

Infants understand collaboration: Neural evidence for 9-month-olds' attribution of shared goals to coordinated joint actions

Katarina Begus , Arianna Curioni, Guenther Knoblich and Gyorgy Gergely

Department of Cognitive Science, Central European University, Budapest, Hungary

ABSTRACT

Interpreting others' actions as goal-directed, even when the actions are unfamiliar, is indispensable for social learning, and can be particularly important for infants, whose own action repertoire is limited. Indeed, young infants have been shown to attribute goals to unfamiliar actions as early as 3 months of age, but this ability appears restricted to actions performed by individuals. In contrast, attributing shared goals to actions performed by multiple individuals seems to emerge only in the second year of life. Considering the restrictions that this would impose on infants' understanding and learning from interactions in their environment, we reexamine this ability by introducing 9-month-old infants to simple joint actions, in which two agents coordinate their actions toward the same goal. To establish whether infants formed an expectation about future actions of these agents, infants' cortical activity was measured using functional near-infrared spectroscopy (fNIRS). The hemodynamic response, recorded in (p)STS, indicated that infants attributed goals to simultaneous and coordinated joint actions of two individuals. Thus, even prior to actively engaging in collaborative activities themselves, infants can attribute shared goals to observed joint actions, enabling infants to learn from, and about, the complementary roles of social interactions, a central characteristic of human culture.

ARTICLE HISTORY

Received 27 June 2019
Revised 30 October 2020
Published online 24
December 2020

KEYWORDS

Joint action; goal attribution;
infants; fNIRS

Introduction

Humans' ability to attribute goals to observed actions and to anticipate agents' future goal-directed behaviors plays a vital role in learning about novel goals and in planning appropriate instrumental actions to achieve them (Csibra & Gergely, 2007; Gergely & Csibra, 2003; Yin et al., 2016). Inferring the goals of unfamiliar actions can be particularly important for young observational learners, such as human infants, whose own action repertoire does not yet include the means to achieve the goals of many actions that they observe. Indeed, there is convergent evidence showing that young infants possess a precocious ability to interpret others' actions by attributing goals to them as early as 3 months of age, significantly before they have active experience with performing such goal-directed actions themselves (Choi et al., 2018; Luo, 2011; Luo & Baillargeon, 2005). Furthermore, it has been shown that infants can attribute goals not only to unfamiliar actions, but also to actions of unfamiliar abstract entities (geometrical figures), and even to actions that are biologically impossible for humans to perform (Gergely & Csibra, 2003; Király et al., 2003; Southgate et al., 2008), as long as the observed actions bring about the goal in an efficient manner given the physical constraints of the situation.

While these findings suggest a rather general and abstract early ability to attribute goals to actions, it has been proposed that young infants' ability for goal attribution is, in fact, rather restricted and applies only to individual actions performed by single agents.

This hypothesized restriction has been based on studies investigating infants' capacity to interpret actions performed by multiple agents pursuing a shared goal (i.e. agents acting collaboratively, coordinating their actions so as to jointly bring about a change in the environment (Sebanz et al., 2006)). These studies have found that infants attribute shared goals to such collaborative actions much later than they are able to interpret individual actions (Fawcett & Gredebäck, 2013, 2015; Henderson et al., 2013; Henderson & Woodward, 2011; Warneken et al., 2012). Furthermore, even in the second year of life, infants were reported to attribute goals to joint actions only if they first received a significant amount of training with performing the same collaborative actions themselves (Henderson et al., 2013). Based on such findings, it was proposed that first-person motor experience with collaborative actions may be a necessary prerequisite for attributing shared goals to observed joint actions of others (Fawcett & Gredebäck, 2013, 2015; Henderson et al., 2013;

CONTACT Katarina Begus  katarina.begus@gmail.com  Department of Cognitive Science, Central European University, Budapest, Hungary

© 2020 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way.

Henderson & Woodward, 2011). This hypothesis was further supported by observations from everyday life, indicating that children indeed start engaging in goal-directed joint activities only during their second year (Aureli & Presaghi, 2010; Bakeman et al., 2010; Hay, 1979).

However, there are several reasons to doubt the hypothesis that motor experience with joint actions is necessary for infants to be able to attribute shared goals to joint actions performed by others. Firstly, it is unclear why the same lack of first-person experience would not similarly limit the capacity of younger infants to attribute goals to unfamiliar or even impossible actions of individual agents (Gergely & Csibra, 2003; Király et al., 2003; Southgate et al., 2008). Secondly, very young infants frequently observe collaborative interactions of multiple agents, such as caregivers or siblings, which often involve bringing about shared goals through coordination of individual actions, and it seems unclear why infants would be unable to interpret and learn from such information. Lastly, empirical evidence demonstrates that young infants can, in fact, track and interpret various coordinated or contingent actions of interacting agents (such as imitation, turn-taking interactions, or helping actions) and draw specific, informative, and adequate inferences based on such social interactions. For example, preverbal infants expect members of the same group to act alike, indicating that they can represent individual agents' behaviors as determined by (and indicative of) their belonging to a social group, before having had active experience with engaging in such group activities themselves (Powell & Spelke, 2013, 2018). Furthermore, 5 to 10-month old infants' preferences are influenced by agents' behavior toward third parties in so-called helping and hindering scenarios (Hamlin, 2013; Hamlin & Wynn, 2011; Hamlin et al., 2007) where, in order to formulate their preferences, infants need to consider not only the separate goals of individual agents, but also the social interaction between the agents in relation to their goals (but see Schlingloff et al., 2020). Although these goal-directed social scenarios do not always involve joint actions per se, they demonstrate that, at least in certain contexts, infants are able to simultaneously consider actions of multiple agents and can infer the relations between those actions. Such findings therefore converge to suggest that attribution of shared goals to joint actions should be well within young infants' capacities.

Based on these considerations, we propose that the lack of evidence for young infants' attribution of shared goals might not reflect a late onset of this ability, but rather that it plausibly resulted from the specific processing requirements of the tasks that have been employed

to test it. The empirical evidence for the late-emerging capacity of shared goal attribution comes from studies in which infants observe two agents engaging in a complementary multi-step action sequence; with one agent performing the first step (e.g., opening a box), and the second completing the sequence (e.g., retrieving an object from the same box) (Fawcett & Gredebäck, 2013, 2015; Henderson et al., 2013; Henderson & Woodward, 2011; Warneken et al., 2012). In this set up, the final goal outcome, brought about by the second agent's action, presupposes and is enabled by the realization of the sub-goal that had been achieved by the first agent's preceding action. These studies aimed to test whether infants infer that the two agents performed their respective actions in order to jointly achieve their shared goal (i.e. achieving the final outcome) or perceive each agent's actions as aimed at individual and independent (sub-) goals. The behavioral evidence (looking time and anticipatory saccades) produced by these studies suggested that infants younger than 14 months of age do not attribute a shared goal to such sequences of actions unless they first receive extensive first-hand training in performing the collaborative task that they later observe (Fawcett & Gredebäck, 2013, 2015; Henderson et al., 2013; Henderson & Woodward, 2011; Warneken et al., 2012). However, it is important to note that in order for infants to attribute a shared goal to these individual actions, they would need to recognize the hierarchical goal structure of the observed actions, represent the individual actions performed by different agents as complementary components of a joint action sequence, and functionally relate these actions to the achievement of a shared final goal. These required computations likely exceed the limited working memory and processing capacities of young infants, thus providing a plausible alternative explanation for the apparent lack of young infants' attribution of shared goals at this early stage.

However, there are much simpler cases of joint actions that involve simultaneously performed, coordinated actions and would likely necessitate less working memory and cognitive effort for the observing infant to establish that they involve the pursuit of a shared goal. The primary aim of this paper was therefore to design a less demanding joint action paradigm and test the hypothesis that young infants can, in fact, attribute shared goals already during the first year of life, prior to having active motor experience with such actions themselves. Our secondary aim was to test this hypothesis using fNIRS neuro-imaging methodology, in order to explore and gain new insight into the neural mechanisms supporting the attribution of shared goals to joint actions. To these ends, we designed a modified version of the Woodward paradigm (Woodward, 1998), which has been widely used for testing

infants' goal attribution to actions of individual agents. In the classic Woodward paradigm infants first see an agent approach one out of two alternative target objects repeatedly, before viewing the same agent either continuing to approach the same target in a novel location or approach the alternative target in the same location. Infants, from as early as the age of 3 months (Choi et al., 2018; Luo, 2011; Sommerville et al., 2005), reliably react with surprise (reflected in their increased looking time) to the change in the agent's target but not to the change in the agent's movement path, indicating that they have interpreted the agent's actions as goal-directed and predicted that the goal (the target) would be consistent in future actions (Woodward, 1998). We developed a joint action version of this task and presented one group of infants with videos of two agents repeatedly coordinating their actions to reach the same target (Joint Action group); and another group with identical stimuli, with the exception of the second agent remaining static, while the first agent pursues the target individually (Single Agent group).

Crucially, in order to investigate whether infants attribute a *shared* goal to the agents' actions, it was necessary to control for the possibility of infants in the Joint Action group attributing *individual* goals to the actions performed by either of the two individual agents alone, as the responses to shared and individual goals may not be distinguishable. To this end, the actions displayed in our stimuli differed from those in classic Woodward paradigms in two important ways. Firstly, only a single target object was present during the familiarization parts of the trials, as opposed to the two alternative target objects used in the standard Woodward tasks. In the absence of competitor target objects, several studies have shown that infants fail to attribute goals to the observed actions, due to the lack of evidence for the agent's preference between the alternative objects (e.g., Luo & Baillargeon, 2005). However, other studies (Hernik & Southgate, 2012) demonstrated that an absence of an alternative target object does not necessarily disrupt goal attribution, so long as the actions that the infants observe follow the principles of rationality or efficiency (Biro, 2013; Csibra, 2008; Gergely et al., 1995), such as agents approaching a target by taking a path that is no longer than necessary and is justified by the situational constraints (Hernik & Southgate, 2012). Thus, the second modification in our stimuli compared to the standard Woodward task was such that both agents approached the targets by taking unnecessary detours, thereby making their actions individually inefficient. Therefore, because both agents in the Joint Action group act individually inefficiently (and only a single target object is available), infants should not interpret the final outcome to be the goal of either individual

agent alone. However, if infants interpret the observed actions as coordinated and joint, then the inefficiency of individual actions, which generally disrupts individual goal attribution, may be disregarded or processed in a different manner.

Why might such inefficiency play a different role in joint actions? This hypothesis builds on the observation that the characteristics of inefficient actions, such as indirect, slowed down, or exaggerated movements, which were used in this study, are in fact very common in contexts of two agents coordinating their actions toward a shared goal (Candidi et al., 2015; Pezzulo et al., 2019). Not only is individual inefficiency permissible in coordinated joint action, it is often used as a means of signaling between the agents, thereby facilitating the success and accuracy of coordination in joint action (Vesper et al., 2010; Vesper & Richardson, 2014; Vesper et al., 2016). Therefore, in contrast to the Single Agent group, where the features of the agent's actions should disrupt individual goal attribution; if infants in the Joint Action group interpret the observed actions as parts of a coordinated and joint action, the attribution of a shared goal may be justified. If this is the case, infants in the Joint Action condition should exhibit evidence of a violation of expectation when they observe a change in the target object that the agents jointly approach.

To establish whether infants attribute a shared goal to coordinated joint actions, we utilized fNIRS, measuring continuous changes in oxygen levels in the blood in the brain, indicative of cortical activity (Lloyd-Fox et al., 2010). The age (9 months), fNIRS head-gear, and the stimuli used in this study were designed to match the only preceding fNIRS study that has measured goal attribution in the infant brain (Southgate et al., 2014), using repetition suppression (Southgate et al., 2014). Repetition suppression provides a neural measure analogous to the behavioral measures of attenuation and reengagement of infants' attention, measured in the standard habituation procedures such as the Woodward paradigm (Woodward, 1998), without the need for overt behavioral responses on behalf of infants (Nordt et al., 2016). If a brain region is sensitive to a specific property of a stimulus, it should exhibit increasingly suppressed activation in response to each subsequent repetition of the particular aspect of the stimulus (e.g., repeated goal), and a release from suppression (reactivation) when this aspect of the stimulus is changed (e.g., change of goal) (Grill-Spector et al., 2006). Such a release from suppression was found in 9-month-olds' (Southgate et al., 2014) and adults' (Hamilton & Grafton, 2006; Ramsey & Hamilton, 2010) left anterior parietal region, when they observed a change in goal of actions performed

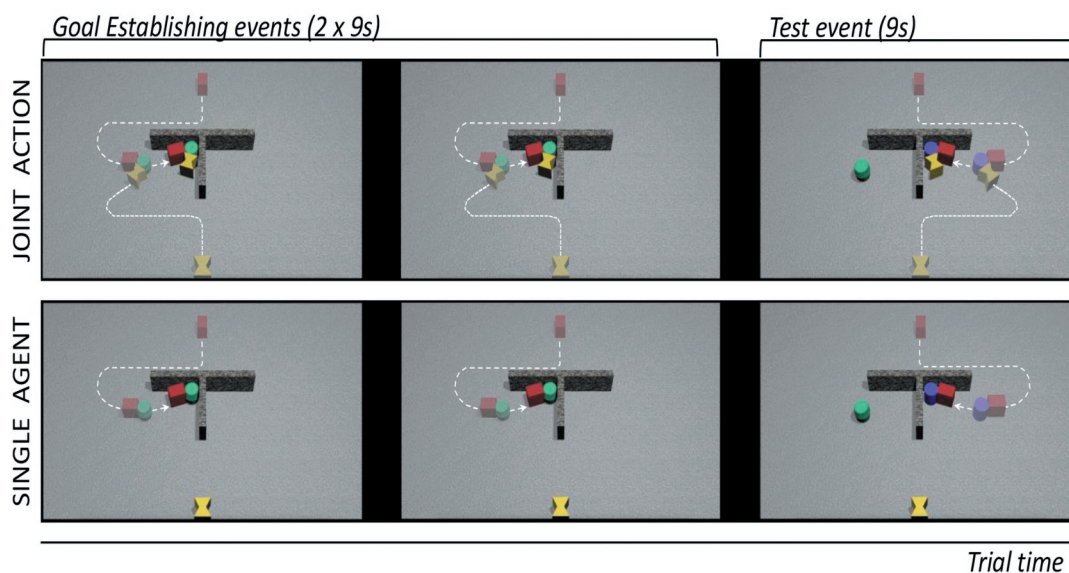


Figure 1. Experimental design depicting an example of a New Goal – New Side trial for Joint Action (Top) and Single Agent group (Bottom). Each trial displayed a sequence of 3 events; two Goal-Establishing events (9s each), and a Test event (9s), separated by 0.5s black screen. Images depict the final scenes of each event within a trial, with the dotted lines illustrating the agents' paths (not visible in the animations) and the initial and intermediate positions of agents and targets superimposed (transparent) over the still-frame. Side of targets was counterbalanced across trial repetitions, and trials were interleaved with 8s baselines.

by a single agent, whose actions were both efficient and selective (two potential target objects were present throughout).

Due to our modifications on the standard stimuli, namely removing the competitor target and making the agent's actions inefficient, no such response was expected in the Single Agent group. In contrast, if the neural response in the Joint Action group shows a release from suppression in response to the change of target reached by the coordinated joint action, it would support the hypothesis that 9-month-old infants attributed a *shared* goal to the joint actions that they observed. Importantly, neural structures responding to a change of goal in the Joint Action group may differ from those known to respond to goal change of individual efficient actions (as reported in Southgate et al., 2014), due to the social and interactive nature of joint actions. Adult studies, in which social interactions (Isik et al., 2017) or collaborative actions (Walbrin et al., 2018) are displayed, for example, report activity localized to the superior temporal sulcus (STS). The headgear used in this study, monitoring bilateral temporal (including STS) and parietal cortices (including anterior parietal regions; see Procedure for details), therefore allows us to establish whether the underlying neural mechanisms that support infants' goal-attribution to joint actions differ from those supporting the attribution of individual goals.

Materials and methods

Participants

Forty 9-month-olds (16 female, age range 260–287 days) participated in the study and were randomly assigned to 1 of 2 experimental groups (20 infants per group). An additional 52 infants were tested but excluded from the final sample because they did not contribute the minimum number of 3 trials per condition required (due to fussiness (27), poor data quality (11), inattention (10), or poor hat fit (4)). The number of infants excluded did not differ between the experimental groups (Joint Action (25); Single Agent (27)). Participants were recruited from a database of infants whose parents had volunteered to take part in infant studies at the Cognitive Development Center, Department of Cognitive Science, Central European University, Budapest. Written consent form was obtained from the infants' caregiver before the experiment was conducted. The procedure was approved by the ethics committee of the Department of Cognitive Science, Central European University, Budapest.

Stimuli

The stimuli animations were designed based on the ones used in 2 previous studies investigating goal attribution in infants (Hernik & Southgate, 2012; Southgate et al., 2014), and were created using the free software *Blender*.

Joint Action (Figure 1, upper panel). The animations depicted an agent (a red cube, Agent 1) moving from a central location at the top of the display, detouring a horizontally placed T-shaped wall in the center of the screen, and approaching a solitary target (either a smooth purple or a rigged green cylinder) placed in front of the wall, on the left or the right side. Simultaneously, a second agent (a yellow double-triangle shape, Agent 2), moved from a central location at the bottom of the display, approached the central vertical axis of the T-shaped wall, briefly paused, and proceeded to approach the same target as Agent 1. Both agents took a wide curved path, initially surpassing the target's location on the horizontal dimension, before turning and in a coordinated manner synchronously arriving in contact with the target object, and proceeded to jointly push the target to the same-sided corner of the T-shaped wall. *Single Agent* (Figure 1, lower panel). The animations were identical to the ones presented to the Joint Action group, with the exception of Agent 2 remaining static in its initial central position at the bottom of the display throughout the entire animation sequence.

Using a paired repetition suppression design (Southgate et al., 2014), each trial consisted of a sequence of 3 events. The first two events (Goal-Establishing events) were always identical (in both events the same solitary target, located on the same side, was approached and pushed). In the third event of every trial (Test event), two alternative targets (a smooth purple and a rigged green cylinder) appeared, each placed at one of the opposite sides in front of the wall. The agent(s) either approached the same target as in the preceding Goal-Establishing events of the trial (Old Goal condition), or the new target (New Goal condition). Each of the 3 events, comprising a trial, lasted 9 s, and events were separated by a 0.5 s gap (black screen), giving a total duration of 28 s per trial. In order to control for predictions that infants could form based on the location of the targets, or the side that the agent(s) approached, both the position of the target object and the side approached could either remain the same in Test as in the Goal-Establishing events of a trial, or it could switch. This resulted in 16 different trials, categorized into 4 types based on the changes between Goal-Establishing and Test events: Old Goal – Old Side, Old Goal – New Side, New Goal – Old Side, New Goal – New Side (see Table S1 in Supplementary materials for full list of the trials). The order of presentation was pseudo-randomized with the restriction that each trial type would be presented within every 4 trials, and that within the first 6 trials, an equal number of Old and New Goal trials was presented. Each trial was preceded by an 8 s Baseline, comprised of 4 static images of houses, animals,

landscapes and faces, each presented for 2 seconds. To maintain infants' interest, different sounds were presented alongside the visual stimuli; whenever an image changed during Baseline, and at the beginning of each of the 3 events of the trials.

Procedure

Data acquisition

Neuroimaging data was obtained using fNIRS (University College London topography system NTS (Everdell et al., 2005)), which provides continuous measurements of hemoglobin (Hb) concentration changes in the cortex, by using two wavelengths of light at 770 and 850 nm, reflecting changes in deoxy-hemoglobin (HbR) and oxy-hemoglobin (HbO) concentrations respectively. Infants wore a custom-built headgear with sources and detectors, separated by 2.5 cm, arranged in two arrays (placed over the left and right hemisphere), resulting in a total of 38 channels (19 on each hemisphere). The headgear matched entirely the headgear used in a study investigating goal attribution in same aged infants (Southgate et al., 2014), with its temporal arrays matching the ones used in a study co-registering fNIRS and MRI data in infants (Lloyd-Fox et al., 2014). This allows for direct comparison of channel localization onto the cortex as calculated in these papers (Lloyd-Fox et al., 2014; Southgate et al., 2014). The (bilateral) temporal parts of the source detector array extended from inferior frontal gyrus (anterior) to middle temporal gyrus (posterior) (Lloyd-Fox et al., 2014); the bilateral parietal parts of the headgear were positioned primarily over the supramarginal gyrus, the angular gyrus and the inferior parietal sulcus of the parietal lobe (Southgate et al., 2014). The distance from the middle of the headband above the nose (the glabella) to the channels above the ears (Channel 5 left hemisphere and Channel 24 right hemisphere, see Figure S1 Channel map) was fixed at 12.5 cm and aligned approximately with T3 and T4 of the 10–20 system on an average 9-month-old infant head (Southgate et al., 2014). Head measurements of the participants (circumference: $M = 44.9$ cm, $SD = 1.19$ cm; distance from glabella to ear (T3/T4): $M = 12.66$ cm, $SD = 0.65$ cm; distance between ears measured over the top of the head: $M = 22.28$ cm, $SD = 0.89$ cm) obtained from the current sample match closely those previously obtained from the same age group (Southgate et al., 2014).

Experimental procedure

Infants were sat on their caregiver's lap, at approximately 1 m distance from a 90 cm (width) by 50 cm

(height) screen. The size (width) of the agents comprised approximately 3.9° and the size of the targets approximately 3.2° of the visual angle (6.9 cm and 5.6 cm on screen, respectively). After the fNIRS headgear was fitted on the infant's head, the caregiver was instructed to orient the infant toward the screen, remain silent throughout the experiment, and try to prevent the infant from interfering with the headgear. Infants saw a sequence of trials, presented continuously and interleaved with Baseline periods, until the infant became inattentive or fussy, or until the maximum of 16 trials (8 for each condition) was presented. Infant behavior was video-recorded from a camera directly above the presentation screen and infants' looking time was coded off-line. In order for a trial to be included in the analysis, the infant had to attend to the screen during the agent(s) (exaggerated) detour around the barrier as well as during the part when the agent(s) pushed the target object, and attend overall at least 50% of each of the 3 events in the trial. As in previous studies, a minimum of 3 valid trials per condition was required for inclusion in the final sample. The median of valid trials (after exclusion based on inattention) contributed by infants in the Joint Action group was 8.5 trials (New Goal median = 4; range: 3–6; Old Goal median = 4; range: 3–7), and in the Single Agent the median of valid trials was 8 (New Goal median = 4; range: 3–6; Old Goal median = 4; range: 3–5).

Data processing and analysis

The raw fNIRS data was first converted using a custom written Matlab script (The MathWorks, Inc., Natick, MA, USA) into a format compatible with Homer2, an open-source NIRS analysis software package (Huppert et al., 2009), which was used for pre-processing. The performed processing stream followed the procedures highlighted as optimal for data with few trials and contaminated with motion artifacts (typical of infant fNIRS data) (Brigadoi et al., 2014). Channels with raw intensities smaller than .001 or larger than 10 volts were excluded from analysis. As this exclusion was done on each dataset individually, the number of infants that contributed data to each channel varied. This is reflected in varying degrees of freedom in the statistical reports. If valid data was recorded in less than 2/3 of the sample (14 infants), the channel was excluded from further analysis. This resulted in exclusion of channel 10 in both groups, and channel 35 in the Joint Action group (see *Figure S1, Channel map*). After trials, in which infants were not attending, were manually excluded, the remaining data were processed using wavelet motion correction with an interquartile range of 0.5 (Cooper et al., 2012; Molavi & Dumont, 2012). The data was then filtered using a bandpass filter from 0.01–0.5 Hz, to reduce slow drifts

and high frequency noise (Brigadoi et al., 2014), and converted to concentration of each hemoglobin chromophore according to the modified Beer-Lambert Law (Delpy et al., 1988), assuming a pathlength factor of 5.1. These pre-processed concentration data were used in the statistical analysis (described below). Finally, solely for the purpose of plotting the HRF curves, the mean hemodynamic response was obtained by block-averaging trials within the conditions (time range: 4 s prior to 36 s post trial onset), producing 2 mean HRFs (one per condition), for each channel and each participant.

The statistical modeling of the data was performed on the non-averaged concentration data using a combination of custom Matlab scripts and the SPM-NIRS toolbox (Ye et al., 2009). A design matrix with 5 regressors was created for each infant, modeling 5 cognitive conditions: Baseline, 1st Goal-Establishing event, 2nd Goal-Establishing event, New Goal, and Old Goal events. Each regressor had the same length as the total recorded data and was set to 1 at each time point of the presentation of the event, and to 0 for the rest of the recording. This created a series of non-overlapping "boxcars", with different durations (Baseline: 8 s; (1st & 2nd) Goal-Establishing: 9 s; New goal & Old goal: 9 s), with time-points corresponding to excluded trials set to 0. These 5 regressors were then convolved with the standard hemodynamic response function (HRF) and fit to the data using the SPM-NIRS toolbox general linear model, modeling separately the HbO and HbR measures, obtained as output from Homer2. Beta parameters were obtained for each of the 5 regressors and were used to calculate the New Goal > Old Goal contrast and 1st Goal-Establishing > Baseline contrast for each infant and each channel. To ensure statistical reliability, a significant contrast at a single channel was considered meaningful only if there was also a significant contrast in the same direction at a spatially adjacent channel. This criterion has been used in numerous infant studies with a comparable design (Lloyd-Fox et al., 2011; Southgate et al., 2014), and reduces the possibility of mistaking local changes in oxygenation, resulting from fluctuations in the blood in the scalp, as cortical activation. Furthermore, based on the co-registration of an analogous fNIRS headgear with the infants' corresponding structural MRI scans ((Lloyd-Fox et al., 2014; Southgate et al., 2014) see also Table S3 for channel localization), activation in any of the cortical areas covered by the channel-array, used in this study, would be expected to be reflected in groups of 2, 3 or 4 channels activating together. Taking into account the number and arrangement of channels in the fNIRS channel-array, adjusted per-channel *p*-value thresholds were calculated, maintaining a whole-array threshold of $p < 0.05$ for finding clusters of 2, 3 or 4 adjacent channels activated together by chance (false positive). This calculation resulted in corrected

individual-channel p -values of $p = 0.0253$ for clusters of 2; $p = 0.0665$ for clusters of 3; and $p = 0.1094$ for clusters of 4 channels (see Supplementary materials for details and equations). Only the effects present in clusters of channels, within which each of the channels falls under these adjusted per-channel thresholds, are reported. No clusters of neighboring channels exhibiting significant HbR activation were found (studies with infants typically do not find reliable HbR changes (Lloyd-Fox et al., 2010; Southgate et al., 2014)), therefore the presentation of the results will focus on HbO activity, however individual channels exhibiting significant contrasts in either of the measures are reported in Table S2, in Supplementary materials.

Results

Violation of expectation in response to a change of goal

Analysis of the New vs. Old Goal contrast revealed a cluster of 4 channels showing significantly greater activation in response to viewing New Goal events compared to Old Goal events in the Joint Action group (effects averaged over the channels included within each cluster are reported here, for statistical details on effects in individual channels, see Table S2 in Supplementary materials). The cluster of channels, located over the right temporal lobe (channels 26, 29, 33 and 36, marked red in Figure 2) exhibited significantly greater activation, reflected in increased HbO

concentration, in response to seeing New Goal compared to Old Goal events. This contrast was only significant in the Joint Action group ($t(19) = 2.812$; $p = 0.011$), whereas no significant difference in activation between New and Old Goal events was found in the same channels of the Single Agent group ($t(19) = 0.820$; $p = 0.422$). Importantly, the increase in HbO concentration was recorded in absence of a concurrent increase in HbR concentration (see supplementary materials, Table S2 for individual channel statistics and Figure S2 for HbO and HbR curves.) Based on co-registration analyses, previously performed on a matching fNIRS headgear and age appropriate infant MRI scans (Lloyd-Fox et al., 2014; Southgate et al., 2014), we can localize channels 26 and 29 as likely to project onto the right superior temporal sulcus (STS) and channels 33 and 36 as likely to project onto the posterior part of the right STS (see Figure S1 and S3. Localization of channels in Supplementary materials for more details).

Establishing the shared goal

To explore whether the neural activation in response to observing joint as opposed to individual inefficient actions differed even prior to the Test events, a second contrast, modeling the Baseline and the first Goal-Establishing event (irrespective of condition), was run separately for the Single Agent and the Joint Action group of infants. This analysis revealed three clusters of channels, which exhibited significant activation in response to viewing the first Goal-Establishing event as compared to Baseline activity. Two

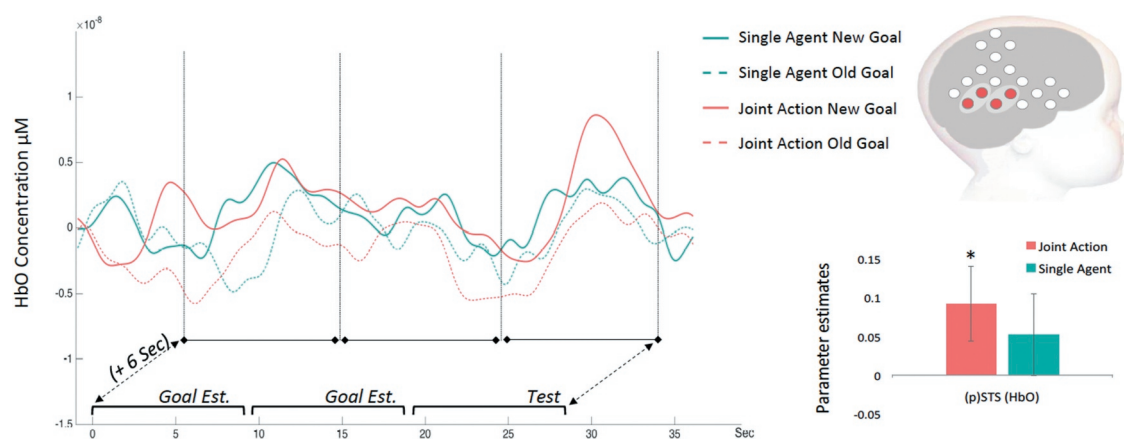


Figure 2. Hemodynamic response function, plotting HbO activation from trial onset to 36 seconds after, averaged over the cluster of channels (26, 29, 33, 36 marked in red on channel map), where significantly greater activation for New Goal than Old Goal Test events was found in the Joint Action group. HRF curves are presented separately for the two groups of infants and the two conditions. The sequence of events within a trial is marked on the timeline (two Goal Establishing events (9s each), and a Test event (9s)). The vertical lines, depicted over the HRF curves, mark the time of the expected hemodynamic response to the events (accounting for the typical time-lag of 6 s assumed in infant fNIRS research (Powell et al., 2018)). The averaged beta parameter estimates, modeling the HbO contrast between conditions for each group of infants are depicted in the bar plot. The cluster of channels exhibiting a significant New Goal > Old Goal contrast is estimated to project onto the right (posterior) superior temporal sulcus ((p)STS).

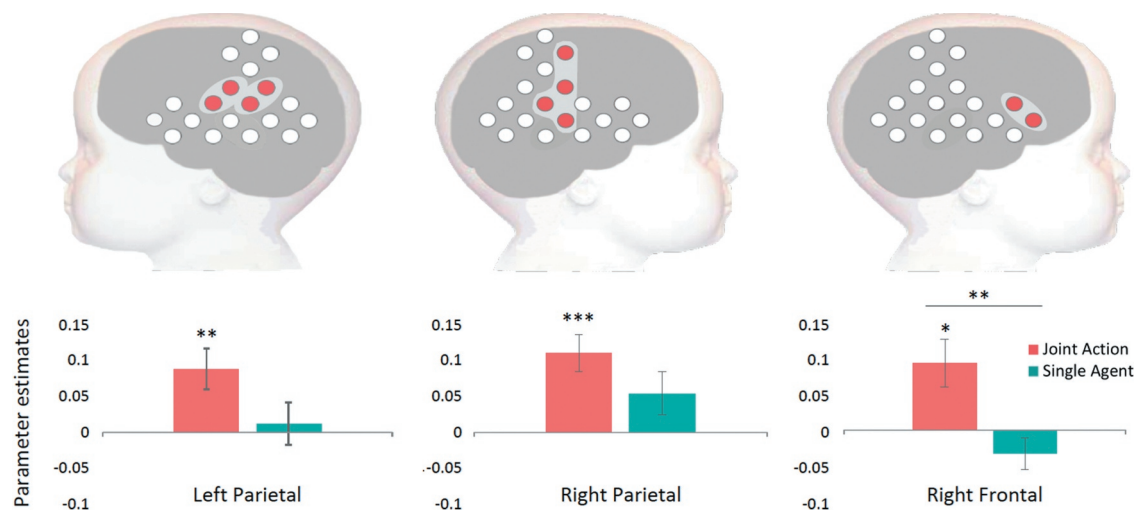


Figure 3. Channel maps indicating clusters of channels (marked in red) exhibiting significant activation during the first Goal-Establishing event in Joint Action group, with corresponding bar plots indicating beta parameters averaged over the channels within each cluster, for each group separately. Significant activation compared to Baseline (and between groups) is represented with asterisks above bars; error bars represent 1 SEM.

of these clusters can be localised as most likely projecting onto bilateral anterior parietal regions (Southgate et al., 2014) (Figure 3), and exhibited significant activation in the Joint Action (left parietal channels (6, 8, 11 and 15): ($t(19) = 3.113, p = 0.006$); right parietal channels (26, 27, 28 and 29): ($t(19) = 4.326, p < 0.001$)) but not in the Single Agent group (left parietal: $t(19) = 0.391, p = 0.700$; right parietal: $t(19) = 1.801, p = 0.088$). The third cluster (channels 20 and 22, Figure 3) exhibiting significant activation in response to the first Goal-Establishing event is likely to project onto the right inferior frontal gyrus (IFG) (Lloyd-Fox et al., 2014) and it likewise showed significant activation in the Joint Action group ($t(19) = 2.772, p = 0.012$) but not in the Single Agent group ($t(19) = -1.482, p = 0.155$). A direct comparison of the two groups revealed that the increase in activation in the IFG channels is significantly greater in the Joint Action than in the Single Agent group ($t(38) = 3.133, p = 0.004$), whereas the activation in the clusters projecting onto parietal areas did not significantly differ between the groups.

Discussion

Forming and attributing shared goals or intentions has been proposed to be a species-unique human capacity, fundamental for our social and cognitive development and underlying many of the differences between humans and our closest evolutionary relatives (Tomasello et al., 2005). While previous studies suggested that infants, in their first year of life, can make sophisticated inferences about observed social interactions (Hamlin, 2013; Hamlin & Wynn, 2011; Hamlin et al., 2007; Powell & Spelke, 2013,

2018), and can readily attribute goals to instrumental actions of individuals (Gergely & Csibra, 2003; Hernik & Southgate, 2012; Luo, 2011), the studies examining infants' ability to attribute shared goals to joint actions of multiple agents, in contrast, placed the emergence of this ability well into the second year of life (Fawcett & Gredebäck, 2013, 2015; Henderson et al., 2013; Henderson & Woodward, 2011). We hypothesized that the lack of evidence for shared goal attribution to joint actions in infants prior to 14 months of age may in fact not demonstrate a late onset of infants' understanding of shared goals. Instead, we propose that these findings reflect a limit on young infants' ability to identify and represent the structure of the observed collaborative actions. Using simultaneously performed coordinated joint actions, our neuroimaging results provide strong support for the hypothesis that infants can, in fact, attribute a shared goal to joint actions as early as 9 months of age.

In a paired repetition suppression design, using fNIRS, we measured the neural activity in the cortex of two groups of infants, while they observed animated agents repeatedly approaching targets in a modified Woodward paradigm (Woodward, 1998). One group of infants watched videos of two agents coordinating their actions toward a singular target (Joint Action group); and another group saw identical stimuli, except that one of the agents did not move while the other approached the target individually (Single Agent group). Crucially, all actions that the agents performed involved individually unnecessary spatial and temporal deviations from the optimal trajectories toward the goal object within the given situational constraints, making

the individual actions of each agent inefficient when considered alone. Based on previous studies, we predicted that infants observing inefficient actions performed by a single agent should not attribute a goal to these actions, as they provide no cues of goal-directedness, being neither selective (only one target was available during goal-establishing events) nor efficiently related to the target (the agent took an unnecessary detour before approaching the target) (Hernik & Southgate, 2012). In contrast, building on findings indicating that action inefficiency is common in contexts of joint action or collaboration (Vesper et al., 2010; Vesper & Richardson, 2014; Vesper et al., 2016), we hypothesized that when observing individually equally inefficient actions, which are, however, performed by two agents coordinating their actions, infants may interpret these as actions directed at the same shared goal. If infants processed the actions of the two agents as joint and goal-directed, an increase in activation (release from suppression) would be expected in response to the two agents approaching a novel target after having repeatedly approached a different target together first. In line with our predictions, this response was found in the Joint Action group of infants (but not in the Single Agent group) and was recorded in channels projecting onto the right (p)STS.

As expected, no response to a change in the approached target was recorded in the Single Agent group. This suggests that our modifications of the classic Woodward task (actions were inefficient and unselective) successfully disrupted goal attribution in this group. Had infants attributed goals to the observed single-agent actions, a response would have been expected in the left anterior parietal region, previously reported in same-aged infants as sensitive to goal violations of single agent actions (Southgate et al., 2014). The absence of such a response in the Single Agent group, combined with a distinct neural area responding to changes in the approached target in the Joint Action group, strongly suggest that these two types of actions are processed differently. Increased activation in the (p) STS region in response to the change of goal pursued by the coordinated joint actions is consistent with previous findings reporting activity in (p)STS in adults in response to a violation of expectations with respect to intentions, goals, and plausibility of observed (biological and non-biological) actions (Brass et al., 2007; Gao et al., 2012; Pelphrey et al., 2004; Vander Wyk et al., 2009). Crucially, (p)STS has also been shown to be involved in processing specifically social interactions, as opposed to independent actions of multiple agents performed at the same time (Isik et al., 2017), and to differentially activate in response to adults observing dyads of animated agents engaging in collaborative, as compared to competitive, interactions (Walbrin et al., 2018).

Therefore, we propose that the results of the Joint Action group reflect infants' attribution of a *goal*, as the release from suppression was observed specifically in response to a change in the target that the agents approached, and could not reflect low-level attentional shifts in response to a change in agents' paths (which was counterbalanced). Moreover, we propose that the attributed goal was a *shared goal*, because this goal could not have been attributed to individual agents due to the violations of efficiency in their target approach (as confirmed by Single Agent group results), and because the activation was found in (p)STS, a cortical region identified not only as sensitive to violations of predictions regarding observed actions, but also specifically as responsive to the processing of social and collaborative interactions (Isik et al., 2017; Walbrin et al., 2018).

As a secondary analysis, we explored what neural activation precedes, and possibly supports, infants' attribution of a shared goal to coordinated joint actions. This analysis revealed activation over (bilateral) anterior parietal regions in the Joint Action group of infants. This activity is consistent with activity reported in same-aged infants when attributing a goal to the efficient actions of a single agent (Southgate et al., 2014), suggesting that, although not sensitive to the change in the attributed shared goal, parietal regions may be involved in the processing of observed actions, also when performed by multiple agents. We note that the static images displayed in the Baseline differ from the dynamic videos of Goal-Establishing events in several aspects. Thus, drawing conclusions about the neural activation based on this comparison alone would be problematic. However, the Goal-Establishing events of the Single Agent and Joint Action group were perceptually very similar (the only difference was whether one or both agents were moving). Yet, the activity in bilateral parietal regions was observed only in the Joint Action group of infants, indicating that there may be important differences in how these stimuli are interpreted at a more conceptual level. Furthermore, a direct comparison between the two groups also revealed differential activation over the right IFG, where significantly greater activation was found in infants in the Joint Action group. Importantly, the distribution of cortical activity in the Joint Action group, including bilateral anterior parietal regions, right IFG and right (p)STS, bears a striking resemblance to the cortical areas which constitute the so-called Action Observation Network (AON) (Kilner, 2011). According to the model, proposed to explain the interconnections between the AON nodes, the parietal and frontal areas would provide goal and context-related representations of observed actions, such that expectations about the forthcoming events can be formulated via forward connections (Hamilton & Grafton, 2006;

Iacoboni et al., 2005). The temporal areas would play an important role in processing the available perceptual information in relation to the formulated expectations, and potentially respond to violations of these expectations (Kilner, 2011). The pattern of activation found in the present study seems to map onto the functional model of the AON; within the time course of the trials, pSTS activation followed the activation of the anterior parietal and inferior frontal areas and responded selectively to the change in the shared goal of the collaborative agents, presumably reflecting a violation of the expectation formulated during the goal establishing events. However, without further investigation, potentially employing dynamic causal modeling to explore the connections and the directionality of information flow among these areas of interest, the analogy between our results and adult AON remains merely speculative (see S4 in Supplementary materials for further discussion of these results).

Notwithstanding the limitations on interpreting the location of the found pattern of activation, our results indicate that 9-month-olds are sensitive to a change in goal when observing coordinated goal-directed actions of two agents, supporting the hypothesis that they can attribute a shared goal to simultaneously performed joint actions. How infants represent and attribute goals to observed coordinated joint actions, however, remains an open question. It is possible that infants are sensitive to the same cues of coordination as adults and therefore interpreted the actions as jointly efficient, being timed and performed in a coordinated manner in such a way that they together efficiently realize the shared goal with minimal relative (joint) effort (Török et al., 2019). Alternatively, infants may have disregarded the specific characteristics that rendered agents' actions individually inefficient and attributed the goal potentially by focusing on the outcome of the joint actions, which was likely to be salient due to the simultaneous approach by two agents.

While the mental representations involved in computing shared goals remain to be elucidated, our results are in line with the proposal that infants can make sense of coordinated joint actions they observe and interpret them as goal-directed much earlier than was previously thought. Given that young children typically start engaging in truly collaborative activities only toward the end of the second year of life (Warneken et al., 2012), our findings speak against previous proposals that infants require first-person motor experience with engaging in collaborative activities in order to be able to interpret them as such when only observing them performed from a third-person perspective (Fawcett & Gredebäck, 2013, 2015; Henderson et al., 2013; Henderson &

Woodward, 2011). Furthermore, the results of our study also challenge the theoretical proposal that young infants can represent other agents either as involved in goal-directed instrumental actions, or as social beings interacting with other agents, but not as both at the same time (Spelke, 2016). According to this proposal, these representations are initially encapsulated in separate core knowledge systems of the preverbal infant cognition and can become integrated only through conceptual change that is made possible by the emergence of combinatorial linguistic abilities during the second year of life (Spelke, 2016). Before this conceptual integration, infants should not be able to make sense of actions that are both instrumental *and* social, such as collaboration (Spelke, 2016). Contrary to this view, our results indicate that preverbal infants can attribute an instrumental goal to actions that can only be interpreted as goal-directed if represented as joint coordinated actions of two interacting agents. Therefore, the present results provide evidence that, at 9 months of age, infants may indeed already possess a concept of social agents, who can engage with one another to achieve a shared instrumental goal.

In conclusion, the results of this study strongly support the proposal that prior to being able to actively engage in goal-directed joint activities themselves, 9-month-old infants can attribute a shared goal to joint actions of others, in a purely observational context. In the same way as interpreting individual instrumental actions as goal-directed enables infants to discover new goals, novel artifact functions, and learn new means actions for achieving such goals, the ability to attribute shared goals to the collaborative actions of multiple agents should enable young infants to interpret and exploit the rich information available from observing collaborative activities in their social environment. In addition to enabling prediction and action learning from observing joint actions of others, attributing shared goals to cooperating social agents may also contribute to understanding social interactions in terms of the complementary roles of different agents, a learning task that plausibly constitutes a crucial step in infants' development into functional, collaborative members of their social environment.

Acknowledgments

We would like to thank Eszter Kortvelyesi and Marianna Nagy for their assistance with testing; Carina de Klerk and Dimitris Askitis for their help with data analysis, and Gina Antonia Tanqueray for the continuous source of inspiration.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by the European Research Council (ERC) under the European Union's Seventh Framework Programme [FP7/2007-2013/ERC Grant 609819], project SOMICS.

ORCID

Katarina Begus  <http://orcid.org/0000-0002-0264-4534>

References

- Aureli, T., & Presaghi, F. (2010). Developmental trajectories for mother-infant coregulation in the second year of life. *Infancy, 15*(6), 557–585. <https://doi.org/10.1111/j.1532-7078.2010.00034.x>
- Bakeman, R., Adamson, L. B., Bakeman, R., & Adamson, L. B. (2010). Coordinating attention to people and objects in mother-infant and peer-infant interaction published by: Blackwell publishing on behalf of the society for research in child development stable. *Coordinating Attention, 55*(4), 1278–1289. <https://doi.org/10.2307/1129997>
- Biro, S. (2013). The role of the efficiency of novel actions in infants' goal anticipation. *Journal of Experimental Child Psychology, 116*(2), 415–427. <https://doi.org/http://dx.doi.org/10.1016/j.jecp.2012.09.011>
- Brass, M., Schmitt, R. M., Spengler, S., & Gergely, G. (2007). Investigating action understanding: Inferential processes versus action simulation. *Current Biology, 17*(24), 2117–2121. <https://doi.org/10.1016/j.cub.2007.11.057>
- Brigadoi, S., Ceccherini, L., Cutini, S., Scarpa, F., Scatturin, P., Selb, J., Gagnon, L., Boas, D. A., & Cooper, R. J. (2014, January, 15). Motion artifacts in functional near-infrared spectroscopy: A comparison of motion correction techniques applied to real cognitive data. *Neuroimage, 85*(Pt 1):181–191. Retrieved 2014 Dec 12 <http://www.ncbi.nlm.nih.gov/pubmed/23639260>
- Candidi, M., Curioni, A., Donnarumma, F., Sachelì, L. M., & Pezzulo, G. Interactional leader – Follower sensorimotor communication strategies during repetitive joint actions. 2015.
- Choi, Y. J., Mou, Y., & Luo, Y. (2018). How do 3-month-old infants attribute preferences to a human agent? *Journal of Experimental Child Psychology, 172*, 96–106. <https://doi.org/10.1016/j.jecp.2018.03.004>
- Cooper, R. J., Selb, J., Gagnon, L., Phillip, D., Schytz, H. W., Iversen, H. K., Ashina, M., & Boas, D. A. (2012). A systematic comparison of motion artifact correction techniques for functional near-infrared spectroscopy. *Frontiers in Neuroscience, 6*, (OCT):1–10. <https://doi.org/10.3389/fnins.2012.00147>
- Csibra, G. (2008). Goal attribution to inanimate agents by 6.5-month-old infants. *Cognition, 107*(2), 705–717. <https://doi.org/10.1016/j.cognition.2007.08.001>
- Csibra, G., & Gergely, G. (2007). Obsessed with goals: Functions and mechanisms of teleological interpretation of actions in humans. *Acta Psychologica, 124*(1), 60–78. <https://doi.org/10.1016/j.actpsy.2006.09.007>
- Delpy, D. T., Cope, M., Van Der Zee, P., Arridge, S., Wray, S., & Wyatt, J. (1988). Estimation of optical pathlength through tissue from direct time of flight measurement. *Physics in Medicine and Biology, 33*(12), 1433–1442. <https://doi.org/10.1088/0031-9155/33/12/008>
- Everdell, N. L., Gibson, A. P., Tullis, I. D. C., Vaithianathan, T., Hebden, J. C., & Delpy, D. T. (2005). A frequency multiplexed near-infrared topography system for imaging functional activation in the brain A frequency multiplexed near-infrared topography system for imaging functional activation in the brain. *The Review of Scientific Instruments, 093705*(2005), 1–6. <https://doi.org/10.1063/1.2038567>
- Fawcett, C., & Gredebäck, G. (2013). Infants use social context to bind actions into a collaborative sequence. *Developmental Science, 16*(6), 841–849. <https://doi.org/10.1111/desc.12074>
- Fawcett, C., & Gredebäck, G. (2015). Eighteen-month-olds, but not 14-month-olds, use social context to bind action sequences. *Infancy, 20*(1), 115–125. <https://doi.org/10.1111/inf.12062>
- Gao, T., Scholl, B. J., & McCarthy, G. (2012). Dissociating the detection of intentionality from animacy in the right posterior superior temporal sulcus. *The Journal of Neuroscience, 32*(41), 14276–14280. <http://www.jneurosci.org/cgi/doi/10.1523/JNEUROSCI.0562-12.2012>
- Gergely, G., & Csibra, G. (2003). Teleological reasoning in infancy: The naïve theory of rational action. *Trends in Cognitive Sciences, 7*(7), 287–292. [https://doi.org/10.1016/S1364-6613\(03\)00128-1](https://doi.org/10.1016/S1364-6613(03)00128-1)
- Gergely, G., Nádasdy, Z., Csibra, G., & Bíró, S. (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*(2), 165–193. [https://doi.org/10.1016/0010-0277\(95\)00661-H](https://doi.org/10.1016/0010-0277(95)00661-H)
- Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: Neural models of stimulus-specific effects. *Trends in Cognitive Sciences, 10*(1), 14–23. <https://doi.org/10.1016/j.tics.2005.11.006>
- Hamilton, A. F., & Grafton, S. T. (2006). Goal representation in human anterior intraparietal sulcus. *Journal of Neuroscience, 26*(4), 1133–1137. <https://doi.org/10.1523/JNEUROSCI.4551-05.2006>
- Hamilton, A. F. D. C., & Grafton, S. T. (2006, January, 25). Goal representation in human anterior intraparietal sulcus. *Journal of Neuroscience, 26*(4):1133–1137. Retrieved 2012 Mar 19 <http://www.ncbi.nlm.nih.gov/pubmed/16436599>
- Hamlin, J. K. (2013). Failed attempts to help and harm: Intention versus outcome in preverbal infants' social evaluations. *Cognition, 128*(3), 451–474. <https://doi.org/http://dx.doi.org/10.1016/j.cognition.2013.04.004>
- Hamlin, J. K., & Wynn, K. (2011). Young infants prefer prosocial to antisocial others. *Cognitive Development, 26*(1), 30–39. <https://doi.org/http://dx.doi.org/10.1016/j.cogdev.2010.09.001>
- Hamlin, J. K., Wynn, K., & Bloom, P. (2007). Social evaluation by preverbal infants. *Nature, 450*(7169), 557–559. <https://doi.org/10.1038/nature06288>
- Hay, D. F. (1979). Cooperative interactions and sharing between very young children and their parents. *Developmental Psychology, 15*(6), 647–653. <https://doi.org/10.1037/0012-1649.15.6.647>

- Henderson, A. M. E., Wang, Y., Matz, L. E., & Woodward, A. L. (2013). Active experience shapes 10-month-old infants' understanding of collaborative goals. *Infancy, 18*(1), 10–39. <https://doi.org/10.1111/j.1532-7078.2012.00126.x>
- Henderson, A. M. E., & Woodward, A. L. (2011). "Let's work together": What do infants understand about collaborative goals? *Cognition, 121*(1), 12–21. <https://doi.org/10.1016/j.cognition.2011.05.008>
- Hernik, M., & Southgate, V. (2012). Nine-months-old infants do not need to know what the agent prefers in order to reason about its goals: On the role of preference and persistence in infants' goal-attribution. *Developmental Science, 15*(5), 714–722. <https://doi.org/10.1111/j.1467-7687.2012.01151.x>
- Huppert, T. J., Diamond, S. G., Franceschini, M. A., & David, A. (2009). HomER: A review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics, 48*(10), 280–298. <https://doi.org/10.1364/AO.48.00D280>
- Iacoboni, M., Molnar-Szakacs, I., Gallese, V., Buccino, G., & Mazziotta, J. C. (2005). Grasping the intentions of others with one's own mirror neuron system. *PLoS Biology, 3*(3), e79. <https://doi.org/10.1371/journal.pbio.0030079>
- Isik, L., Koldewyn, K., Beeler, D., & Kanwisher, N. (2017). Perceiving social interactions in the posterior superior temporal sulcus. *Proceedings of the National Academy of Sciences, 114*(43), E9145–E9152. <http://www.pnas.org/lookup/doi/10.1073/pnas.1714471114>
- Kilner, J. M. (2011). More than one pathway to action understanding. *Trends in Cognitive Sciences, 15*(8), 352–357. <https://doi.org/10.1016/j.tics.2011.06.005>
- Király, I., Jovanovic, B., Prinz, W., Aschersleben, G., & Gergely, G. (2003). The early origins of goal attribution in infancy. *Consciousness and Cognition, 12*(4), 752–769. [https://doi.org/10.1016/S1053-8100\(03\)00084-9](https://doi.org/10.1016/S1053-8100(03)00084-9)
- Lloyd-Fox, S., Blasi, A., & Elwell, C. E. (2010, March). Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy. *Neuroscience & Biobehavioral Reviews, 34*(3), 269–284. Retrieved 2012 Mar 6 <https://doi.org/10.1016/j.neubiorev.2009.07.008>
- Lloyd-Fox, S., Blasi, A., Everdell, N., Elwell, C. E., & Johnson, M. H. (2011). Selective cortical mapping of biological motion processing in young infants. *Journal of Cognitive Neuroscience, 23*(9), 2521–2532. <https://doi.org/10.1162/jocn.2010.21598>
- Lloyd-Fox, S., Richards, J. E., Blasi, A., Murphy, D. G. M., Elwell, C. E., & Johnson, M. H. (2014). Coregistering functional near-infrared spectroscopy with underlying cortical areas in infants. *Neurophotonics, 1*(2), 025006. <https://doi.org/http://neurophotonics.spiedigitallibrary.org/article.aspx?doi=10.1117/1.NPh.1.2.025006>
- Luo, Y. (2011). Three-month-old infants attribute goals to a non-human agent. *Developmental Science, 14*(2), 453–460. <https://doi.org/10.1111/j.1467-7687.2010.00995.x>
- Luo, Y., & Baillargeon, R. (2005). Can a self-propelled box have a goal? Psychological reasoning in 5-month-old infants. *Psychological Science, 16*(8), 601–608. <https://doi.org/10.1111/j.1467-9280.2005.01582.x>
- Molavi, B., & Dumont, G. A. (2012). Wavelet-based motion artifact removal for functional near-infrared spectroscopy. *Physiological Measurement, 33*(2), 259–270. <https://doi.org/10.1088/0967-3334/33/2/259>
- Nordt, M., Hoehl, S., & Weigelt, S. (2016). The use of repetition suppression paradigms in developmental cognitive neuroscience. *Cortex, 80*, 61–75. <https://doi.org/http://dx.doi.org/10.1016/j.cortex.2016.04.002>
- Pelphrey, K. A., Morris, J. P., & McCarthy, G. (2004). Grasping the intentions of others: The perceived intentionality of an action influences activity in the superior temporal sulcus during social perception. *Journal of Cognitive Neuroscience, 16*(10), 1706–1716. <http://www.mitpressjournals.org/doi/10.1162/0898929042947900>
- Pezzulo, G., Donnarumma, F., Dindo, H., & Ausilio, A. D. (2019). The body talks: Sensorimotor communication and its brain and kinematic signatures. *Physics of Life Reviews, 28*, 1–21. <https://doi.org/10.1016/j.plrev.2018.06.014>
- Powell, L. J., Deen, B., & Saxe, R. (2018). Using individual functional channels of interest to study cortical development with fNIRS. *Developmental Science, 21*, e12595. <https://doi.org/10.1111/desc.12595>
- Powell, L. J., & Spelke, E. S. (2013). Preverbal infants expect members of social groups to act alike. *Proceedings of the National Academy of Sciences, 110*(41), E3965–72. <https://doi.org/10.1073/pnas.1304326110>
- Powell, L. J., & Spelke, E. S. (2018). Human infants' understanding of social imitation: Inferences of affiliation from third party observations. *Cognition, 170*(September 2017), 31–48. <https://doi.org/10.1016/j.cognition.2017.09.007>
- Ramsey, R., & Hamilton, A. F. D. C. (2010). Triangles have goals too: Understanding action representation in left aIPS. *Neuropsychologia, 48*(9), 2773–2776. <https://doi.org/http://dx.doi.org/10.1016/j.neuropsychologia.2010.04.028>
- Schlingloff, L., Csibra, G., & Tatone, D. (2020). Do 15-month-old infants prefer helpers? A replication of Hamlin et al. (2007). *Royal Society Open Science, 7*, 191795. <https://doi.org/10.1098/rsos.191795>
- Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences, 10*(2), 70–76. <https://doi.org/10.1016/j.tics.2005.12.009>
- Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' actions. *Cognition, 96*(1), 1–11. <https://doi.org/10.1016/j.cognition.2004.07.004>
- Southgate, V., Begus, K., Lloyd-Fox, S., Di Gangi, V., & Hamilton, A. (2014). Goal representation in the infant brain. *Neuroimage, 85*(Part 1), 294–301. <https://doi.org/http://dx.doi.org/10.1016/j.neuroimage.2013.08.043>
- Southgate, V., Johnson, M. H., & Csibra, G. (2008). Infants attribute goals even to biomechanically impossible actions. *Cognition, 107*(3), 1059–1069. <https://doi.org/10.1016/j.cognition.2007.10.002>
- Spelke, E. S. (2016). Core knowledge and conceptual change: A perspective on social cognition. In D. Barner & B. AS (Eds.), *Core knowledge and conceptual change* (pp. 279–301). Oxford University Press.
- Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: The origins of cultural cognition. *Behavioral and Brain Sciences, 28*(5), 675–735. <https://doi.org/10.1017/S0140525X05000129>
- Török, G., Pomiechowska, B., & Csibra, G. Rationality in joint action: Maximizing efficiency in coordination rationality in joint action: Maximizing efficiency in coordination. 2019, May.

- Vander Wyk, B. C., Hudac, C. M., Carter, E. J., Sobel, D. M., & Pelphrey, K. A. (2009). Action understanding in the superior temporal sulcus region. *Psychological Science*, 20(6), 771–777. <https://doi.org/10.1111/j.1467-9280.2009.02359.x>
- Vesper, C., Butterfill, S., Knoblich, G., & Sebanz, N. (2010). A minimal architecture for joint action. *Neural Networks*, 23(8–9), 998–1003. <https://doi.org/http://dx.doi.org/10.1016/j.neunet.2010.06.002>
- Vesper, C., & Richardson, M. J. (2014). Strategic communication and behavioral coupling in asymmetric joint action. *Experimental Brain Research*, 232(9), 2945–2956. <https://doi.org/10.1007/s00221-014-3982-1>
- Vesper, C., Schmitz, L., Safra, L., Sebanz, N., & Knoblich, G. (2016). The role of shared visual information for joint action coordination. *Cognition*, 153, 118–123. <https://doi.org/http://dx.doi.org/10.1016/j.cognition.2016.05.002>
- Walbrin, J., Downing, P., & Koldewyn, K. (2018). Neuropsychologia Neural responses to visually observed social interactions. *Neuropsychologia*, 112(September 2017), 31–39. <https://doi.org/10.1016/j.neuropsychologia.2018.02.023>
- Warneken, F., Gräfenhain, M., & Tomasello, M. (2012). Collaborative partner or social tool? New evidence for young children's understanding of joint intentions in collaborative activities. *Developmental Science*, 15(1), 54–61. <https://doi.org/10.1111/j.1467-7687.2011.01107.x>
- Woodward, A. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, 69(1), 1–34. [https://doi.org/10.1016/S0010-0277\(98\)00058-4](https://doi.org/10.1016/S0010-0277(98)00058-4)
- Ye, J. C., Tak, S., Jang, K. E., Jung, J., & Jang, J. (2009). NIRS-SPM: Statistical parametric mapping for near-infrared spectroscopy. *Neuroimage*, 44(2), 428–447. <https://doi.org/http://dx.doi.org/10.1016/j.neuroimage.2008.08.036>
- Yin, J., Xu, H., Ding, X., Liang, J., Shui, R., & Shen, M. (2016). Social constraints from an observer's perspective: Coordinated actions make an agent's position more predictable. *Cognition*, 151, 10–17. <https://doi.org/http://dx.doi.org/10.1016/j.cognition.2016.02.009>