudheen, 2015). Chunk-based learning, on the other hand, does not distinguish between pedagogical and observational situations. Instead, the learner attempts to process all information continuously, but only retains information that can be interpreted within the limits of the learner's memory constraints and the complexity of the input. Nevertheless, sensitivity to ostensive signals and chunk-based learning are not mutually exclusive. It is possible that humans have evolved an innate sensitivity towards ostensive signals and exploit them for efficient chunking in pedagogical contexts. It is also compatible with other theoretical accounts on infants' learning of ostensive-referential signals, for example, work on gaze-following suggesting that infants need a sufficiently strong but not overbearing preference for faces in order to learn to follow gaze reliably (Triesch et al., 2006).

Whereas the teleological account of goal-directed actions is mainly concerned about the perception of actions that share features of intentionality, Event Segmentation Theory and Cognitive Chunking accounts describe learning across a wider range of contexts based on the interaction of low-level visual features and higher-order knowledge. According to this view, many of the conditions for understanding goal-directed actions discussed by Biro and Leslie (2007) are linked to perceptual features of movement, variation and perceptual change (e.g. when an action has an effect) that are essential to the segmentation of events or could be used to chunk information.

4.5 Ostensive cues as signifiers of action boundaries

To investigate whether ostensive signals can lead to increased imitation of actions, it is particularly interesting to look at multi-step actions consisting of different subunits that are not clearly identifiable on their own. An example of such an action sequence is children's differentiated imitation of an experimenter sliding or hopping a toy animal across a board before putting it into a house discussed earlier (Carpenter et al., 2005). Previous research has already shown that children in this task are sensitive to communicatively presented prior information (Esseily, Rat-Fischer, O'Regan, & Fagard, 2013; Southgate et al., 2009). If children were told in advance about the goal of putting the animal into the house, (Southgate et al., 2009), they are almost twice as likely to imitate the manner of the action, compared to when the actor does not mention the goal outcome or they discover the goal of the action on their own (Southgate et al., 2009). The authors interpreted these results as providing evidence that 18-month-olds understand communicative relevance. Because the children already know about the goal, they take the demonstration of the mouse hopping/sliding into the house to be about novel, relevant information, i.e. the manner of the action.

On a more general level, these results provide evidence that top-down information can influences the interpretation of events, as predicted by event segmentation theory (cf. Zacks, 2004), cognitive chunking (Christiansen & Chater, 2016), and teleological accounts (Behne, Carpenter, Call, & Tomasello, 2005). However, it is possible that bottom-up information can fulfil a similar role (Zacks, 2004) and alter toddlers' interpretation of an action sequence. Communicative signals, such as direct gaze, infant-directed speech would be ideal candidates for breaking segmenting actions in pedagogical contexts (cf. Brand et al., 2002, 2007). If children use communicative signals to segment actions, then they might show different rates of imitation for the actions' subunits depending on the placement of the communicative signal within the unfolding stream of actions.

The methodology is based on Carpenter et al. (2005) and Southgate et al. (2009) who demonstrated a toy animal moving to a house, either by hopping or sliding the animal across a playing field. Infants in Carpenter et al. (2005) were either presented with the action of sliding/hopping and the goal outcome of moving the animal into the house, or no observable goal outcome. In Southgate et al. (2009) infants were either told about the action's outcome before the demonstration or received an action-irrelevant piece of information.

According to Event Segmentation and Cognitive Chunking theories, both top-down and bottom-up information influence the way that information is segmented and processed, and this information can be used to segment other events. It is possible that providing prior information about the action goal has allowed children to segment the hopping/sliding action from the Outcome (cf. Braukmann et al., 2017; Paulus, Schuwerk, Sodian, & Ganglmayer, 2017; Southgate et al., 2009). However, it is possible that ostensive signals can provide similar segmentation cue through their placement within the action stream.

In the study proposed here, we would like to investigate whether communicative signals can help to segment an action sequence and change children's imitation of the actions. Instead of conveying the goal of the action linguistically, we use an ostensive signal at the boundary after the sliding/hopping action and before putting the animal into the house to segment the action. The control condition matches the House-Condition in Carpenter et al. (2005) by providing the entire action, including the goal of putting the animal into the house.

We hypothesise that the position of ostensive signals within the unfolding action can have a similar effect to providing the information about the action goal communicatively (Southgate et al., 2009) by breaking up the action stream and emphasising the manner as a separate event. As in previous studies, we expect that all children will imitate the goal of the action as it is a salient outcome, as the action of putting the animal into a house is a perceptually marked event on its own. However, we predict that infants in the boundary-marked condition will show higher imitation of manner compared to the unmarked condition.

To ensure that the data is comparable with the previous studies (Carpenter et al., 2005; Southgate et al., 2009), we decided to investigate the same age group of 18-month-old toddlers. These studies have shown that by the age of 18-months, (and to a lesser extent, by 12-months Carpenter et al., 2005), toddlers are less likely to imitate only one outcome of an action, but not the manner, and that the presence of a prior communicative context potentially modulates the imitation of the action (Southgate et al., 2009). Therefore, we would expect that the effect of communicative cues on action segmentation and their subsequent imitation is strongest in 18-month-olds.

4.6 Methods

The methodology, hypotheses and analyses were registered on `aspredicted.org`, reference number #5771.

Participants

We tested 40 18-month-old infants ($Mean: 18\,m, Min: 17.5\,m, Max: 18.5\,m$). An additional 10 infants were tested, but excluded due to being unwilling to engage with the game (6), parental or sibling interference during all trials (2), incorrect age at time of testing (1), or experimenter error (1).

Materials

The actions were presented on a green cardboard mat ($42 \times 60cm$) with a small cardboard house (yellow, red). Four small toy animals (fox, rabbit, hedgehog, squirrel, all approximately 6-8 cm tall) were used to act out the actions. The animals were kept in a small, colourful box prior to the experiment. Additionally, we used a wooden stacking game during the warm-up phase.

Procedure

Infants were sitting on their caregiver's lap. After a warm-up session to familiarise the infant with the room and the experimenter, the experimenter presented each animal to the infant with a short statement (e.g. "The squirrel has a bushy tail"). The infant was allowed to play with all animals for one minute. Afterwards, the animals were returned to the box and the experimenter drew the child's attention to the house.

The modelling phase began during which the experimenter took out one animal, placed it on the board and said: "Look what the [animal] does!" (German original: "Schau mal, was das [Tier] macht!") He then moved the animal across the table with either the sliding or the hopping action. In the *boundary-marked* condition, the adult looked up to the infant and said "Wow", before putting the animal into the house. In the *boundary-unmarked* condition, the adult put the animal into the house before looking and addressing the child. See Figure 4.1 for a graphical representation of the procedure. After the animal was put into the house, the experimenter said "Great! Did you see what the [animal] did? Now it's your turn!" (German original: "Toll! Hast du das gesehen was das [Tier] gemacht hat? Jetzt bist du dran!") before pushing the board to the child. Each trial demonstration lasted approximately 10 seconds, and the child had 30 seconds to respond. If the child did not engage with the animal, the experimenter encouraged the child by saying "Now you can play with it!" ("Jetzt kannst du damit spielen"), "Now it's your turn" ("Jetzt bist du dran") or similar. If the child attempted to pull the house off the board, the experimenter said: "That's fixed" ("Das ist fest.").

Each child was presented with up to four trials of the actions. The actions were shown in a fixed order of sliding–hopping–hopping–sliding, (cf. Southgate et al., 2009). Half of the children saw the action in the boundary marked condition, and the other half in the boundary unmarked condition (between-subject).

Coding

Infants were scored on whether they (1) imitated the action manner (2) imitated the goal/outcome of the action. In line with previous research (Carpenter et al., 2005; Southgate et al., 2009), the action manner was coded as sliding when the animal moved continuously without breaking contact with the mat. The child imitated the hopping action, when the animal broke contact and made contact at least once again with the mat. The goal of putting the animal into the house was achieved if the child put the animal into the house at least once, even if the child removed the animal afterwards.

A second coder naïve to the hypothesis coded manner and outcome for 24 videos. The inter-rater agreement was $\kappa = .899, p < .0001$ for manner and $\kappa = 0.935, p < .00001$ for outcome.

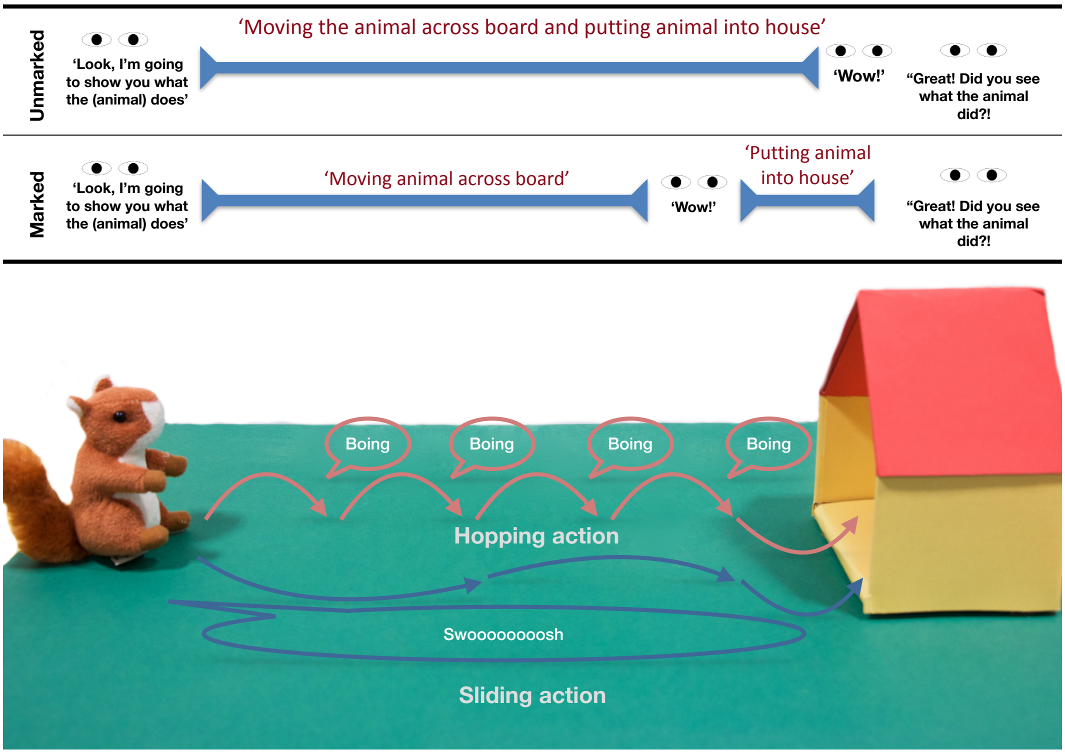

Figure 4.1: Diagram of the procedure, demonstrating the hopping and sliding actions and the location of the ostensive signals.

Children were included in the analysis if they contributed at least 50 %of the trials. After coding, 148 trials were included in the analysis. An additional 12 trials (6 hopping, 6 sliding) were excluded from the analysis due to the child not touching the animal (1), being fussy (3), parental interference (6) and experimenter error (2).

Statistical Analysis

Because some trials were missing, we decided to compute a generalised linear mixed effects model based on the binomial distribution using R (R Core Team, 2018) version 3.5 using the lme4 (Bates et al., 2015) package version 1.1.17. Based on our pre-registration, we compared a model with Boundary Marker (yes/no) to a null model containing the intercept only. In an exploratory analysis, we also tested the interaction between Action Type (hopping/sliding) and Boundary Marking. Trial number and Subject-ID were used as random effects. In line with the recommendations by Barr et al. (2013), we investigated the maximally converging random effects structure. For the model predicting manner imitation, this included the slope for Manner nested in the random effect for Trial Number. More complex models failed to converge, i.e. the optimizer failed to establish a reliable solution to the model. For the model predicting outcomes, the model with no slopes was the maximal converging model.

4.7 Results

Manner imitation: For the imitation of manner, the model containing the Boundary Marker only was not significantly better than the null model ($\chi^2(1) = 0.99, p = .32$). However, the model containing the interaction between Action Type and Boundary Marker showed evidence against the null ($\chi^2(3) = 9.27, p = .02$) and the main effect only model ($\chi^2(2) = 8.28, p = .016$). A detailed overview of the results can be seen in Table 4.1. An analysis of subsets of the Action Type factor shows a significant effect of marking for sliding ($\beta = 1.55, SE = 0.65, p = 0.017$), but not hopping ($\beta = -0.36, SE = 0.56, p = 0.52$). According to this model, marking increased the imitation of the sliding action from 12% (95% CI: 5 – 27%) to 40% (95% CI: 24 – 57%). For the hopping actions, no such increase was observed, and the imitation of unmarked (M = 50%, 95% CI: 33 – 67%) and marked (M = 42%, 95% CI: 27 – 59%) actions was not significantly different (see Figure 4.2).

Table 4.1: Model comparison for the manner imitation analysis. The formula for the full model was $Imitation(0/1) \sim Marked \times Action + (1|VP.No.) + (1 + Marked|TrialN)$*, representing the maximally converging model*

	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
$Intercept$	5	197.569	212.555	-93.784	187.569			
$Marker$	6	198.577	216.561	-93.289	186.577	0.991	1	0.319
$Action \times Marker$	8	194.300	218.278	-89.150	178.300	8.277	2	0.016

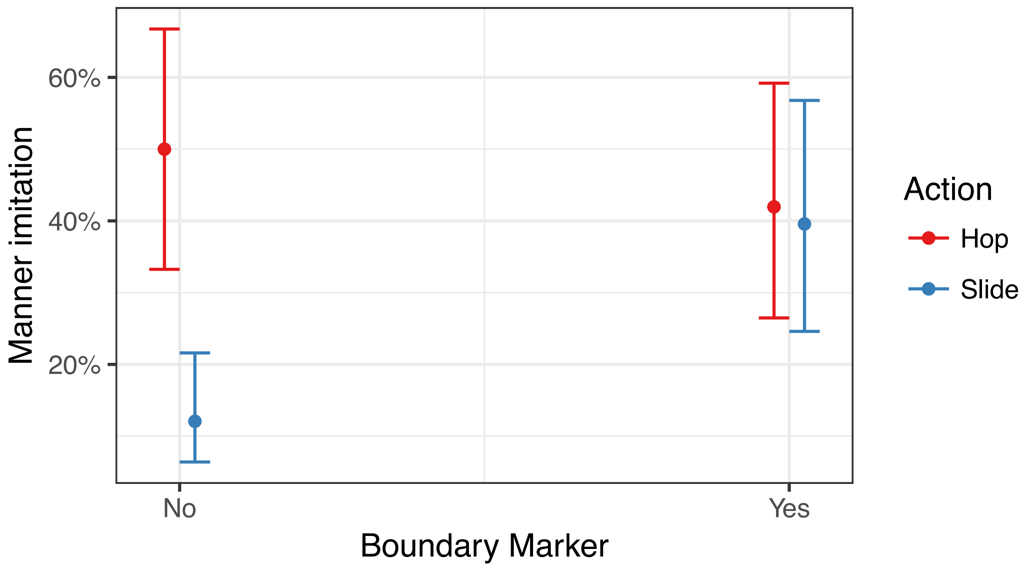

Figure 4.2: Means and confidence intervals of manner imitation for the interaction between the Action (hopping and sliding) and the position Boundary Marker (no/yes).

Outcome imitation: For the outcome imitation, the model containing the Boundary Marker only was not significantly better than the null model ($\chi^2(1) = 0.05$, $p = .82$).We did not find a significant interaction with Action, and there is evidence against the model containing the interaction term compared to the null ($\chi^2(3) = 0.48, p = .92$)) and the boundary marker main effects model ($\chi^2(2) = 1.21, p = .55$).). A detailed overview is provided in Table 4.2. Overall, imitation of outcome was at ceiling, with 99.9%.

4.8 Discussion

Although the study's hypotheses were only confirmed for one type of action, this study provides information on the role of communicative signals in everyday action's segmentation in infants. For the salient hopping action, marking the

Table 4.2: Model comparison for the outcome imitation analysis. The formula for the full model was $Imitation(0/1) \sim Marked \times Action + (1|VP.No.) + (1|TrialN)$*, representing the maximally converging model*

	Df	AIC	BIC	logLik	deviance	Chisq	Chi Df	Pr(>Chisq)
$Intercept$	3	84.965	93.957	-39.482	78.965			
$Marker$	4	86.912	98.901	-39.456	78.912	0.053	1	0.819
$Action \times Marker$	6	90.481	108.464	-39.240	78.481	0.432	2	0.806

boundary between the action manner and the outcome did not increase the level of imitation that was already high in the unmarked condition. However, for the less salient sliding action, marking the event boundary increased imitation considerably. These results are broadly compatible with Event Segmentation Theory, Cognitive Chunking and a Natural Pedagogy. Additionally, our results also suggest that more salient actions are potentially more likely to be segmented and imitated.

Our results are compatible with domain-general learning accounts, such as chunking (Christiansen & Chater, 2016; Gobet, Lane, & Lloyd-Kelly, 2015; Isbilen & Christiansen, 2018). According to these accounts, the brain tries to predict the incoming stream of information and attempts to meaningful chunks of information on different representational levels. Prior knowledge, as well as the structure of the incoming knowledge, are contributing to the processing and structuring of information. Input that can be integrated into existing knowledge is processed further and any inputs that cannot be processed is discarded. The data from our study is compatible with such a model and there are two potential mechanisms that could explain our results. Communicative signals might act as boundary cues that either (1) give children extra time to process the preceding action segment (e.g. the hopping/sliding), or (2) provide a cue to segment the action and process it as a separate action on its own. Consequentially, in the unsegmented sequence, only the outcome of the action will be stored in memory. The manner of the action will be discarded, unless it can be interpreted on its own. According to our data, children did not require segmentation cues for the hopping action. It is possible, that the hopping action was already interpretable and children were able to store, process and retrieve the action as a separate event without an additional segmentation cue.

Event Segment Theory also suggests that bottom-up and top-down processes influence the perception of an incoming stream of events (Zacks & Swallow, 2007), such as the action sequence observed by the children in our study. According to Event Segmentation Theory, the way that an event is segmented affects how it is interpreted, with similar behavioural consequences as in Cognitive Chunking. Subsequently, the segmentation of an action should lead to a different interpretation of the action sequence. Whereas the unsegmented action sequence is reduced interpreted as "putting the animal into the house" (by any means), the segmented event sequence is interpreted as two separate events of "hopping/sliding" and "putting the animal into the house". In line with this interpretation, it is possible that the hopping action provided sufficient information to be segmented from the overall action sequence.

Importantly, our results suggest that any effect of communicative signals only generalises to the sliding action, since children already imitated the hopping action reliably. It is possible that the children in our study were able to segment the hopping action because it is more easily identified, for example, due to its salience. Previous research has already highlighted the role of salience in children's imitation of actions. For example, toddlers between 12–30-months were more likely to imitate a hammering action compared to a less salient pulling action (Gampe, Prinz, & Daum, 2016) and 12-month olds were better at learning to anticipate reaches towards large, compared to small objects (Adam et al., 2016; Henrichs et al., 2012). Importantly, there is also evidence that the presence of communicative signals affects low and high salience actions differently. For example, at 16 months children are less likely to imitate actions without direct, observable consequences unless they are cued by social signals (Brugger et al., 2007). Three- to five-year-olds were more likely to imitate outcomes when these were accompanied by verbal information, but this effect was even stronger for less salient outcomes (Elsner & Pfeifer, 2012). Therefore, the contribution of communicative signals to goal-directed action segmentation might be to identify action boundaries in low salience actions. As the results of our experiment only show an effect of marker location on one of the two actions, future investigations need to systematically broaden the range of actions and their salience to generalise the findings to other actions.

Whilst some action units have clear boundaries that allow for their segmentation and subsequent processing, other units are not as easily segmented from the ongoing stream of information and are not processed and stored in memory. Studies by Hespos et al. (2009); Hespos, Grossman, and Saylor (2010) provide evidence that already by the age of 6 months, infants are more likely to detect changes of events with clear outcomes, compared to changes in the transitions between events, e.g. when a ball moving across the screen bounces down, instead of up, before arriving at its goal location. This distinction is evident in our results, where children imitated the more salient hopping action irrespective of the segmentation information provided by the model.

However, although the transition events investigated by Hespos et al. (2009, 2010) are in principle similar to the hopping/sliding actions in our study, the 18-month-old children in our study clearly imitated the hopping action even without further segmentation cues. This might indicate an age-related difference in children's action segmentation, or a difference between the transitional events used in both studies. In our study, the hopping action was more repetitive than the single-bounce used in Hespos et al. (2009, 2010). Indeed, domain-general models of learning (e.g. Goldstein et al., 2010; Twomey, Lush, Pearce, & Horst, 2014) have also emphasised repetitions and variations as important sources of learning about events and structures, particularly in parent-child interactions. The hopping event is highly repetitive within one presentation and therefore may stand out on its own. Such repetitions might be an important source of variation in infant learning and the way that parents shape the input that children receive in order to facilitate learning.

Children may have been more likely to perceive the hopping action as intentional, as it is not instrumental in moving the animal into the house. Whether or not an action is carried out intentionally plays an important role in its imitation (Behne et al., 2005; Meltzoff, 1995; Loucks & Meltzoff, 2013). Furthermore, previous research has found that adults perceive actions that cannot be explained by another goal are perceived as goals on their own (Schachner & Carey, 2013). In fact, this is also a key finding of the original research by Carpenter et al. (2005), who found that children only imitate the manner of the action when they could no longer appeal to the higher goal of putting the animal into the house. Repetitive, non-goal-directed actions are also perceived as communicative by adults (Royka, Aboody, & Jara-Ettinger, 2018) and therefore might be sufficient to initiate a communicative context to boost pedagogy.

Children's increase in their imitation of the sliding motion after being addressed after the sliding and before putting the animal into the house is also compatible with Natural Pedagogy Theory. In inferential accounts of infant learning such as Natural Pedagogy, the communicative and the informative intention are two separate intentions (Csibra, 2010). In pedagogical interactions, infants still need additional information about actions and their constituents to understand *which* parts of the actions are relevant. Children may have attributed a different informative intention to the second “Wow” depending on its location. The interruption of the action to address the children provides important information on interpreting the meaning of events by providing *temporal* reference, in addition to *spatial* reference that can be established through referential gaze to object locations (S. C. Butler, Caron, & Brooks, 2000; Senju et al., 2008) or pointing (Gliga & Csibra, 2009; Melinder, Konijnenberg, Hermansen, Daum, & Gredebäck, 2014; Morissette, Ricard, & Décarie, 1995). In just the same way that pointing can be used to disambiguate which object a speaker refers to, interrupting an action can be used to show that the action consists of multiple parts.

Importantly, the manipulation in our study has boosted the imitation of a *preceding* event (see also: Nie, Ding, Chen, & Conci, 2018), rather than creating a referential expectation for an upcoming event. This appears to go against an interpretation of Natural Pedagogy in which the communicative intention precedes the informative intention. However, the action demonstration took place within an already established communicative context, as the experimenter addressed the child at the beginning of the action demonstration (c.f. Csibra & Shamsudheen, 2015). Since communication is already established, infants may actively look for an interpretation of the action based on its location in time and by doing so establish the relevancy of the sliding action.

Although our study has shown that communicative signals can help to increase the imitation of a non-salient action manner in 18-month-old children, our study did not show whether this effect is unique to social signals. Social signals share certain properties that make them particularly useful for this purpose. For example, infants show a stimuli-specific preference towards gaze (Farroni et al., 2000, 2002; Michel, Wronski, et al., 2017; Michel, Pauen, & Hoehl, 2017) and infant-directed speech (Dominey & Dodane, 2004) and direct gaze appears to interrupt working memory (J. J. Wang & Apperly, 2016). However, so far we do not know whether these effects extend to action segmentation. Other, non-social signals may have similar effects on action segmentation and increase the imitation of action manner in this paradigm. It is possible that a non-social, self-directed ‘hmmm’ or a ‘beep’ initiated by a button press may have a similar effect on action segmentation. Furthermore, it is possible that even a simple pause might be sufficient to induce the segmentation of an action. For example, 6- (Sharon & Wynn, 1998) and 10–11-month old (Baldwin et al., 2001) infants that have been familiarised with video sequences of everyday actions look longer if the video sequence is paused within an intentional action, compared to a pause between intentional actions. Therefore, the effect might not be specific to social signals and any pause may be sufficient to segment non-salient actions for children and subsequently increase their imitation.

However, not every interruption is beneficial for the understanding of an event sequence. For example, Sonne et al. (2016) found that occlusions at event boundaries impaired children’s memory for movie clips after a two-week delay and this particularly affected 20-month-old children, compared to 16-month-olds. Our current experiment has only tested the immediate recall of a relatively short event sequence and we cannot make any inferences about the long term retention of these action sequences. However, segmenting a stream of actions into too many chunks is degrading to memory retention, since too many items would need to be stored (Christiansen & Chater, 2016). Therefore, it is likely that the usefulness of segmentation follows a reverse-u shape, with more segmentation clues leading more accurate imitation of an action sequence up to a point where too many items will have to be remembered and the number of successful actions within a sequence declining again. There is evidence that parents may take into account such a relationship during naturalistic interactions with their children, as older children receive more frequent, but shorter periods of direct gaze (Brand et al., 2007). This sensitivity may reflect children's increasing memory capacity or prior knowledge about the actions they are shown.

Previous research has shown that parents use communicative signals particularly at event boundaries (Brand et al., 2013). We were interested in whether children use this information in order to determine whether or not to imitate the manner of a transient action. The results of the current study suggest that they do, but only for actions that are not salient on their own. For these types of actions, they may be able to fulfil a similar role to verbal information about the action (e.g. Carpenter, Call, & Tomasello, 2002; Southgate et al., 2009). However, other parts of an action sequence may be salient enough on their own may not benefit from the additional information provided by the location of such social signals. The results of our experiment suggest a potential mechanism on how communicative signals provide information beyond their function as a marker for the presence of communication.

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Chapter 5

General discussion: Communication and Action Understanding

Communication and language shape human culture. Pragmatic theories of communication have argued that humans have a special sensitivity towards recognising communicative intentions (Scott-Phillips, 2007). Natural Pedagogy has built on these theories and proposed that infants already show a basic use of communicative intentions in the presence of specific communicative signals, such as direct gaze, infant-directed speech and contingent reactivity (Csibra, 2010; Csibra & Gergely, 2009, 2011; Csibra & Shamsudheen, 2015). Children's processing of actions in the presence of communicative signals is informative about the origins of a pragmatic understanding of communication because it allows us to investigate the role of communication before language is fully established as a mechanism of cultural transmission.

This thesis has looked at two different ways that communication and the presence of communicative signals may shape how infants understand others' actions. Chapters 2 and 3 derived their central hypotheses from Natural Pedagogy and investigate how infants learn about actions in communicative and non-communicative contexts. The experiments reported in these chapters are similar in conceptualisation and link closely to previous research in action understanding (Reid et al., 2009; Hunnius & Bekkering, 2010), but extend this line of research by investigating the effect of communicative signals on action understanding and prediction. Furthermore, Chapter 4 has looked at how ostensive signals can provide structural information to support how infants learn about actions by contributing towards their segmentation.

5.1 General Findings

Effects of communicative signals on action understanding

The central question of this thesis has been whether and how the presence of communicative signals may help children to understand, predict and imitate actions. Despite their different methodologies, all three experimental chapters investigated a similar question: Do communicative signals make the following action demonstration more meaningful? The four experiments reported in Chapters 2–4 suggests that, given the right circumstances, this may be the case.

Summary of ERP evidence

The main evidence that communication directly affects the meaning of actions directly comes from the analysis of the N400 and Pb components in Chapter 2. According to the canonical interpretation, the N400 indexes the violation of pre-activated semantic memory (Kutas & Federmeier, 2000, 2011). In the experiments in Chapter 2, showing a picture of an actor holding a spoon lead to a more positive deflection towards the following picture, when the actor moved the object to their forehead instead of putting it to their mouth. We observed this effect in both infant samples and the adult control group in the first experiment, but not the adults in the second experiment.

Critically, the two experiments reported in Chapter 2 found a small, but reliably increased N400 effect (as indicated by the difference between expected and unexpected mean amplitudes towards the outcome picture) for communicatively presented actions. This effect is not straightforward to interpret, as it does not come up in commonly used analyses, yet replicates across all three experimental groups that showed an N400 effect. Therefore, communicative signals may lead to a slightly higher activation of semantic expectations.

The results are also broadly compatible with recent interpretations of the N400 effect suggesting that the N400 reflects a probabilistic interpretation of meaning (Rabovsky et al., 2018). According to this account, the N400 reflects the probabilistic likelihood of an event taking place, based on previous constraints. The increased N400 effect may reflect infants' expectation that communicatively presented information is more predictable overall.

The experiments reported in Chapter 2 may have only found a very small effect of communication on the N400, because it is masked by the repeated stimulus presentation within each experimental sessions. Because ERP analyses aggregate multiple ERP data over time, it is difficult to conclude whether the differences between communicative and non-communicatively presented action outcomes changes over time. For example, it is possible that the presence of communicative signals initially leads to a higher semantic activation at the beginning of a series of action observations, but then gradually decreases when the unexpected action outcome has been observed repeatedly. However, it is also possible that the reverse is also true and communicative signals may facilitate action expectations over time and thereby to an increase ERP deflection for unexpected action outcomes. Given the slight increase of the ERP deflection for communicative-unexpected outcomes, there are several possibilities as to why we observe an increased N400 ERP:

1. Communicatively presented unexpected action outcomes lead to an increased ERP amplitude, compared to non-communicatively presented unexpected action outcomes.

2. Communicatively presented unexpected action outcomes increase the ERP amplitude for the unexpected condition over time.

3. Communicatively presented unexpected action outcomes show an initially larger ERP amplitude that decreases over time.

Mixed Effects Regression Analyses on the raw ERP measurements for each time window may be able to shed light on such effects. Such analyses would be informative about how communicative signals shape infants' learning and allow us to look at the mechanisms behind socio-communicative learning.

The second ERP experiments reported in Chapter 2 also suggests that communication might play an important role much earlier in the processing of the actions, provided that the input is reliable enough or that models use additional referential signals. The key finding is that the Pb takes into account both, the presence of communicative signals prior to the action outcome as well as the outcome congruency. We found that infants showed a more positive Pb deflection towards actors that were either communicative and congruent, or not communicative and incongruent. Since we did not find a Pb component in Experiment 1, the Pb appears to be sensitive to either the presence of referential signals or the predictability of an actor. Only in the presence of referential signals and a more predictive presentation of the stimuli, as investigated in Experiment 2, did we find a differentiated Pb response. Overall, this response is likely to reflect a seeking of information and increased interest in the stimuli that precedes the semantic integration of the information as indexed by the N400 component.

Summary of Eye Tracking evidence

The study of anticipatory looking in 7-month old infants reported in Chapter 3 did not find any evidence of communication on anticipation of novel action outcomes. The main findings of this study are that infants show more anticipatory looks towards the mouth region, irrespective of how they were addressed or whether they are familiar with the action and its outcome.

The findings on their own suggest that infants of this age are potentially not able to form adequate representations of the actions to reliably anticipate them, e.g. because they did not yet have sufficient experience with the type of actions we presented them with. If this is the case, Chapter 3 may have simply failed to replicate Hunnius and Bekkering (2010). Either children at this age do not anticipate such action outcomes reliably or our stimuli were more complex than the original ones.

Discussion: Action semantics during communication

It is possible that the divergent results between Chapter 2 and Chapter 3 are due to developmental differences between the two age groups and 7-month-old infants may not anticipate action outcomes reliably. There is mixed evidence that infants of this age reliably anticipate action outcomes in such naturalistic environments. On the one hand, Reid et al. (2009) found evidence of an N400 ERP component only in 9-month-olds and adults, but not in the 7-month old age group. On the other hand, recent findings by Michel, Kaduk, et al. (2017) suggest that infants discriminate between familiar and unfamiliar action outcomes at the age of five months, if simplified stimuli are used. Importantly, the stimuli this study no longer use a semantic priming paradigm, but show the outcome pictures on their own. Therefore, the evidence that children actively *anticipate* such complex actions at this age is limited.

Meaning through segmentation

Chapter 4 of this thesis explored a novel question of the role that communicative signals may play in action understanding by looking at their contribution to toddlers' imitation of the parts of an action sequence. It takes a more functional interpretation of the role of communicative signals in children's interpretation of actions, by positing that the placement of communicative signals within an action can modify children's imitation of an action sequence. This chapter draws upon a wide range of different theoretical approaches that discuss the structure of action sequences and their corresponding units. An important implication of a potential role of ostensive signals contributing to the segmentation of actions is that according to multiple models of cognition the segmentation of an action is crucial for its interpretation. According to Event Segmentation Theory, the way that events (and therefore actions) are segmented predicts how they are remembered (Lassiter, Stone, & Rogers, 1988; Sargent et al., 2013).

Do communicative signals increase infants' arousal?

An underlying thread running through this thesis is the difference between Natural Pedagogy and domain-general learning mechanisms. This question is strongly tied up in *how* communication may facilitate infants learning. I investigated infants' measures of arousal in Chapter 2 and in Chapter 3. However, despite the use of multiple methodologies by investigating the ERPs and the Pupillary Light Reflex (PLR), I did not find evidence of increased arousal towards communicatively presented actions. Neither the Nc component in the two experiments in Chapter 2 nor the Pupillary Light Reflex measurements taken in the experiment in Chapter 3 found evidence of increased arousal after infants had been communicatively addressed by the actor. Only the Nc component in the second experiment of Chapter 2 showed some evidence of a differentiated response in communicative contexts. We found that in our control condition, congruent eating actions show an increased Nc response, but such a difference was absent in the communicative condition.

These results provide evidence against accounts that argue that the effect of ostensive signals can be explained by an increase in arousal when infants are addressed with ostensive signals, such as direct gaze or infant-directed-speech (e.g. Gredebäck et al., 2018; Szufnarowska et al., 2014). However, the experiments presented in this thesis cannot rule out an ostension-is-attention explanation entirely. The experiments discussed in Chapters 2 and 3 use screen-based experiments and it is possible that the videos used as stimuli were not sufficiently different in manipulating infants' arousal or conveying communicative intentions. Since the results of the experiment reported in Chapter 3 do not provide any evidence of an effect of communication on infants' action outcomes, it may be that for these younger infants, the communicative signals were simply not strong enough to elicit an effect of attention sufficient for enhanced processing of the actions. It is also possible that the adult-directed control condition already triggers a referential expectation. Both sets of studies used adult-directed speech and averted gaze as a control condition for communication. Despite this, similar research used adult-directed speech as a control, finding that infants process novel tools (Hernik & Csibra, 2015) and show differential retention of object location following communicative signals (Yoon et al., 2008). Furthermore, there is evidence that children at the age of five months show distinct neural markers towards infant-directed speech and direct gaze, or a combination thereof (Parise & Csibra, 2013). Therefore, infants do appear to show a differentiated response towards infant-directed speech, compared to adult-directed speech.

Additional findings

The third important thread running through this thesis is the importance of goal outcomes and the salience of actions. The relationship between the role of ostensive communication and the salience of different aspects of an action has emerged as a key question for future research. The finding that toddlers are more likely to imitate a salient hopping action compared to the less salient sliding action in Chapter 4 is possibly the clearest of the studies presented in this thesis for such an interaction. However, even for the studies presented in Chapters 2 and 3, the salience of the outcomes may have contributed to the results that we observed. For example, the N400 ERP components for the infant data in Chapter 2 suggest that infants are predominantly sensitive to the outcome. Any modifications of the N400 component were only observed in the Bayesian analysis. Furthermore, the Pb response has revealed a complex response pattern that takes into account the presence of communication, but *also* the congruency in the outcomes. The seven-month-old infants in Chapter 3 showed most anticipatory looks to the mouth region, but only few to the target area at the head.

Since we did not find effects of congruency or communication it appears that this is mainly due to the mouth area being generally more interesting to infants, compared to the upper head (Kato & Konishi, 2013). Furthermore, the mouth-directed actions also had a well-defined target for actions, whereas the actions directed towards the upper head did not have such a well-defined target area. Apart from visual saliency, the results are also compatible with teleological interpretations of anticipatory looking in infancy, since infants may have been able to understand the purpose of the mouth-directed actions better even for objects that typically do not go to the mouth.

In Chapter 4, I have looked at how communicative signals may provide reference in time, in addition to space. I have found that the effect of such signals may differ depending on the actions themselves. Indeed, most actions investigated in this thesis have clearly defined endpoints. The eating action is completed when the food is in the mouth or the ear. The endpoints are characterised by a stop in the motion and in the case of the mouth-directed actions, also a clearly visible target. The same holds true for the animals hopping and sliding into the house, which also constitutes a well-defined end point of the action. Taken together, these results show the need to understand the role that communicative signals play in understanding different parts of an action and different action types. They highlight the need to connect infants' use of communicative signals to basic mechanisms of perception and learning.

5.2 Theoretical challenges in researching an early understanding of communication

One of the challenges of conducting research on the role of communicative signals in action understanding has been that the underlying theoretical models are underspecified. Consequentially, there are not always clear predictions that allow us to compare and contrast Natural Pedagogy with domain-general accounts of learning. The studies reported in this thesis all address central points that are relevant to Natural Pedagogy and statistical learning accounts, such as curiosity-based learning. By and large, the results are compatible with both theoretical frameworks. This is in part due to a theoretical overlap between them.

For example, the definition of *relevance* according to Relevance Theory shares important similarities with the *Goldilocks effect* discussed in the curiosity literature. Sperber and Wilson define relevance as the following:

> Extent condition 1: An assumption is relevant in a context to the extent that its contextual effects in that context are large. Extent condition 2: An assumption is relevant in a context to the extent that the effort required to process it in that context is small. (Sperber & Wilson, 1987, p. 703)

The so-called *Goldilocks Effect* (Kidd et al., 2012; Kidd, Piantadosi, & Aslin, 2014; Twomey, Ranson, & Horst, 2013; Twomey & Westermann, 2017) embodies a similar principle within the curiosity literature, according to which learners actively seek out information that is of intermediate complexity and disengage from stimuli that are too simple or too difficult to integrate into existing knowledge. Kidd et al. (2012) describe it as follows:

> [...] infants avoid spending time examining stimuli that are either too simple (highly predictable) or too complex (highly unexpected) according to their implicit beliefs about the probabilistic structure of events in the world. Rather, infants allocate their greatest amount of attention to events of intermediate surprisingness—events that are likely to have just enough complexity so that they are interesting, but not so much that they cannot be understood. (Kidd et al., 2012, p. 1)

The consequence of both principles is similar—learners will avoid stimuli that do not change their knowledge state and seek out those that can easily be integrated into existing knowledge.

The key difference between Relevance Theory and Curiosity based learning lies in the specialisation of the underlying cognitive architecture. Relevance Theory assumes innate, domain-specific modules that allow for the fast processing of social information and the recognition of communicative intent (Sperber & Wilson, 2002). Curiosity based learning is grounded in domain-general learning mechanisms. Any specialisation emerges from the accumulation of previous experience (Twomey & Westermann, 2017). Therefore, if there are effects of communicative signals on learning in infancy, they are due to the way that parental interactions scaffold learning. Curiously, Relevance Theory also places the burden of relevance on the sender in formulating a message that is relevant (i.e. cognitively interesting) to the receiver (Sperber & Wilson, 1987). Furthermore, the actual process of recognising relevance takes place within domain-general central cognitive processes (Sperber & Wilson, 1987), only the processes related to recognising communicative intent are massively modular (Sperber & Wilson, 2002). These descriptions highlight the considerable theoretical overlap between these conceptually very different theoretical frameworks. Therefore, an important task for future research will need to disambiguate the predictions that can be derived from these theories and work out testable predictions.

One of the key notions of Natural Pedagogy is that communicative signals create a referential expectation that the following information is relevant to the infant and generalisable to other contexts (Csibra & Shamsudheen, 2015). Crucially, this expectation, according to Natural Pedagogy, is innate and present at birth (Csibra, 2010). Although there are numerous studies that show that infants already prefer looking at human eyes (e.g. Farroni, Massaccesi, et al., 2004; Farroni et al., 2005) and face-like configurations (e.g. Courchesne et al., 1981; Reid et al., 2017) within the first month after birth, these findings do not constitute evidence that infants already have a referential expectation. The experiments described in this thesis have investigated children between the ages of 7–18 months of age, but by this age, infants could have already learned about the relevance of social signals. There is evidence that already infants understand the referential nature of communicative signals by the age of four months (Michel et al., 2015; Michel, Pauen, & Hoehl, 2017; Wahl et al., 2013).

The discussion in Chapter 4 has also shown how the structures of caregiver-infant interactions can provide the 'cradle for social learning' (as coined by Shneidman & Woodward, 2016). Studying how infants understand everyday actions offers an important aspect of how infants learn from others. Repetitive, overemphasised actions have a Natural Meaning and offer ways of abstracting from individual observations (Stahl et al., 2014; Waterfall, Sandbank, Onnis, & Edelman, 2010). Like spoken language, they are also highly transient. Both have commonalities in structure (Maffongelli et al., 2015, 2018), meaning (Amoruso et al., 2013; Kutas & Federmeier, 2000, 2011) across space and time. Future work will need to specify computational models of the different theoretical accounts that have been discussed here, so that more detailed predictions can be developed and reviewed.

By looking at actions as a stream of events in need of segmentation, it is also possible to draw from a wide range of theoretical literature previously not been used to study action understanding in early infancy. In particular, event segmentation theory (Zacks & Tversky, 2001; Zacks, 2004; Zacks et al., 2009) and the chunking account (Christiansen & Chater, 2016; Isbilen & Christiansen, 2018). However, toddlers may also perceive the actions themselves as more meaningful if they are segmented, and therefore the results are also compatible with accounts that are founded in a teleological interpretation of infants' action understanding (Biro & Leslie, 2007; Gergely & Csibra, 2003).

Spike et al. (2016) have reviewed computational accounts on the emergence of stable communication systems and identified three properties that are necessary to develop a functional communication system: (1) a mechanism to establish reference, (2) a bias against ambiguity that ensures that meaningful information is retained, and (3) some form of information loss that facilitates abstraction by removing irrelevant information. This work has important implications on the role of communicative signals for assigning meaning in interactions. Based on these three principles, ostensive-referential signals fulfil the function of linking signals and referents in time and space, cognitive memory bottlenecks and lossy social transmission contribute to their generalisation: According to this view, children will attempt to generalise social and non-social information equally, but child-directed interactions provide more reliable structures in which relevant units are emphasised (Brand & Shallcross, 2008; Koterba & Iverson, 2009; Rutherford & Przednowek, 2012), and therefore allow for an easier identification of the sub-units. The results of the experiment reported in Chapter 4 have contributed to this literature by emphasising the role that communicative signals may play in segmenting actions. Repetitions in child-directed interactions (e.g. Brand et al., 2009) allow the identification of candidates for generalisation (Brodsky, Waterfall, & Edelman, 2007; Baldwin, Andersson, Saffran, & Meyer, 2008; Goldstein et al., 2010). Finally, there are multiple mechanisms of how infant-directed interactions might reduce the information retained in each interaction, and future research may attempt to disambiguate these: (1) infant-directed interactions potentially reduce the information load by directing infants' attention to key aspects and moments in time and thereby reduce the overall information that is transmitted. (2) infant-directed interactions potentially increase the cognitive load and/or the amount of information transmitted and thereby ensure that less information actually gets encoded. (3) The learner's memory constraints act as a further source of information loss to abstract away from single observations, and generalise to other instances of the events. The success of achieving previously observed goal outcomes or parents' corrective feedback (for example by repeatedly demonstrating actions, varying the demonstrations) prevents overgeneralisation (i.e. too much information loss) and achieves successful transmission. Such a learning mechanism could potentially account for children's differentiated learning in the presence of communication without appealing to an innate referential expectation being triggered by communicative signals.

5.3 Methodological contributions

This thesis has also used different methodological approaches. By using Bayes Factors I was able to test specific predictions about the direction and size of the

ERP effects in Chapter 2. This has allowed me to establish the absence of the N400 effect for the adults in Experiment 2, as well as the absence of effects on the Nc component in Experiment 1. So far, only very few ERP studies have used Bayes Factors for the analysis (e.g. Fu et al., 2013, 2017). At the time of writing, this thesis is one of the first papers that have used Bayes Factors in the developmental electroencephalography literature. The use of Bayes Factors has also raised important questions on the conceptualisation of ERPs. Determining the minimally and maximally interesting effect sizes required a survey of the literature, but many papers do not report raw ERP measures in the first place. To make the best use of specific ERP-related predictions we need to better understand the variance and parameters that determine the amplitude and their differences for different ERP components. Future electrophysiology research should embrace Bayesian analyses. In particular, in combination with the pre-registration of methodology and analyses, they can offer a powerful tool to test specific predictions, and also ascertain the absence of effects (see Lakens, Scheel, & Isager, 2018, for an alternative approach using classical null hypothesis testing).

Furthermore, although eye tracking and pupil dilation measurements have become a commonly used technique in developmental research, the use of the Pupillary Light Reflex (PLR) has not been used in many developmental studies (see: Hepach et al., 2012, 2016, 2017, for some examples). Although this measure has not shown to be sensitive to the manipulations used in the experiment in Chapter 2, it is a potentially useful indicator of measuring arousal in infants and is easily integrated into already existing methodologies (Hepach, 2016; Hepach & Westermann, 2016).

5.4 Limitations of the Thesis

Of course, this thesis cannot settle the question about how infants use communicative signals to understand and predict actions.

It is possible that the effects of communication that I described in Chapters 2 and 3 were relatively small or absent, since the control conditions were very strong. The control conditions for the experiments used adult-directed speech as a baseline. It is possible that infants are in fact already sensitive to adult-directed communication, and therefore already associate some degree of informativeness to the actors in the control condition as well. Furthermore, the actors in the videos were facing the child and the presentation of the actions was highly predictable and systematic. Therefore, they used a highly structured and repetitive presentation that may have made it equally easy for infants to understand the actions they were interested in.

One limitation of the experiments in Chapters 2 and 3 is that most of the actions investigated were actions that infants are familiar with. This provides the advantage that, in particular, for the eating actions, infants will have had considerable experience with observing these actions, and may already attempt some of them already. However, because of this, we cannot control how much experience infants had prior to taking part in our studies. It is possible, for example, that some infants may have had more experience with using cups and spoons than others, and the same holds true for their parents' use of mobile phones for calling and using a hairbrush. To control for such effects, the experiment used novel object-action relationships to create a baseline that other the actions can be compared against. However, in the absence of effects in Chapter 3, the lack of anticipations is best explained by the lack of familiarity for the sets of action-object relationships, and novel generalisations may take some time to allow children to reliably anticipate the actions.

Future research on everyday actions might use questionnaires and home reports using apps to query infants' exposure to certain types of actions, to control for such effects. This would also allow for the study of how individual differences in infants' environment can influence the processing of actions. However, such measures can only be a crude way of taking into account the variance that children are exposed to, and another way of explicitly reducing (or even manipulating) the variance that children are exposed to is the use of a home training programme for parents and their children, during which children are taught novel actions over a prolonged period of time (c.f. Kaduk, 2017).

Chapter 4 looked at the role of communicative signals in a unique way, and it has raised important questions on the role of communicative signals in segmenting actions. Because of this, the conclusions are limited to the two actions that we presented to infants. However, to ascertain that the salience and/or instrumental distinction between the hopping and sliding action is determining the effect of the temporal placement of communicative signals, it is necessary to investigate a wider range of actions along these distinctions. One way to extend these findings is the use of longer action sequences to combine (e.g. Elsner, Hauf, & Aschersleben, 2007; Loucks & Meltzoff, 2013).

Furthermore, from the experiment in Chapter 4, it is not possible to conclude that communicative signals themselves are special in their role of action segmentation for less salient, instrumental actions. It is possible that a non-communicative pause can have similar effects in breaking up the action into different units. Other sources of information may also contribute to action segmentation, and may play an even greater role in action segmentation. For example, knowledge about an event unit can contribute to its segmentation, in the same way that knowing a word can support the segmentation of other words within a phrase (Christiansen & Chater, 2016; Monaghan & Christiansen, 2010; Tomasello, 2000), or the partial repetition of words within phrases in variation sets (Brodsky et al., 2007; Goldstein et al., 2010; Waterfall et al., 2010).

A constraint of the study of action segmentation is posed by the earliest ages at which infants and toddlers can imitate actions and action sequences. Many other studies on event segmentation have used looking times (e.g. Baldwin et al., 2001; Hespos et al., 2009, 2010), but the interpretation of passive viewing may be more informative if combined with other methods, such as EEG (e.g. Braukmann et al., 2017).

One of the issues raised in Chapter 4 was that the prior ostensive context has led children to be more likely to attribute meaning to segmentation information. Csibra and Shamsudheen (2015) raised similar concerns about studies by L. P. Butler and Markman (2012, 2013, 2014), who found that three-year-olds did not explore pedagogically and intentionally presented objects, compared to intentionally but not pedagogically presented objects. However, the older children were more likely to imitate the pedagogically presented objects. Csibra and Shamsudheen (2015) that the younger children may associate the non-pedagogical demonstration of the objects to an earlier interaction with the experimenter that had pedagogical features.

This issue is present in many other studies. For example, Moore and colleagues (R. Moore, Liebal, & Tomasello, 2013; R. Moore, Mueller, Kaminski, & Tomasello, 2015) showed that children are able to infer an experimenter's communicative intention without ostensive signals, such as gaze or speech. However, in both studies, children were playing with the experimenter prior to this demonstration of the game and apparatus used. Therefore, they may have still perceived the experimenter as a communicative partner during the test trial. Hoehl, Zettersten, et al. (2014) conducted one of the few studies that presented a completely non-communicative action demonstration, albeit investigating much older children. The five-year-old children in their study were not more likely to imitate unnecessary actions in an action sequence, irrespective of whether the model interacted with them in a pedagogical-communicative manner, or whether they acted aloof. Only observing a communicative, but more efficient actor during the next observation reduced their levels of overimitation, suggesting that the effect of communicative signals may only appear over consecutive trials. These results demonstrate the complex relationship between action understanding, sensitivity towards communicatively presented information and age, and future research will need to investigate these relationships more systematically.

5.5 Future research

The results of the thesis open up new questions for future research. For example, humour and pretence offer an interesting case of parents use of communicative signals. Such interactions are fairly common throughout childhood, but are distinct from classical pedagogical exchanges since at least some information shown here is not meant to be generalised beyond the current context. However, previous research by Hoicka (2016) has shown that parents actually provide *more* ostensive signals, but fewer referential signals during humorous interactions. These results support the notion that the role of ostensive signals itself is all-or-nothing, and that it is not the quantity of communicative signals that affects what a learner takes away from an interaction. Instead, the key question is how the information is disambiguated by referential signals that determine *what* is being learned. These points also come up in the current thesis. For example, it is possible that the cheerful ostensive address without the combination with referential signals in Chapter 2, Experiment 1 primed children towards a humorous interpretation of the stimuli, and therefore potentially masked the effects we found on the Pb in Experiment 2.

By investigating how ostensive signals, such as direct gaze and Infant-Directed Speech, can provide temporal reference, Chapter 4 has broadened our current understanding of how they might contribute to action understanding. This conceptualisation of communicative signals as potential segmentation markers provides important links about how children identify the units of an action sequence, particularly for units that are low in salience on their own.

An important alternative to classical ERP paradigms is the use of time-frequency analysis. Time-frequency analysis allows a wider range of stimuli, and is more robust towards the presentation of animated stimuli, including videos and live interactions. An important frequency band associated with social cognition and motor activity is the *mu* frequency range (Cuevas, Cannon, Yoo, & Fox, 2014). *Mu*-desynchronisation has been observed for for unexpected action observations similar to chapter 2 and 3 (Stapel et al., 2010), when infants learn to shake a rattle (Paulus, Hunnius, van Elk, & Bekkering, 2012), observe actions they can carry out themselves (van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008) or for goal-directed reaching (Nyström, Ljunghammar, Rosander, & von Hofsten, 2011). Increased *mu*-desynchronisation has also been observed in infants during dyadic turn-taking with their mothers. (Liao, Acar, Makeig, & Deak, 2015). Since previous research has linked the *mu*-frequency to action and social processing, it may be interesting to investigate whether communicative signals affect increase desynchronisation during action processing.

The current thesis has used four different methodologies to investigate the effect of communication on how infants learn from others. We combined eye tracking and pupil dilation Chapter 3. However, in particular, the combination of EEG with behavioural measures would open up a promising avenue towards interpreting the neural markers underlying what infants and young children actually take away from pedagogical demonstrations. Such work would enhance our understanding of how neural markers are linked to actual behaviour.

5.6 Summary

This PhD thesis has contributed to the understanding of how children may use communicative signals to learn about actions. It has explored the effect of communication on infants' and toddlers' understanding of actions using four different methodologies—EEG, Eye Tracking, Pupil Dilation and Behavioural measures. Although it has largely used Natural Pedagogy as a reference framework to specify hypotheses for Chapter 2 and 3, it has also conceptualised the role of communicative signals in a novel way by looking at how they provide structural information within communicative interactions (Chapter 4).

The thesis has shown that it is likely that communicative signals enhance the processing of semantic information and information seeking, given the right circumstances. The EEG study in Chapters 2 found tentative evidence for an increased action N400 effect for communicatively presented actions in 9-month-olds, in addition to an interaction at the PB component, suggesting that infants seek more information after ostensive-expected and non-ostensive unexpected action outcomes, provided that the presentation is predictable or the actors use referential signals towards the objects during the greeting. Furthermore, the experimental results in Chapters 2 and 3 provide evidence that the mere presence of communicative signals does not appear to lead to an increase in arousal. Since we do not find any evidence of such an increase, it is unlikely that the effects we observed on the N400 and Pb component in the experiments in Chapter 2 can be explained by the arousal account proposed by Szufnarowska et al. (2014) and Gredebäck et al. (2018). Additionally, we also did not find an increase in arousal towards communicatively presented actions, as measured by the Pupillary Light Reflex in Chapter 3. This provides further evidence against an arousal-driven account of communication. However, the 7-month-old infants in the eye tracking experiment did not show evidence of increased learning as measured by their anticipatory looking either. Therefore it is possible that the methodology used in this Chapter was not successful in eliciting the communicative expectation in the first place.

The results of the behavioural experiment reported in Chapter 4 have shown that toddlers use communicative signals to segment less salient actions. However, if actions are already salient on their own and can be easily identified as intentional, toddlers do not appear to require additional segmentation information. This study has contributed a novel way of looking at the role that communicative signals can help learning about actions in infancy.

However, many more questions remain to be answered, and this thesis has also contributed novel open questions. So far, little is understood about the neural underpinnings of the effects of communication on infants' processing of information in general, and actions in particular. Future research will need to disambiguate whether the results on the Pb component between Experiment 1 and

Experiment 2 are due to the higher predictability of the actions carried out by each actor, or whether they are related to the actors' use of referential signals during their communication. Another realm for future research lies in the role of communicative signals providing structural information about actions, and how this may feed into existing theories of cognition.

This PhD thesis has contributed to the question of how communicative signals contribute to the understanding of actions during infancy. It has shown that communicative signals play a role in action understanding by creating a preparedness to learn (Pb), increase semantic processing (N400) and segment less salient actions.

Appendix A

Supporting information for Chapter 2

Please turn over

A.1 Anova tables for Experiment 1

Table A.1: Exp. 1, Infants: Anova table for the Pb between 200 and 350 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	0.049	0.828		0.001
2	Communication	1	15	0.005	0.945		0.0001
3	Outcome:Communication	1	15	1.375	0.259		0.025

Table A.2: Exp. 1, Infants: Anova table for the Nc between 350 and 700 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	0.495	0.493		0.010
2	Communication	1	15	0.228	0.640		0.004
3	Outcome:Communication	1	15	0.400	0.536		0.010

Table A.3: Exp. 1, Infants: Anova table for the parietal N400 between 700 and 900 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	10.032	0.006	*	0.202
2	Communication	1	15	0.898	0.358		0.027
3	Outcome:Communication	1	15	1.423	0.251		0.015

Table A.4: Exp. 1, Adults: Anova table for the parietal N400 between 300 and 500 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	7.173	0.017	*	0.236
2	Communication	1	15	0.048	0.830		0.001
3	Outcome:Communication	1	15	15.057	0.001	*	0.116

A.2 Anova tables for Experiment 2

Table A.5: Exp. 2, Infants: Anova table for the Pb between 200 and 350 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	0.020	0.889		0.0005
2	Communication	1	15	0.002	0.962		0.0001
3	Outcome:Communication	1	15	9.609	0.007	*	0.135

Table A.6: Exp. 2, Infants: Anova table for the Nc between 350 and 700 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	1.788	0.201		0.037
2	Communication	1	15	0.027	0.871		0.001
3	Outcome:Communication	1	15	4.175	0.059		0.049

Table A.7: Exp. 2, Infants: Anova table for the parietal N400 between 700 and 900 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	7.089	0.018	*	0.146
2	Communication	1	15	2.309	0.149		0.040
3	Outcome:Communication	1	15	0.432	0.521		0.011

Table A.8: Exp. 2, Adults: Anova table for the parietal N400 between 300 and 500 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Outcome	1	15	2.152	0.163		0.062
2	Communication	1	15	0.695	0.417		0.008
3	Outcome:Communication	1	15	0.387	0.543		0.009

A.3 Anova tables for the additional analyses

Please turn over

Table A.9: Exp. 1 and Exp. 2, Infants: Comparison of the Pb components of between 200 and 350 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Experiment	1	30	4.196	0.049	*	0.046
2	Outcome	1	30	0.066	0.799		0.0005
4	Communication	1	30	0.007	0.934		0.0001
3	Experiment:Outcome	1	30	0.003	0.957		0.00002
5	Experiment:Communication	1	30	0.0002	0.990		0.00000
6	Outcome:Communication	1	30	1.607	0.215		0.009
7	Experiment:Outcome:Communication	1	30	8.862	0.006	*	0.048

Table A.10: Exp. 1 and Exp. 2, Infants: Comparison of the fronto-central Nc components between 350 and 700 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Experiment	1	30	15.159	0.001	*	0.173
2	Outcome	1	30	2.040	0.164		0.013
4	Communication	1	30	0.184	0.671		0.001
3	Experiment:Outcome	1	30	0.162	0.690		0.001
5	Experiment:Communication	1	30	0.030	0.864		0.0002
6	Outcome:Communication	1	30	0.350	0.558		0.002
7	Experiment:Outcome:Communication	1	30	2.722	0.109		0.015

Table A.11: Exp. 1 and Exp. 2, Infants: Comparison of the parietal N400 components between 600 and 800 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Experiment	1	30	0.026	0.874		0.0004
2	Outcome	1	30	11.954	0.002	*	0.086
4	Communication	1	30	4.024	0.054		0.020
3	Experiment:Outcome	1	30	0.257	0.616		0.002
5	Experiment:Communication	1	30	0.100	0.754		0.001
6	Outcome:Communication	1	30	1.069	0.309		0.006
7	Experiment:Outcome:Communication	1	30	0.138	0.713		0.001

Table A.12: Exp. 1 and Exp. 2, Adults: Comparison of the parietal N400 components between 300 and 500 ms

	Effect	DFn	DFd	F	p	p<.05	ges
1	Experiment	1	30	3.300	0.079		0.065
2	Outcome	1	30	9.315	0.005	*	0.062
4	Communication	1	30	0.393	0.535		0.001
3	Experiment:Outcome	1	30	2.429	0.130		0.017
5	Experiment:Communication	1	30	0.066	0.799		0.0002
6	Outcome:Communication	1	30	4.192	0.049	*	0.010
7	Experiment:Outcome:Communication	1	30	8.963	0.005	*	0.022

Appendix B

Supporting information for Chapter 3

B.1 Data points for the anticipation analysis

	Congruency			
Communication	Congruent	Incongruent	Novel	Total
Ostensive	42 (47)	34 (40)	40 (45)	116 (132)
Control	35 (42)	36 (42)	38 (46)	109 (130)
Total	77 (89)	70 (82)	78 (91)	225 (262)

Table B.1: Number of data points available for the anticipation analysis. Each data point represents one block containing 5–9 measurements The numbers in brackets indicate the data points in the original sample.

B.2 Data points for the pupil dilation analysis

	Congruency			
Communication	Congruent	Incongruent	Novel	Total
Ostensive	32 (44)	28 (39)	28 (42)	88 (125)
Control	29 (37)	29 (37)	36 (42)	94 (116)
Total	61 (81)	57 (76)	64 (84)	182 (241)

Table B.2: Number of data points available for the pupil dilation analysis. The numbers in brackets indicate the data points in the original sample.

B.3 Offset correction for the gaze measurements

Offsets were calculated for infants that consistently looked at the centre fixation point during the pupil dilation measurements. If the fixation

Offsets were computed by subtracting the difference of the fixations from the target point, excluding any fixations deviating by two standard deviations from the mean (to exclude outliers and measurements where the child has not consistently fixated the target point). The corrected points were visually inspected to check that they provided an improved accuracy. If they did, the offset correction was applied to all the gaze data for this participant.

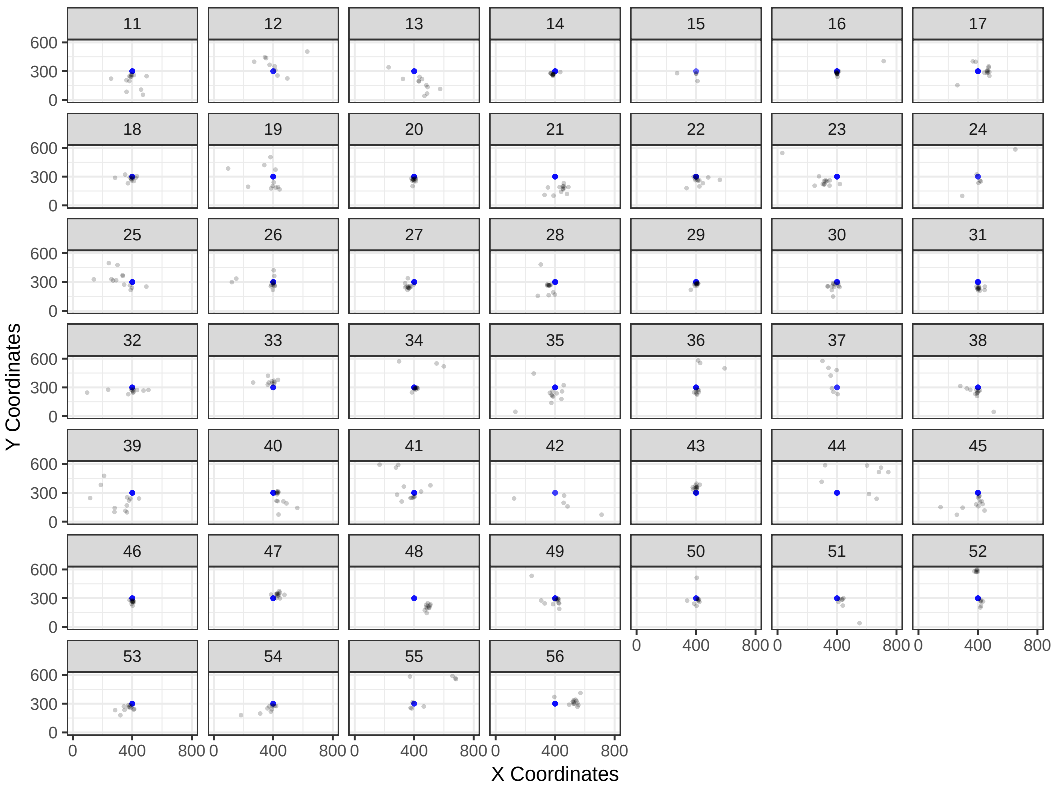

Figure B.1: Uncorrected fixations at the fixation point for each participant.

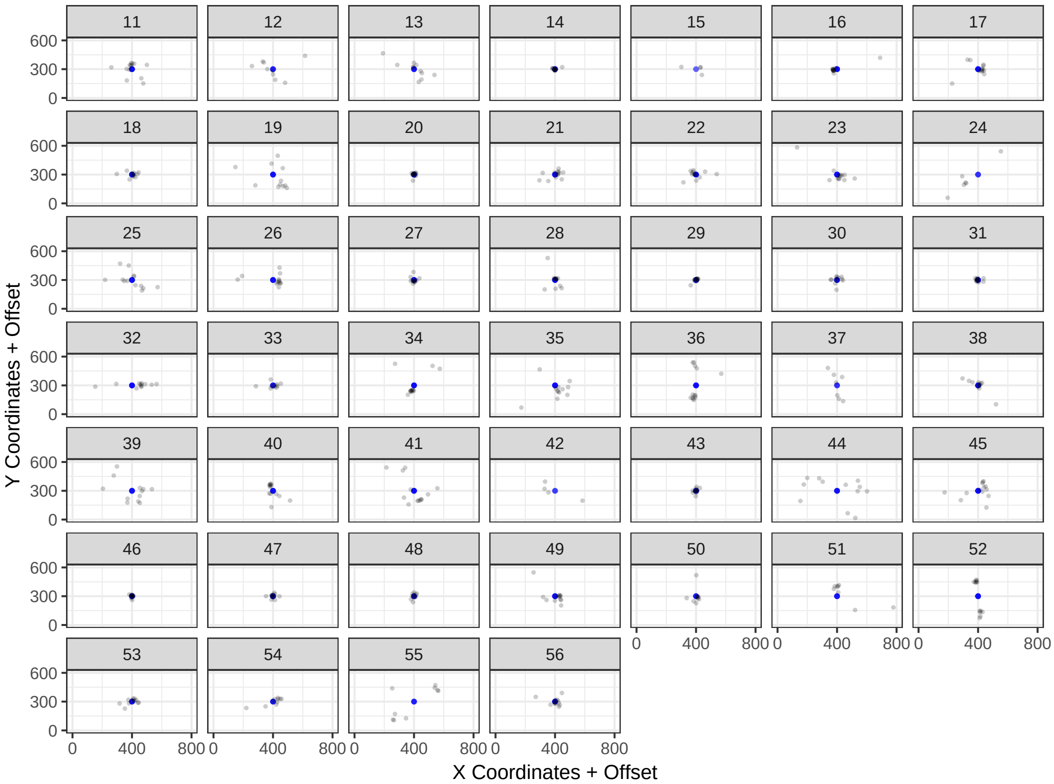

Figure B.2: Fixations on the fixation point for each participant after correction.

B.4 Residuals vs fits plots for the Proportion and Elog-corrected models

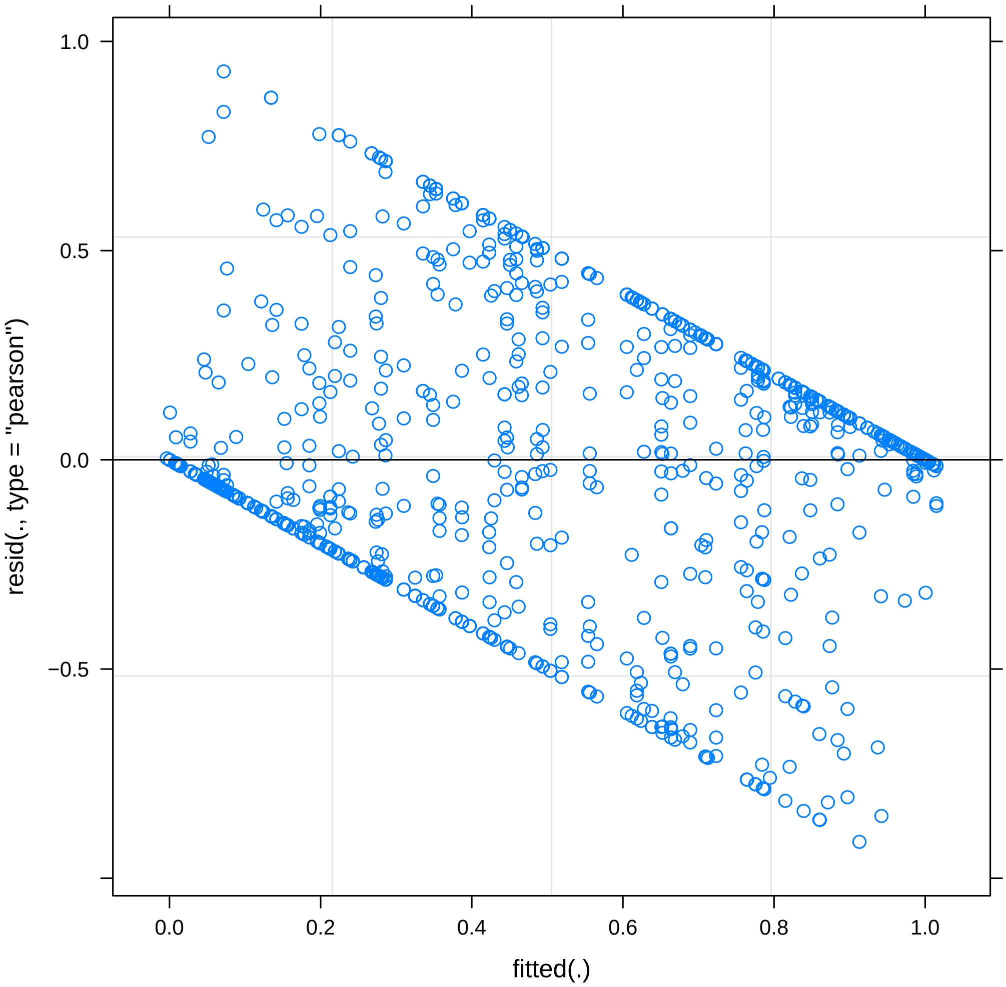

Figure B.3: Residuals vs. fits plot for the raw proportion model.

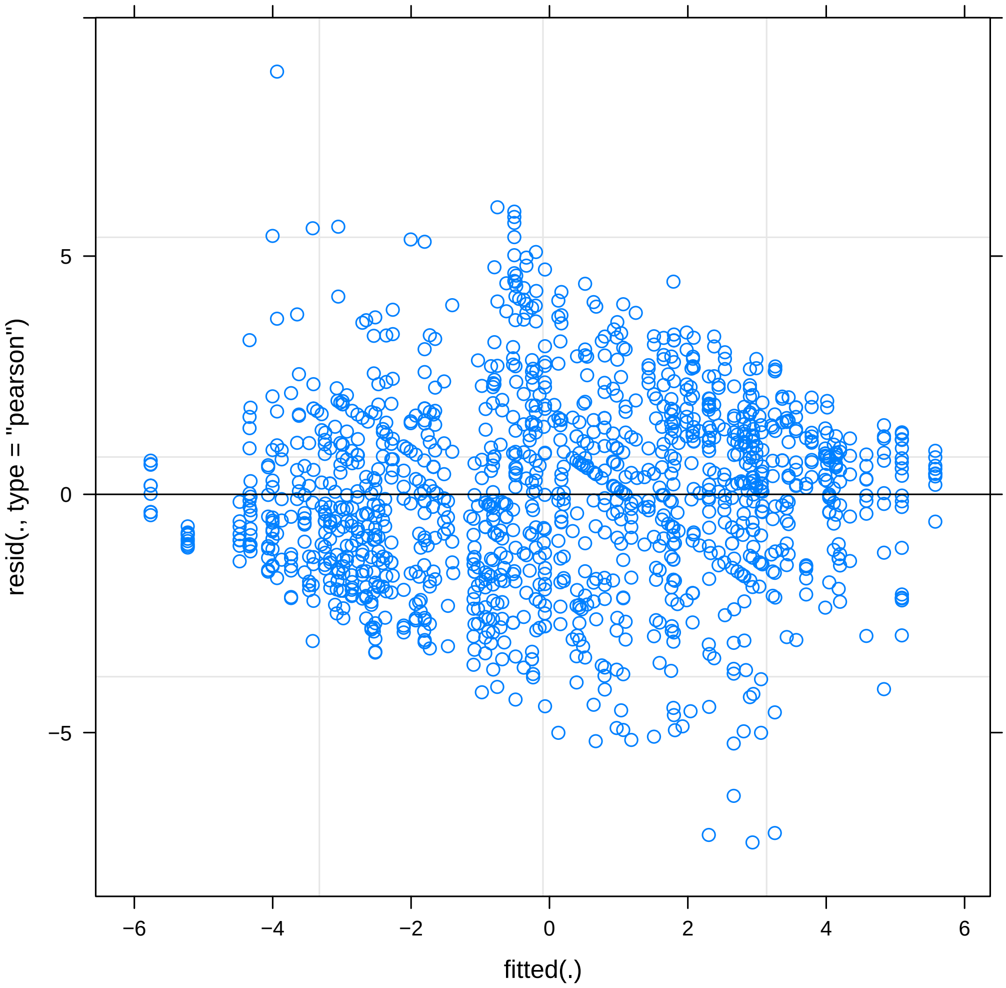

Figure B.4: Residuals vs. fits plot for the empirical log-corrected proportion model

B.5 Predicted proportions based on the complex interaction model

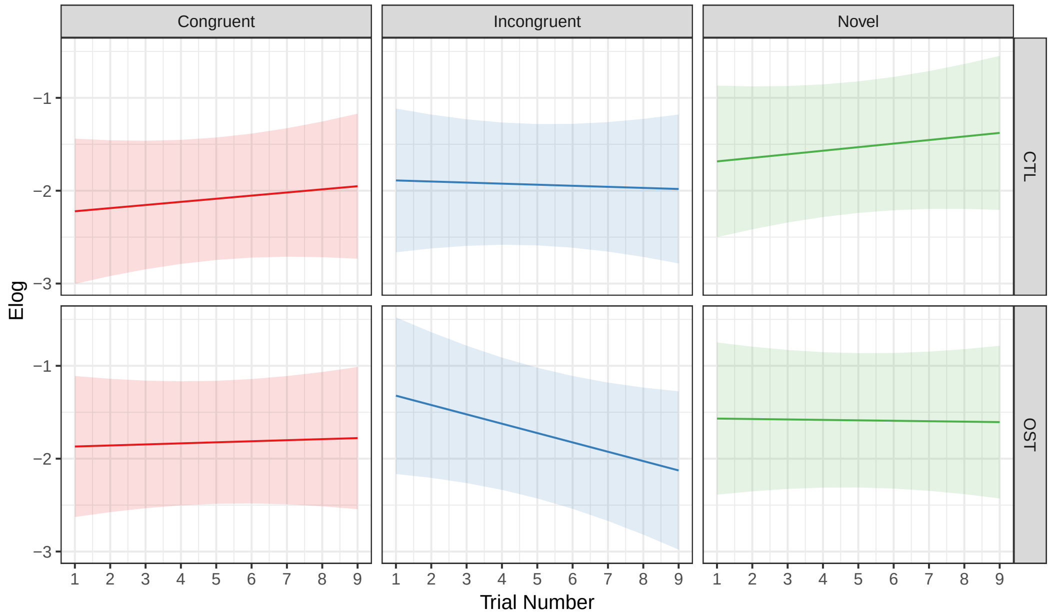

Figure B.5: Predicted proportion of looks to the target vs. competitor, based on the complex model for the $Communication \times Congruency \times TrialNumber$ interaction. Error bars represent confidence intervals.

B.6 Graphs for the pupil dilation analysis

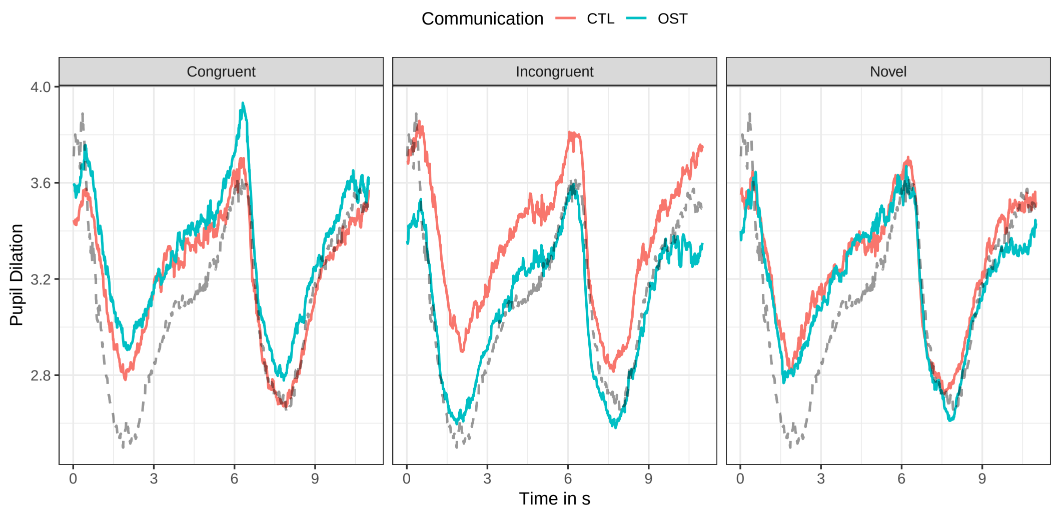

Figure B.6: Raw data of the averaged pupil dilations measurements. Grey lines indicate the baseline measurement.

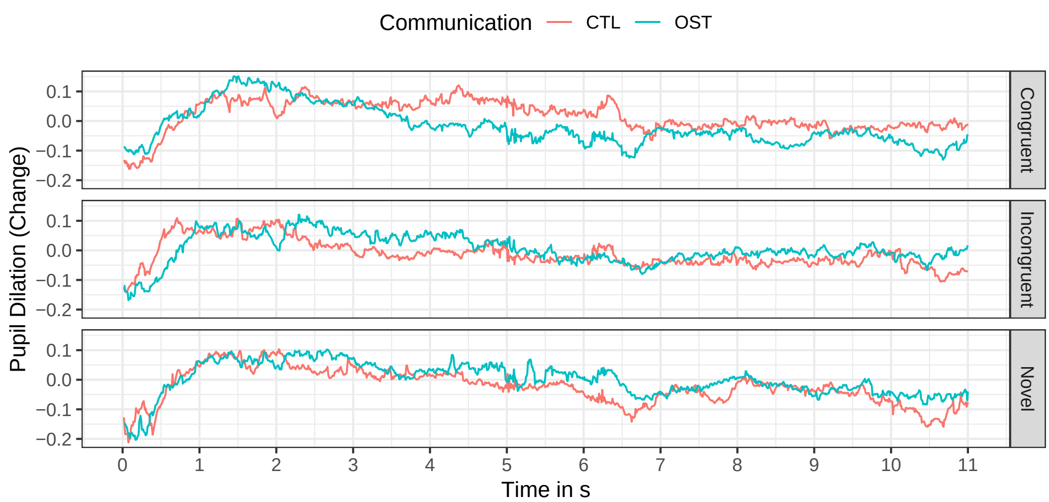

Figure B.7: Baseline-corrected change in pupil dilation measurements for the investigated Outcome × Communication interaction.

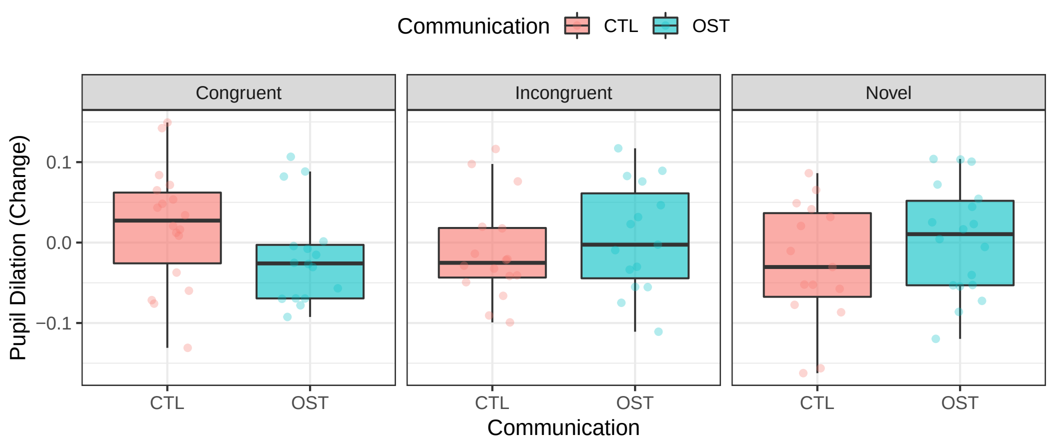

Figure B.8: Boxplot of the mean over time baseline-corrected change in pupil dilation for the investigated Outcome × Communication interaction. The scatterplots indicate individual datapoints.

Appendix C

Supporting information for Chapter 4

C.1 Pre-registration with aspredicted.org

Please turn over

OSTSEG – Structural information provided by ostensive-referential communic (#5771)

Created: 09/29/2017 06:17 AM (PT)
Shared: 06/18/2018 08:05 AM (PT)

1) Have any data been collected for this study already?

No, no data have been collected for this study yet.

2) What's the main question being asked or hypothesis being tested in this study?

We are interested in whether toddlers use ostensive signals, such as direct gaze and infant-directed speech to segment actions and determine which parts of a two-stage action sequence are worth imitating.

Caregivers often use ostensive signals, such as direct gaze and infant directed speech to communicate with their infants and transmit new and relevant information (Csibra, 2010). A large part of research investigated the effect that communicative signals have on infants' interpretation of actions (e.g. Nielsen, 2006; Király et al., 2013). However, ostensive signals and communicative interactions also provide lower level, structural information. Parents use direct gaze particularlyat event boundaries (Brand et al., 2007) and adapt the use of their signals to the infant's knowledge by providing younger infants with fewer, but longer gaze (Brand et al., 2007). Furthermore, brief periods of direct gaze disrupt visual working memory (Wang & Apperly, 2016), making ostensive signals ideal candidates in breaking up a stream of events.

Previous research already indicates that segmenting a stream of events is an important part of making sense and anticipating event sequences (Zacks et al., 2001, 2007, 2009; Sonne et al., 2016; Baldwin et al., 2001). The coarseness and detail of action segmenting in itself provides important information about an agents' goals and intentions (Zacks, 2004). Research in infants has shown that interrupting event sequences mid-stream, rather than at boundaries, makes infants perceive these events as novel (Baldwin et al., 2001).

The methodology is based on Carpenter et al. (2005) and Southgate et al. (2009) who demonstrated a toy animal moving to a house, either by hopping or sliding the animal across a playing field. Toddlers in Carpenter et al. (2005) were either presented with the action of sliding/hopping and the goal outcome of moving the animal into the house, or no observable goal outcome. In Southgate et al. (2009) infants were either told about the action's outcome before the demonstration or received an action-irrelevant piece of information.

However, instead of conveying the goal of the action linguistically, we use an ostensive signals to mark the boundary after the sliding/hopping action and before putting the animal into the house to segment the action. Such a cue may provide low level information that segments the hopping/sliding action into two separate events.We expect that, if toddlers use direct gaze and/or infant directed speech to segment and chunk events, toddlers in the boundary-marked condition will show higher manner imitation compared to the unmarked condition.

We expect that, if toddlers exploit direct gaze and/or infant directed speech to segment and chunk events, toddlers in the boundary-marked condition will show higher manner imitation compared to the unmarked condition.

3) Describe the key dependent variable(s) specifying how they will be measured.

We are interested in two dependent variables:

1. How many toddlers (in percent) imitate the manner of the action? (i.e. hopping or sliding action)
2. How many toddlers (in percent) imitate the goal of the action? (i.e. putting the animal into the house)

4) How many and which conditions will participants be assigned to?

We will have two conditions, in a between-subjects design.

Participants

We aim to test 18-month-old toddlers (same age as in Southgate et al., 2009, Carpenter et al., 2005)

Materials and Methods.

An adult experimenter presents the toys to the infant and they can play with the animals for one minute. Afterwards, the experimenter removes the animals by placing them into a small box and draws the child's attention to the house.

The modelling phase begins with the experimenter greeting the child in and saying 'Look, I'm going to show you what the (animal) does'. The experimenter takes one animal and moves it across the table either in a sliding or hopping action. In the in the boundary marked condition, the experimenter looks up to the child and says "Wow!" between the sliding action and putting the animal into the house. In the boundary unmarked condition, the experimenter puts the animal into the house, before looking at the infant and saying "Wow!". Following the presentation, the experimenter concludes the modelling phases by saying 'Look, the (animal) went into the house', and passes the mat with house and the animal to the child, and encourages them to play with it by saying 'Now it's your turn!'. If toddlers do not pick up the animal, the experimenter prompts the child again by saying 'What are you going to do with the (animal)?'. A trial is concluded if an infant gives a clear response by leaving the animal on the mat, leave it in the house, return it to the experimenter, or if a child does not touch the animal for 60 seconds. If an infant does not respond within 60 seconds, the experimenter requests the animal from them. If the infant then puts the animal into the house or returns the animal in a hop-ping/sliding motion, these will be coded as valid responses. However, trials where the infant only returns the animal to the experimenter will not be

counted.
Toddlers will be presented with four different trials, each using a different animal. Based on piloting by Southgate et al. (2009), the order of the action manners will be fixed (slide, hop, hop, slide), as toddlers had an inclination to prefer the hopping action. Each action will be accompanied by a sound.

5) Specify exactly which analyses you will conduct to examine the main question/hypothesis.
We aim to conduct two t-tests of the number of imitation for the manner and the goal location scores. We will also conduct two Bayesian t-tests to investigate whether there is evidence that there is no difference between groups.

6) Any secondary analyses?
n/a

7) How many observations will be collected or what will determine sample size? No need to justify decision, but be precise about exactly how the number will be determined.
Based on similar research, we aim to test twenty children / condition, forty children in total. This does not include children that meet the exclusion criteria specified below.

8) Anything else you would like to pre-register? (e.g., data exclusions, variables collected for exploratory purposes, unusual analyses planned?)
We will be using the same exclusion criteria as Southgate et al. (2009) and (Carpenter et al., 2005) and exclude children who are (a) uncooperative and refuse to touch the mouse (b) hand the mouse back to the experimenter, (c) return the mouse to the experimenter, (d) cry or are otherwise fussy. We will also exclude trials with parental interference and with experimenter error (e.g. E did not mark the conditions).
Based on the outcome of this study, we are planning a series of follow up studies to investigate whether other signals, beyond direct gaze and infant-directed speech, may have a similar function.

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