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Human Children's Representation of Informativeness

Marie Aguirre

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Marie Aguirre. Human Children's Representation of Informativeness. Cognitive science. Université de Lyon, 2021. English. NNT : 2021LYSE1149 . tel-04945802

HAL Id: tel-04945802

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Submitted on 13 Feb 2025

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Numéro National de Thèse : 2021LYSE1149

THÈSE de DOCTORAT DE L'UNIVERSITÉ DE LYON
opérée au sein de
l'Université Claude Bernard Lyon 1

École Doctorale Neurosciences et Cognition n°476

Discipline : Sciences Cognitives

Soutenue publiquement le 08/07/2021, par :

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**Human Children's Representation of
Informativeness**

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Remerciements

Mes premiers remerciements s'adressent aux rapporteuses Rana Esseily et Nausicaa Pouscoulous, et aux examinateurs Pierre Jacob et Yves Rossetti. Je vous suis reconnaissante d'avoir accepté de participer à mon jury et pour le temps que vous avez consacré à évaluer mes travaux. Je remercie aussi François Osiurak et Olivier Pascalis pour leurs rendez-vous annuels de suivi de thèse riches en conseils et soutiens.

Je te remercie Anne pour m'avoir accueillie, m'avoir fait confiance, pour ta disponibilité, ta réactivité, tes corrections minutieuses, ton soutien et d'avoir su préserver un environnement paisible. Toujours attentive, c'était agréable et rassurant de travailler tout en sachant que je pouvais compter sur toi. Merci merci !

Olivier, je suis très fière d'avoir eu l'honneur d'être ta première doctorante, merci d'avoir prolongé notre aventure qui a débuté il y a 5 ans déjà pour mon Master. Merci du plus profond de mon cœur pour m'avoir accordé ta confiance, guidé tout au long de ces années, pour ta bienveillance, ta gentillesse sans pareille, ton optimisme sans faille, ta prévenance, et ta patience. Merci de m'avoir intégrée complètement dans ce monde de la recherche à travers des conférences, des publications, des rencontres et de nombreuses discussions passionnantes. Merci d'avoir joué ce rôle de Super-Supervisor, assuré un cadre de travail serein et donné autant d'autonomie. C'est un vrai plaisir et une chance de travailler avec une personne comme toi, merci infiniment.

Tout ce travail d'expérimentation n'aurait pu se faire sans la collaboration d'Auriane, Justine, Maxine, Marielle, Mélanie et Viviane, ainsi que les aides techniques et administratives d'Anne C., Carole, Christiane, Lionel, Sabine et Sophie. Merci pour votre précieuse contribution et nos échanges qui ont permis de créer de belles amitiés. Je garde un chouette souvenir de toute nos conversations.

Cléa, Philippine et Zoé, mes sœurs de thèses, j'ai adoré partager ces années inoubliables avec vous, contente de vous compter parmi mes amies. Zoé, merci pour ta bonne humeur contagieuse, je n'aurais pas pu rêver mieux comme colocataire de bureau !, celui des doléances, celui des rires et 400 coups, mais surtout celui de l'entraide.

Cléa, merci pour tes relectures, ton attention et tous nos appels et messages réguliers qui m'ont reboostée ! Sache que tu peux compter sur moi quand ce sera ton tour.

Philippine tu es la première à t'être jetée à l'eau, tu es ma référence ! Merci de m'avoir fait profiter de ton expérience et d'être ma complice pour Le "clique" final.

Je voudrais aussi remercier l'ensemble des étudiants, ingénieurs, chercheurs et gestionnaires des laboratoires L2C2 à Lyon et INCC à Paris de m'avoir accueilli. Merci notamment pour tous ces bons moments légers et joyeux au cours des déjeuners et pauses.

Merci à tous les enfants pour leur participation enthousiaste, la disponibilité des parents, des crèches et des écoles qui nous ont permis de répondre aux "questions dont on ignorait jusqu'alors les réponses".

Je remercie tout particulièrement mes parents d'avoir cru en moi, pour leur soutien moral, diététique et élixirs (sans qui j'aurai pris ou perdu 15 kilos), matériel et financier, sans lesquels je n'aurais pas pu entreprendre ces études dans les mêmes conditions. Je remercie aussi ma sœur Bérénice pour son coaching et aide pour terminer ce manuscrit.

Merci à mamie Juliette pour ses 3 prières par jour minimum.

Merci à toute la famille y compris celle de Thomas pour leurs encouragements, et particulièrement à Christian, Dominique, Éric et Nicole.

Merci à tous mes proches amis pour leurs soutien moral et encouragements sous toutes ses formes : les moments de détente d'Alexandre, Anaïs, Chloé, Joseph, Hélène, Inès, Ken, Laureline, Marie-Flore, Marine, Nicolas et Quentin, les petites citations de Tony et les balades de Monique.

Le meilleur pour la fin, merci Thomas pour ton incroyable soutien, ta patience, ton aide et ton amour qui m'ont porté même à des centaines de kilomètres.

Ce n'est pas par politesse que j'écris ces phrases, mais plutôt pour vous transmettre à tous et à toutes ma reconnaissance, ma gratitude qui vont bien au-delà des mots. C'est un vrai plaisir d'écrire ces remerciements.

Abstract and Keywords

Title: Human Children's Representation of Informativeness

Humans are incredibly flexible learners, who can adjust their learning strategy by recursively representing the process of learning itself. Such a faculty is crucial to plan new behaviors designed to maximize information and learning gains. The present thesis reports four articles investigating the early development of humans' capacity to model learning, focusing on representations of informativeness, and on their role in supporting individual and social learning. In a context of individual information-seeking, toddlers anticipate the availability and cognitive utility of data, and they adapt their behavior accordingly to optimize their information gains (Article 1). In a context of social learning via communication, toddlers prioritize interpretations of novel cues that are informative, and easy to process. Thus, expectations about the informativeness (and the general cognitive utility) of communicated meanings guide their interpretation from an early age (Article 2). Moreover, there is a developmental switch in children's reliance on expectations about a speaker's informativeness to interpret novel communicative cues, between 18 months and 3 years (Article 3). Finally, humans appear to simplify the representation of other people's search for information, by assuming that people search for what that do not know, and not for information that they are aware of lacking. Such a simplification is evidenced in humans' interpretation of requests for information, from toddlerhood to adulthood (Article 4). The results of this thesis work highlight how precocious competencies to represent informativeness, present from toddlerhood, shape humans' learning.

Keywords: Cognitive Development, Informativeness, Metacognition, Active Learning, Communication, Questions, Toddlerhood, Childhood.

Résumé et Mots Clés

Titre : La Représentation de l'Informativité chez l'Enfant

L'Homme est un apprenant incroyablement flexible, il possède la capacité de se représenter métacognitivement le processus d'apprentissage. Cette faculté est essentielle pour imaginer de nouveaux comportements qui permettent d'obtenir un maximum d'information et d'optimiser l'apprentissage. Cette thèse comporte 4 articles qui étudient le développement précoce, chez l'Homme, des capacités à modéliser l'apprentissage, en particulier la métareprésentation de l'informativité, et leurs rôles dans l'apprentissage individuel et social. Dans un contexte de recherche individuelle d'information, les tout petits anticipent l'accès aux données et leur utilité cognitive, ils sont aussi capables d'adapter leurs actions en conséquence pour optimiser le gain d'information (Article 1). Dans un contexte d'apprentissage social, les enfants âgés de 2 ans utilisent des attentes d'informativité (et d'utilité cognitive) pour comprendre un nouveau signal communiqué, ils priorisent les interprétations informatives et faciles à traiter (Article 2). Aussi, il existe une évolution au cours du développement, des attentes d'informativité de la part d'un locuteur, avec un renforcement de ces attentes entre 18 mois et 3 ans (Article 3). Enfin, depuis tout petits et jusqu'à l'âge adulte, les requêtes d'informations sont interprétées de manière simplifiée i.e, en supposant que la personne cherche ce qu'elle ne sait pas, et non pas des informations qu'elle est consciente d'ignorer (Article 4). Les résultats des travaux de cette thèse mettent en avant des compétences, déjà présentes très tôt chez les tout petits, à se représenter l'informativité leur permettant ainsi de guider leur apprentissage.

Mots Clés : Développement Cognitif, Informativité, Métacognition, Apprentissage Actif, Communication, Questions, Petite Enfance.

Résumé Substantiel

La recherche d'information est l'une des fonctions principales des mécanismes cognitifs. Elle est présente dans beaucoup d'espèces, des systèmes cognitifs les plus simples tel que les invertébrés, aux plus complexes comme les primates. L'Homme, pour sa part, possède l'incroyable capacité de se représenter l'informativité de leur action, lui permettant d'anticiper et de pouvoir imaginer de nouveaux comportements pour optimiser toujours plus son gain d'information et d'apprentissage.

Cette thèse s'est consacrée à explorer le développement précoce, chez l'Homme, des mécanismes cognitifs qui impliquent la métareprésentation de l'informativité et à étudier son rôle dans l'apprentissage individuel et social.

Le 1^{er} article étudie l'ontogénie de cette capacité à se représenter l'informativité, dans un contexte d'apprentissage individuel. Pour ce faire, les structures expérimentales ont été pensées afin qu'en fonction du contexte, une même action génère différents gains informatifs. Dans l'étude 1, des nourrissons de 14 mois ($N = 72$) ont effectué une action (soulever un couvercle) plus rapidement lorsqu'elle leur permettait de voir un objet dans une boîte. Ces premiers résultats suggèrent une recherche d'information flexible basée sur une anticipation de l'accès visuel. Ainsi, les nourrissons considèrent l'accès visuel comme une source d'information potentielle et organisent leurs actions dans un but épistémique (i.e., l'objectif de voir l'objet). Dans l'étude 2, des enfants de 2-3 ans ($N = 36$) devaient trouver une carte cible cachée parmi des leurres. Ils ont retourné plus rapidement une carte lorsque celle-ci leur permettait de réduire leur incertitude. De même, dans l'étude 3 des enfants de 2-3 ans ($N = 36$) devaient choisir parmi deux actions possibles (retourner ou presser un personnage). Ils ont été enclins à effectuer en premier l'action qui était la plus informative selon le contexte. Ces résultats soulignent que les tout petits anticipent l'accès aux données et leur utilité cognitive,

et qu'ils sont aussi capables d'adapter leurs actions en conséquence pour optimiser leur gain d'information. Ainsi, les modèles cognitifs d'apprentissage guident la recherche d'information individuelle dès 2-3 ans.

Dans un 2^{ème} article, nous nous sommes appuyés sur ces premiers résultats et avons examiné comment les représentations de l'informativité pouvaient guider l'apprentissage dans un contexte social. Certaines théories supposent que les locuteurs se veulent informatifs, ainsi lorsqu'un signal est communiqué elles proposent de privilégier les interprétations qui présentent un ratio coût/bénéfice cognitif important. Nous avons donc examiné ce phénomène via un nouveau signal ambigu, sous forme d'indice, qui indique la position d'une récompense. Dans la première étude, l'indice était placé sur un des deux verres opaques, dès lors deux interprétations de l'indice étaient possibles : soit l'indice indiquait la position du verre vide, soit la position du verre contenant la récompense. Les enfants âgés de 2 ans ($N = 18$) ont favorisé l'interprétation à faible coût de traitement cognitif, alors même que l'indice était systématiquement placé sur le verre vide. En somme, les tout petits semblent résister à choisir l'interprétation la plus coûteuse en traitement cognitif, quand une alternative plus simple est disponible. Dans la seconde étude, les tout petits ($N = 36$) ont préféré l'interprétation la plus informative i.e., celle qui leur permettait de réduire leur incertitude quant à la position de la récompense. De même dans l'étude 3, les enfants de 2 ans ($N = 36$) ont été plus susceptibles de découvrir la signification d'un indice s'il était utilisé de manière informative. Ces résultats démontrent une priorisation des interprétations informatives et faciles à traiter cognitivement, lorsque les tout petits cherchent à comprendre la signification d'un nouveau signal. En somme, les tout petits accordent déjà la priorité aux interprétations dont le rapport coût/bénéfice cognitif est élevé lorsqu'ils doivent déterminer la signification de nouveaux signaux de communication. Aussi, les résultats suggèrent que déjà très tôt le développement communicatif est guidé par une attente d'utilité cognitive des informations communiquées. D'une certaine

manière, les jeunes enfants exercent donc une pression sur les systèmes de communication, ce qui pourrait contribuer à les rendre plus efficaces.

Un 3^{ème} article a analysé le développement précoce des capacités mises en avant dans le précédent article, au cours de la petite enfance. Cette recherche a mis en situation deux stratégies opposées d'apprentissage des mots : des inférences basées sur des attentes en matière d'informativité, et le suivi de la cooccurrence entre les mots et leurs référents potentiels. Dans ces études, une expérimentatrice prononçait un mot nouveau en pointant de manière ambiguë vers un ensemble d'objets inconnus : un objet unique, et de nombreuses copies d'un autre type d'objet. En supposant que le locuteur est suffisamment informatif pour pouvoir facilement identifier l'objet qu'il désigne, le nouveau mot devrait faire référence à l'objet unique. Sinon, si les participants s'attachent aux co-occurrences entre le nouveau mot et les référents potentiels, ils devraient associer le nouveau mot à l'objet répliqué. Alors que les 3-5 ans ($N = 73$) s'attendaient à ce que l'orateur soit informatif, les 18 mois ($N = 40$) ont utilisé une stratégie cohérente avec le suivi de co-occurrence. Dans une condition supplémentaire, nous avons également démontré que les enfants en crèche et les maternelles prennent en compte ce que le locuteur peut voir, plutôt que leur propre point de vue. Dans l'ensemble, les résultats suggèrent que les attentes concernant l'informativité des locuteurs changent considérablement au cours de la petite enfance et reposent dès le départ sur une saillance sociale et non perceptive.

Enfin, un 4^{ème} article étudie un autre point de vue, celui de la représentation de la recherche d'information pour autrui lorsque l'on interprète leurs questions. On ne peut rechercher une information que lorsque l'on réalise que celle-ci nous fait défaut. Ainsi, en principe, l'interprétation des demandes d'informations pourrait être guidée par des représentations de l'ignorance socratique (i.e., repérer ce que les gens savent qu'ils ne savent pas). D'un autre côté, l'interprétation des demandes d'informations pourrait être simplifiée en s'appuyant principalement sur un simple suivi des connaissances (i.e., simplement sur le suivi

de ce que les gens savent/ignorent). Nous avons évalué ces hypothèses en testant des enfants de 2-3 ans ($N = 18$), de 5 à 7 ans ($N = 72$), et des adultes ($N = 320$). Dans nos tests, une actrice posait une question qui pouvait être élucidée en suivant son état de connaissance. Nous avons manipulé les accès visuels de l'actrice pour moduler la complexité de la représentation de l'ignorance nécessaire pour désambiguïser sa question. Les tout-petits n'ont montré aucune tendance à faire appel aux représentations de l'ignorance socratique pour interpréter les questions. Les enfants de cinq à sept ans se sont comportés de manière similaire, et ont obtenu de meilleurs résultats lorsque les demandes d'informations pouvaient être clarifiées à l'aide d'un simple suivi des connaissances. Les adultes étaient capables d'utiliser des représentations de l'ignorance socratique pour interpréter les questions, mais ils étaient plus confiants lorsqu'un simple suivi des connaissances suffisait à interpréter des demandes d'informations. De plus, les adultes ont interprété les questions comme si les locuteurs pouvaient demander des informations sur des choses qu'ils ignoraient, même lorsque les locuteurs n'avaient aucune raison d'avoir connaissance de leur ignorance. Ainsi, l'interprétation des demandes d'informations semble reposer principalement sur un simple suivi des connaissances et non sur des représentations de l'ignorance socratique, une heuristique qui réduit les coûts cognitifs de traitements.

En conclusion, ce projet de thèse propose d'importants résultats concernant le développement précoce de mécanismes cognitifs qui impliquent la représentation de l'informativité, et ce dans plusieurs domaines i.e., dans un contexte d'apprentissage individuel et, dans un contexte social lors d'interprétation de nouveaux signaux communiqués et de requête d'information. En outre, les résultats des travaux de cette thèse mettent en avant des compétences, déjà présentes très tôt chez les tout petits, à se représenter l'informativité leur permettant ainsi de guider leur apprentissage.

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Part I

General Introduction

Humans' sensitivity to informativeness

“Information has become like the air we breathe, so pervasive that we scarcely notice its existence and yet so essential that we cannot live without it.”

– Tague-Sutcliffe (1995)

When typing into the google search bar, listening for covid-19 announcement on TV news or radio, opening the window to guess the weather of the day, checking mails, scanning a menu at a restaurant, reading a book about child education, and so forth, people are looking for information. Such behaviors shape a good part of human societies, institutions, and individual daily lives for a good reason: they support learning (Kang et al., 2009).

Searching for information is perhaps one of the most general functions of cognitive mechanisms. One way to collect information is simply to process the stimuli accessible in one's environment, without actively searching for useful information. This strategy may yield learning, up to a point. Yet, this type of passive learning implies a huge cost of opportunity. Indeed, in many cases, an organism can learn a lot more by actively searching for useful information in its environment. Accordingly, there is evolutionary leverage for the emergence of mechanisms supporting the efficient search for information.

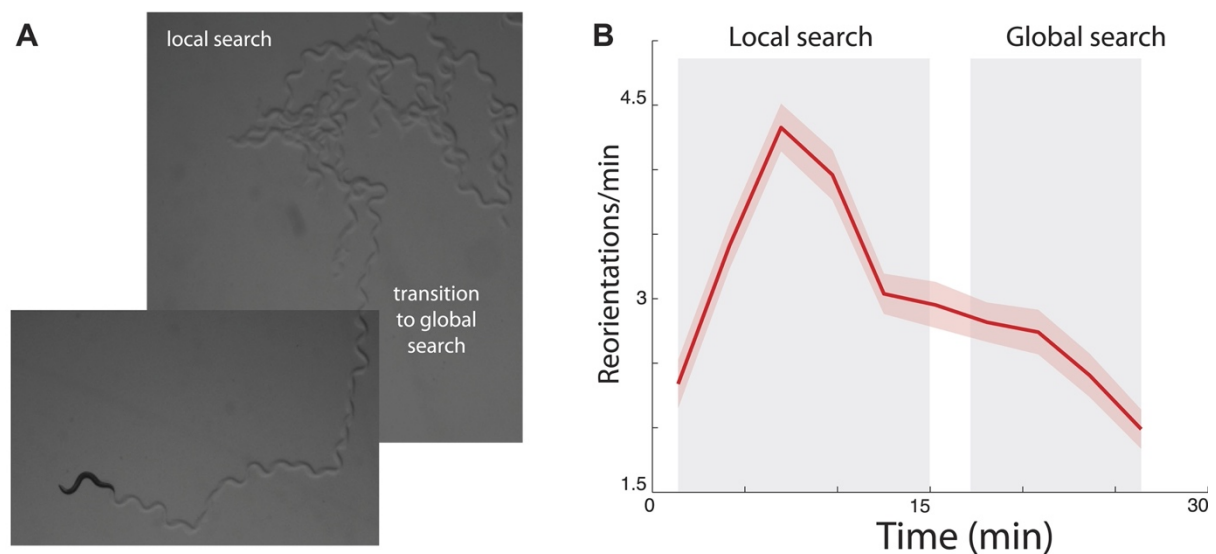
1 Information seeking : a general function of cognition

Many species can adjust their behaviors in order to gather information efficiently. Even the humble worm *C.Elegans*, a nematode of approximately 1mm long, shows evidence of strategic environment inspection that yields information gains. Calhoun and colleagues (2014) have shown that *C.Elegans*, when searching bacteria food on rotten vegetables, are able to keep

track of previous food locations and that they use this capacity to optimize future foraging. First, the worms proceed to a “local search”, characterized by numerous sharp turns in a search target area. If within 15 minutes the foraging is unsuccessful, the nematodes abruptly change their information-seeking strategy to a “global search” by moving along straighter and longer trajectories into the surrounding area (see Figure 1). This strategy optimizes information gains about the location of food. Remarkably, this sophisticated strategy is performed by minuscule worms with less than 400 neurons.

Figure 1

Transition Between Local and Global Search in C. Elegans Foraging Trajectories Following their Removal from Food.



Note: Data from Calhoun and colleagues (2014). Panel A: Animals search the local area by producing a large number of turns before abruptly transitioning to a global search. Panel B: Across many animals, this transition is readily apparent in the mean turning rate. Standard error of the mean is shown as the lightly shaded region around the solid average line.

Other invertebrates can search for information efficiently in their environment in ways that optimize data collection from multiple individuals. For instance, Degen and colleagues (Jacqueline Degen et al., 2015) have shown that the honeybees *Apis mellifera* balance adequately exploratory and foraging flights' behavior at the collective level. At the beginning of their lives, after some flight training, some bees act as experienced foragers, while others become scout bees. Scout bees are the “research and development department” of the hive. They make long-lasting flights covering almost the entire surrounding of the hive, in order to search for novel food source or for new nests sites. The behavior of scout bees provides very compelling evidence for bees' drive for exploration, despite the consumption of energy and time, and exposure to hazards and predators that it implies. Thus, even species with relatively small brains engage in foraging behaviors that strategically balance exploration, and exploitation, and thus, optimize their search for information.

These results confirm that information-seeking is a fundamental and basic function of cognitive mechanisms, one that is likely to be found in many species. Indeed, evidence for behaviors whose apparent function is to gather information is abundant, and found in a wide range of species. Birds and moths fly in zigzag perpendicular to the wind direction in order to find the source of an odor plume, a strategy that improves their collection of olfactory data (Vergassola et al., 2007). Other empirical work provides evidence of mammals' curiosity and ability to search for information (Blanchard et al., 2015; Butler, 1954; Glickman & Sroges, 1966). For instance, in a seminal study by Call and Carpenter (2001), chimpanzees had to search for a reward hidden in one out of several tubes. The participants were more likely to look inside the tubes when they did not witness the baiting of the tubes, i.e., when they did not know where the reward had been hidden. These data suggest that chimpanzee adjust their behaviors adequately to collect visual information. In other words, many species can engage in efficient active learning.

2 Inflexible information-seeking

Crucially, the function of searching for information in an optimal fashion is likely to be implemented by very different cognitive mechanisms depending on the specie in which it is observed. Consider, for instance, the efficient foraging actions of *C. Elegans*. It is likely that these behaviors involve no representation of ignorance on behalf of the nematodes. More simply, *C. Elegans*' foraging behaviors seem to be triggered by the amount of time they spent moving in their environment without finding food. *C. Elegans*' foraging mechanisms are also probably quite inflexible: they have evolved to operate in a specific environment, and to solve a very specific information gathering problem (collecting information about the location of food). It is doubtful that these foraging mechanisms would allow *C. Elegans* to ask novel questions (such as asking why food is abundant at a particular location or how it arrived there). At the other extreme end of the spectrum, human adults can represent what kind of information they lack, and create entirely novel strategies to collect it. In short, the general function of searching for information can be implemented by many different kinds of cognitive mechanisms. Some of these information-search mechanisms are very efficient, and yet, inflexible, especially if they have evolved to solve very specific information gathering problems. Other mechanisms are much more flexible, and they support the creation of novel ways to search for information in one's environment.

3 Representing learning in order to learn in a flexible way

Humans are hungry for information by nature, they are attracted by novelty, and engage in independent exploration or innovation (Berlyne, 1966; Kidd & Hayden, 2015; Pelz & Kidd, 2020; Pisula, 2009; T. Wilson, 2000). Remarkably, humans possess some information search mechanisms that do more than simply trigger efficient information search; they support the discovery of new behaviors that can be informative. In scientific research and in many more

other domains, we can ponder questions that have never been asked before, form innovative hypotheses, and collect relevant information in order to discriminate between hypotheses in a creative way. While this hypothesis testing process is the basis of any scientist's reasoning, it is also commonly used in other domains such as in a police investigation or when caregivers test different types of food one by one to identify which one is causing allergies to their kid. One way to search for information in such an adaptable and creative manner is to represent and anticipate the process of learning itself. By representing the information gain of a stimulus, a cognitive system can anticipate if and when an action will result in learning. As a result, representing the information gain of a stimulus is crucial to plan novel information search behaviors creatively.

4 The aims of this thesis

In short, information-seeking is one of the most general functions of cognitive mechanisms, encountered in many species, from simple cognitive invertebrate to humans. One way to search for information in a flexible and efficient manner consists in representing the process of learning itself, in order to anticipate the informativeness of a piece of data i.e. its capacity to reduce one's own, and other people's, uncertainty over a set of hypotheses.

▷The goal of this PhD is to investigate the early development of the cognitive mechanisms allowing humans to represent informativeness, and to investigate their role in supporting individual and social learning.

Throughout this thesis, the informativeness of a stimulus is defined as its capacity to reduce uncertainty over a set of hypotheses, uncertainty being quantified using the standard entropy measure from information theory (Shannon, 1948).

A first part of the project will focus on the cognitive mechanisms allowing young children to represent informativeness for themselves. This part of the thesis will evaluate to what extent infants' early search for information can be compared to hypothesis testing, and is geared toward obtaining information that can reduce uncertainty over a set of hypotheses (Article 1).

A second part of the project will focus on how young children rely on expectations of informativeness in social contexts, in order to understand what is communicated to them. During social interactions, speakers are sensitive to the epistemic needs of listeners, and they take into account what could be informative for them. This implicit assumption, essential for an efficient communication, may create expectations of informativeness in listeners. This part of the thesis will assess to what extent young children expect communicated signals to be informative (and, more generally, cognitively useful), and how children use this expectation to guide their interpretation of novel meanings (Articles 2 and 3).

The third and last part of the PhD project will focus on how children and adults represent information-seeking in others. This part will cast light on the process that humans use to interpret explicit requests for information, formulated by verbal questions (Article 4).

Informativeness and individual learning

“One day, the little Mole poked his head out from underground to see whether the sun had already risen. Then it happened! [...]

“How mean!” cried the little mole. “Who has done this to my head?” [...]

“Did you do this on my head?” he asked the horse who was grazing in the pasture”.

– Werner Holzwrath (1994)

In the classic humorous picture book *The Little Mole Who Knew it Was None of His Business* (see Figure 2, Holzwrath, 1994), a little mole wakes up one morning only to have one of the other farm animals did its business on his head. The little hero then embarks on a quest to find the culprit, and to strike back in his own little way. In his epic adventure, the mole questions each of the farm animals, and refines his hypotheses (needless to say, by observing how they do their business). The incredible success of such a child-friendly “*who dunnit?*” mystery suggests an early capacity and interest for reasoning about information search. Indeed, there are reasons to believe that a sensitivity to the learning consequences of stimuli might emerge early.

Figure 2

Extract from the Picture Book The Little Mole Who Knew it Was None of His Business.



1 Do infants monitor their own learning?

From birth, infants do not allocate their overt attention in a random fashion. They spend more time looking at some stimuli than others. Some of infants' attentional preferences can be accounted for by early developing or even innate preferences for some fixed patterns of stimuli, such as face-like configurations (Di Giorgio et al., 2012; Pascalis et al., 2011). Yet, data suggest that infants' overt attention is also heavily influenced by their past experiences, and may be geared toward supporting optimal learning. For instance, it has been proposed that infants prefer to look longer toward stimuli that are maximally novel (Fantz, 1964) and avoid redundant stimuli more than variable ones (Addyman & Mareschal, 2013). Notably, infants strategically orient their attention toward visual and auditory stimuli that can support their own learning i.e., stimuli that are neither too complex neither too simple to process (Kidd et al.,

2012; Kinney & Kagan, 1976). For instance, in a study by Kidd and colleagues (2012), seven- to eight-month-old infants were exposed to sequences of stimuli varying in complexity. The participants were less likely to look away from the screen for sequences whose complexity was intermediate, i.e., neither too low nor too high. This result suggests that infants' overt attention is attracted by stimuli which elicit a high, or perhaps even optimal, rate of learning (see also Poli et al., 2020). By being attracted to stimuli which are a little more complex than the ones that they have already learned, infants might engage in sequences of learning episodes that gradually increase in complexity, thus making it possible to learn complex information and abilities step by step.

Infants' reaction to surprising stimuli also suggests some sensitivity to their learning consequences. When an outcome is surprising, and thus differs from agents' expectations, the surprised agents can learn from the disagreement between reality and expectations by adjusting their predictions and behavior. Many classic experimental methods from infancy research — the so-called novelty, habituation or violation of expectation paradigms— capitalize on infants' response to surprising events (e.g., Aslin, 2007). Indeed, infants and children show changes in looking time behavior (Baillargeon, 2004; Sim & Xu, 2017), in pupil dilation (Jackson & Sirois, 2009) and brain electrical activity (Berger et al., 2006) when observing an event that is inconsistent with their predictions or expectations. In a famous study conducted by Stahl and Feigenson (2015), eleven-month-old infants were shown scenes involving objects defying physics' property of solidity and spatiotemporal continuity, e.g., a ball which seems to have passed through a wall. Results revealed that infants are more likely to learn novel properties of an object when the latter has been involved in a surprising event. Thus, infants allocate more overt attention to surprising events, and surprise enhances their learning.

Altogether those results indicate that infants are sensitive to the learning consequences of stimuli. The cognitive mechanisms underlying such sensitivity are yet to be fully elucidated.

They may involve representations of informativeness per se. Alternatively, they may rest on monitoring factors that correlate with the informativeness of stimuli, such as their familiarity, or their processing costs. One goal of this PhD thesis is to determine more precisely what kind of cognitive mechanisms support young children's sensitivity to the informativeness of stimuli. While a capacity to react to the learning consequences of stimuli emerges early in infancy, unambiguous evidence for representations of informativeness has been reported only much later, by four years of age.

2 Representing and anticipating the informativeness of stimuli

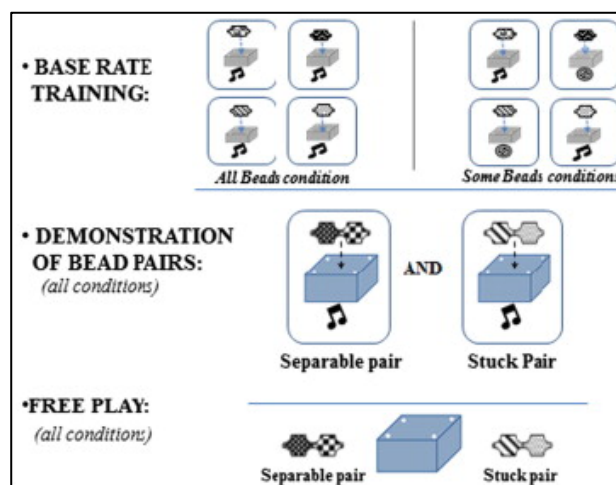
Two strands of literature provide evidence for four-year-old children's capacity to represent the informativeness of stimuli, and to plan actions whose goal is to gather informative evidence. First, preschoolers anticipate the informativeness of data gathered from specific perceptual sources. When they have to choose between two sources of information, four-year-old preschoolers choose the most appropriate one depending on their learning goals (Fitneva et al., 2013; O'Neill & Chong, 2001; Pillow, 1993; Robinson et al., 2008), a capacity that improves as they grow up (O'Neill et al., 1992; Perner & Ruffman, 1995; Robinson et al., 1997). For instance, in a study by Robinson, Haigh and Pendle (2008), participants were asked to determine the identity of a toy hidden in a tunnel cardboard. The participants had to choose between touching the toy, or seeing it. Depending on the trial, the identity of the toy could be determined either by seeing its color, or by feeling whether it was hard or soft. In this study, four-year-old preschoolers were able to choose the appropriate source depending on the type of information they needed to identify the toy (e.g., they were more likely to look at the toy by lifting a curtain when the toy could be identified by its color, than when it could be identified by its hardness). These results reveal two distinct capacities in preschoolers. First, they suggest that children know that a given action can give them access to a specific perceptual source (e.g.,

they know that lifting a curtain to look inside the tunnel can provide them with visual access to the color of the toy). Second, these results suggest that preschoolers take into account the relevance of a perceptual source to judge between specific hypotheses (e.g., they are more likely to try to see the toy when visual data is informative to identify it). In short, these studies suggest that four-year-old preschoolers already have the capacity to anticipate the informativeness of a perceptual source.

Preschoolers' capacity to anticipate the informativeness of their action is also evidenced by studies of exploratory behaviors, which investigate children's behaviors when faced of surprising information, or with ambiguous evidence (Cook et al., 2011; Ruggeri, Swaboda, et al., 2019; Schulz & Bonawitz, 2007; Siegel et al., (in press); Van Schijndel et al., 2015). These studies suggest that preschoolers explore more when they are uncertain. For instance, in the study of Schulz and Bonawitz (2007) four- to five-year-old children were more likely to explore a familiar toy, over a new one, when the familiar toy generated confounded evidence about its causal structure. Moreover, by four years of age, children do not explore indiscriminately. They preferentially engage in actions allowing them to reduce their uncertainty. In a study by Cook and colleagues (2011), four-year-old children observed that pairs of novel beads activated a toy when placed on top of it (thereby making it ambiguous which bead worked). Some of the novel pairs of beads could be separated, while others could not (see Figure 3). When given the opportunity to manipulate the novel beads themselves, four-year-old children were more likely to perform an informative action that disambiguated the evidence. Namely, they were more likely to reach for the beads that could be separated and to place them individually on the machine when they knew that some beads (but not others) activated the toy, than when they knew that all beads activated the toy. Thus, by four years of age, children seem able to select which action might specifically allow them to reduce their uncertainty over a set of hypotheses.

Figure 3

Procedure of the Cook and Colleagues' Experiment (2011).



Other studies examined preschoolers' sensitivity to informativeness in a pedagogical learning context, by testing how they assess informants (Gweon et al., 2014), and how they formulate questions (Legare et al., 2013; Ruggeri et al., 2017). These studies suggest that by four years of age, preschoolers have the capacity to evaluate the informativeness of teachers, and that they rate teachers who are more informative as more “helpful” (Gweon et al., 2014; Gweon & Asaba, 2018). Moreover, as shown in experiments by Ruggeri and colleagues (2017), five-year-old children can identify the most effective type of question to reduce their uncertainty about the reasons why a fictional character (Toma) was late for school over several days. These data suggest that by five years of age, children take into account the future informativeness of answers when deciding which question they should ask.

Overall, the studies reviewed above indicate that by four years of age, children can plan appropriate actions in order to reduce their uncertainty over a set of hypotheses. In contrast, evidence about the early ontogeny of the capacity to evaluate and plan informative actions is mixed. First, four- and five-year-olds' understanding of the specific type of information to be acquired from a particular perceptual source, such as seeing or feeling, is still incomplete (O'Neill et al., 1992; O'Neill & Chong, 2001; Pillow, 1993). Moreover, children have robust

difficulties to identify and to report the source of their beliefs (Gopnik & Graf, 1988; Wimmer et al., 1988). O'Neill and Chong (2001) provide an example of such surprising mistakes: “*To watch a child sniffing a swimming pool and tell you that is how they found out it contained cold water is quite striking!*” (p 812-813). Second, the capacities to identify appropriate perceptual sources of information, to select relevant questions, and to evaluate the informativeness of teachers have all been found to increase during the preschool years (Gweon & Asaba, 2018; O'Neill et al., 1992; Perner & Ruffman, 1995; Robinson et al., 1997; Ruggeri et al., 2017). Thus, the current state of the art leaves it open whether before four years of age, children might be able to anticipate the informativeness of future perceptual inputs.

In fact, very few studies have tested children's capacity to anticipate the informativeness of an input before four years of age. This research lacuna comes, to a large extent, from researchers' reliance on verbal measures, that cannot be used easily with young children. Moreover, this research lacuna may originate from the previously firmly established belief that children would not monitor the causal origins of their own beliefs before developing a full-fledged ability to represent mental states, around four years of age (Gopnik & Graf, 1988; Perner, 1989). This view has been challenged by research which suggests that two key components of information search might develop earlier than previously thought : the capacity to monitor one's own learning, and the capacity to represent one's own ignorance.

3 The ontogeny of representations of informativeness: early or late?

In order to form the goal of seeking information, children must be able to represent their own ignorance, and how to fill gaps in their knowledge. Importantly for a very long time, it was believed that infants and young children's capacity to monitor their own cognition (otherwise known as metacognition) was very limited (Brown, 1978; Flavell & Wellman, 1977). Therefore, it was implausible that before four years of age, children possess the necessary

cognitive abilities to represent their own mental states—thus making it impossible for them to represent what might be informative for themselves. This view has been challenged by recent evidence.

A sizeable body of evidence suggests that young children are sensitive to their own uncertainty by an early age (for a review see Goupil & Kouider, 2019). These studies reveal that children behave differently when they are ignorant than when they are knowledgeable, in opt-out paradigms allowing children to skip trials (Balcomb & Gerken, 2008), or ask for help (Bazhydai et al., 2020; Coughlin et al., 2015; Goupil et al., 2016), in information-seeking paradigms allowing children to search for information before answering (Call & Carpenter, 2001; Kloo et al., 2017; Ruggeri, Swaboda, et al., 2019), and in other experimental designs measuring physiological measure as the pupil dilation (Paulus et al., 2013). For instance, in the study by Goupil and colleagues (2016), twenty-month-old toddlers had to memorize the location of a hidden toy. In an experimental condition, toddlers could turn toward their caregiver to ask them for help. Compared with a control condition in which the caregiver was instructed not to provide any help to their child, toddlers given the opportunity to receive help used this option strategically to improve their performance (i.e., they used this option selectively to avoid making errors). Similarly, in a study by Call and Carpenter (2001) two- and three-year-old toddlers had to search for a sticker hidden in one of several tubes. Depending on the condition the participants witnessed the action of hiding the bait or they did not. When toddlers knew the location of the sticker, they selected the correct tube. In contrast, when they were ignorant about the reward's location they explored the tubes' contents by looking inside them before selecting one tube.

Moreover, children express their ignorance from an early age. Before their second birthday, infants produce the flip gesture i.e., a gesture characterized by the lifting and outward rotation of both hands and the shrugging of the shoulders (See Figure 4). Such body expression

of ignorance was spotted firstly by Acredolo & Goodwyn (1988), then specifically investigated by Bartz (2017) who observed fourteen-month-olds using the flip gesture to communicate their ignorance and eighteen-month-olds associating it with the corresponding utterance “*I don’t know*”. For instance, when a caregiver questioned a child about an object location, “*Do you know where is X?*”, the ignorant child responded with a flipping gesture. The caregiver observed the flip and asked, “*You don’t know?*”, the child answered with a head nod. By two years of age, children use the verb “know” appropriately in conversations; and they specifically utter the sentence “*I don’t know*” to express their ignorance (Bartz, 2017; Harris, Ronfard, et al., 2017; Harris, Yang, et al., 2017). Three-year-old children can explicitly assess their own and other people’s knowledge when no informational access or a full informational access is granted to the individual whose knowledge is evaluated (Pratt & Bryant, 1990). Thus, young children appear to be sensitive to their own uncertainty, at least in certain circumstances. However, the kind of cognitive process underpinning this sensitivity is a matter of debate.

Figure 4

Shrugging Woman Emoji to Indicate a Lack of Knowledge on Numerical Keyboards.



Indeed, several studies reveal striking gaps in children’s capacity to monitor their own ignorance. In one of the experiments conducted by Rohwer and colleagues (2012), 3- to 7-year-old children had to tell whether they knew the identity of an object hidden in a box. Depending on the condition, the participants had no clue about what was in the box, or they knew that it was one of two specific toys (but did not know which one). By three years of age,

children appropriately acknowledged their ignorance about the hidden toy's identity when they had no information at all about what was in the box. In contrast, before six years of age, children tended to overestimate their knowledge when they were only partially ignorant i.e., when they did not know which toy was the hidden out of two (see also Kim et al., 2016; Kloo et al., 2017).

Two types of accounts have been developed to explain children's difficulty to monitor their partial ignorance. A first type of account posits that young children lack crucial abilities to represent mental states. Several authors suggest that before the age of four, young children might not have a full-fledged metacognitive awareness of their own ignorance (Kloo et al., 2017; Perner, 2012; Rohwer et al., 2012). A second type of account posits that before the age of four, children have difficulties representing several alternative possibilities. Some of these accounts posit that maintaining simultaneously the representation of several possibilities is simply too hard for young children (Robinson et al., 2006). Other authors argue that young children would lack the conceptual resources to mark representations as merely possible, thus making it impossible for them to represent several alternative possibilities (Leahy & Carey, 2020).

These hypotheses come with strings attached about the way the search for information might operate in young children. They imply that before four years of age, children should not be able to select which action is relevant to reduce their uncertainty over a set of hypotheses. Instead, the view that young children do not monitor the causal sources of their beliefs imply that when they are ignorant, children will use generalized exploratory strategies. Such strategies would be triggered whenever the child is ignorant, regardless of the availability of information in the environment (see e.g., Kloo et al., 2017; Perner, 2012; Rohwer et al., 2012). In the words of Kloo and colleagues (2017): *“information-seeking responses [...] are early adaptive strategies to a lack of knowledge or uncertainty. These responses are automatically triggered whenever children are in a state of ignorance. For instance, when looking for an*

object knowing that it is in a room but not where in the room, one naturally goes to the room and then explores the room to spot the object. One does not need to reflect on one's ignorance about the object's precise location". Similar claims have been made to account for children's and non-human primates' reaction to their own ignorance in a variety of settings (Carruthers, 2008; Crystal & Foote, 2011; Hampton, 2009; Marsh, 2014).

The view that young children cannot represent several alternative possibilities (Leahy & Carey, 2020; Robinson et al., 2006), implies that when evidence is compatible with several mutually exclusive hypotheses, children under four simply pick one of them, and behave as if it were true. In some circumstances, such process could result in behaviors that, for an external observer, may appear to be information search. However, such behaviors would not involve any representation of informativeness. Leahy and Carey (2020) provide an explicit depiction of such a process (in their example the learner is a chimpanzee, however their argument can be applied to young children as well): *"In contexts where possibilities can be considered and rejected in sequence, minimal representations of possibility will often work fine. For many goal-directed actions, such as a young chimpanzee searching for its mother, it will suffice to generate a guess and act on it. If the guess proves false, the chimpanzee can generate a new guess and repeat the process until the goal is met. Its guesses can be guided by the facts it knows about the actual world (e.g., how often its mother has been in various locations). This requires that the chimpanzee represents the spatial layout of the forest it lives in; that is, knowledge it needs for navigation, foraging, and many other purposes. It need not mark every location in the forest as a potential place where its mother might be found; that is, it need not build multiple, incompatible models of a single present reality. It can draw on a single model of reality (of the forest, and frequencies of past encounters with its mother) to generate a prediction of where its mother is. If it goes to that location, and finds it empty of its mother, it simply generates a new prediction and searches there."*

In short, there is a debate about whether before four years of age, young children might be able (i) to represent their own ignorance, and (ii) to appropriately anticipate the informativeness of future stimuli in order to plan efficient and flexible information search. On the one hand, two-year-old toddlers behave differently depending on whether they are ignorant, or knowledgeable (e.g., Call & Carpenter, 2001; Goupil et al., 2016), and infants are sensitive to the learning consequences of stimuli (e.g., Kidd et al., 2012; Poli et al., 2020; Stahl & Feigenson, 2015). These results make it possible that young children might be capable of representing and anticipating the informativeness of a given stimulus. On the other hand, several authors have argued that before four years of age, young children might lack crucial abilities that are required to represent one's own uncertainty over a set of hypotheses (e.g., Kloo et al., 2017; Leahy & Carey, 2020; Robinson et al., 2006). These accounts predict that before four years of age, children should not be able to select the most informative actions to fill gaps in their knowledge i.e., the actions that are most likely to reduce their uncertainty over a set of hypotheses.

The first article of this PhD thesis addressed this debate empirically. It presents three different studies in which the participants were always ignorant about the same piece of information. In each of the studies, the amount of learning benefits resulting from a specific target action was modulated across conditions. Importantly, we measured the latency with which our participants performed this target action in order to have an estimate of our participants' capacity to anticipate the learning consequences of their action. This measure of anticipation enables us to cast light on the debates about young children's metacognitive capacities, more precisely their capacity to represent cognitively informativeness. If our participants use a fixed information-seeking heuristic (Kloo et al., 2017; Perner, 2012), or if they cannot represent alternative possibilities (Leahy & Carey, 2020; Robinson et al., 2006), they should behave similarly in all conditions. On the other hand, if our participants flexibly

plan their information search by anticipating the learning outcomes of their actions, they should be faster to engage in a given behavior when it yields learning benefits. Our first study tests fourteen-month-old infants' capacity to anticipate the availability of sight and the second and third study investigates toddlers' capacity to anticipate the cognitive utility of sight.

To anticipate, the results showed that infants and toddlers flexibly searched for information in all the studies reported in the first article. These studies indicate that representation of informativeness guide young children's individual learning by an early age. In subsequent studies, we investigated whether young children's capacity to represent the informativeness of stimuli may guide their social learning, in communicative contexts.

Informativeness and social learning

Alan Turing: “What if Christopher doesn’t have to search through all of the settings? What if he only has to search through ones that produce words we already know will be in the message?”

[...]

Joan Clarke: “Look! Look like this one. 0600 hours. Weather is clear. Rain in the evening. Heil Hitler.”

– *The imitation game (2014)*

In the movie scene cited above, Alan Turing and Joan Clarke are searching for a pattern to help a machine (named Christopher) to automatically decrypt coded messages sent by Nazis during World War II. Alan Turing and Joan Clarke eventually made a breakthrough in deciphering Nazis’ coded messages when they stepped out of a brute force coding-decoding strategy. Rather than trying to break to the code to determine what kind of message was transmitted, Turing and Clarke flipped the logic of interpretation on its head. They started to make hypotheses about what kind of message might be transmitted in order to crack the code (Zeitoun & Morain, 2012). Relying on context-driven inferences, they identified plausible messages that the Nazis might have conveyed (such as ritualized greetings, or information about the weather). By making much narrower hypotheses about the kind of information that might be transmitted, Turing and Clarke made the difficult problem of cracking coded messages much more computationally tractable. Eventually, this strategy paid off, thereby considerably influencing the course of the war.

The need to simplify the difficult task of discovering of what others communicate is a recurrent problem, one that is not only faced by cryptologists. As we will see, many theories

posit that humans address the challenge of interpreting what others communicate by making broad assumptions about communicating agents' goals, and about communicated information. In turn, these assumptions make it possible to narrow the range of hypotheses about what each particular instance of communication might convey, thereby facilitating its interpretation. One of these general assumptions is that by communicating, source of messages implies that what they convey should have cognitive benefits to their audience —otherwise, why should audiences bother processing communicated information at all?

As a result, many theories imply that a sensitivity to the cognitive benefits of stimuli may play a central role in the interpretation of communicated information. In the first article of this thesis, we gathered evidence for toddlers' capacity to represent the informativeness of stimuli for themselves, in a context of individual learning. The second part of the thesis investigates how the ability to represent the putative cognitive benefits of a stimulus may guide children's interpretation of communicated information. Note that throughout the thesis, the word "communication" is used refer to what is known as "ostensive communication", a specific form of information transmission uniquely developed in humans, where sources of messages convey information by making their intention to communicate manifest to their audiences (Sperber & Wilson, 1995).

1 Expectations about cognitive benefits guide the interpretation of communication

Communication is a crucial source of information and learning in humans, and it is ubiquitous in our social interactions. Humans' capacity to express feelings, needs, and to share knowledge communicatively are crucial to transmit skills and culture between individuals and generations (e.g., Csibra & Gergely, 2009; De Oliveira et al., 2017; Harris, 2012). Remarkably, human communication is extremely flexible, and can come in different shapes such as points, vocalizations (including language), hand signs, nods and more generally any physical act that

someone can perform. For instance, the simple intention of sharing the information “*I am happy to see you, I wish you a good day,*” can be expressed to someone by waving a hand, or smiling at the person, or saying, “*Good morning!*”. As a result, interpreting what others communicate raises deep challenges. Several theories posit that such a difficult problem can be simplified by relying on expectations about the cognitive utility of communicated information. These theories imply that the capacity to represent the cognitive benefits of a piece of information, such as its capacity to reduce one’s uncertainty over a set of hypotheses, might play a key role in guiding the interpretation of speakers’ meanings.

For instance, Paul Grice (1989) developed an influential theory describing how individuals might interpret what is communicated to them in a context-sensitive fashion. According to the so-called Cooperative principle, speakers and listeners are supposed to cooperate together toward a common conversational goal to enable an efficient communicative exchange. To do so, the speakers are expected to obey four conversational maxims, namely maxims of (i) quality —tell the truth, (ii) quantity —do not say too much or too little, (iii) relation —be relevant, and (iv) manner —be clear and concise. In most cases speakers are supposed to follow these maxims, thereby providing listeners with a sufficient basis to infer their intended meaning (Grice, 1975). These conversational maxims imply that the messages conveyed through communication to a receiver should be cognitively useful, for instance, appropriately informative.

Grice’s theoretical account of communication has sparked many debates and numerous objections, resulting in the development of altered, refined, and more fine-tuned theories. One of these post-Gricean theories named Relevance theory attempts to develop a cognitive account of human communication (Sperber & Wilson, 1995). This approach posits that the interpretation of communication is not based upon a multiplicity of maxims, but on a principle of relevance. Sperber and Wilson (1995), define the “relevance” of a piece of information in a

technical manner, whose meaning is equivalent to the notion of cognitive utility. According to this definition, the higher the positive cognitive effects of a piece of information, and the lower its processing costs, the higher its relevance. Relevance theory posits a cognitive principle of relevance which assumes that, due to evolutionary pressures, cognition tends to be geared toward the maximization of relevance. This general property of cognitive mechanisms would be exploited in communicative contexts to guide the interpretation of speakers' meanings via a communicative principle of relevance. The latter assumes that every instance of verbal and non-verbal ostensive communication conveys the presumption that it is relevant enough to justify processing it. To illustrate, as you are reading those lines we are communicating; the existence of this manuscript (even before you read it) conveys the presumption that it is sufficiently relevant for its potential readers. On the production side, I did my best to present my work in order to convey cognitively useful information to my readers, while making this information as easily accessible as possible (at least, I hope so). Subsequently, positing that I wrote this manuscript trying to make it relevant for my readers, your interpretation of these lines can be guided by the presumption they are relevant to you.

Thus, in Sperber and Wilson's framework (1995), every act of ostensive communication carries a presumption of high, if not optimal, relevance. As a result, when interpreting a speaker's utterance, listeners would follow a path of least effort by considering interpretation in decreasing order of accessibility, and would settle on an interpretation when their expectations of relevance are satisfied. Subsequently, relevance theory implies that listeners interpret communication by postulating that it is sufficiently informative. Indeed, the informativeness of a stimulus, defined as the capacity of a stimulus to reduce one's uncertainty, can contribute to its cognitive effects (note, however, that in this framework, informativeness is just one of the many properties that contribute to the relevance of a piece of information).

Other influential theories imply that the interpretation of communicated information can be guided by expectations about informativeness, such as the recent Rational Speech Act theory (also called RSA). When elaborating this theory, Frank and Goodman built on insights from Gricean's theories and on tools from Bayesian cognitive modeling, resulting in a probabilistic model of the interpretation of communicated information (Frank, 2016; Frank & Goodman, 2012, 2014). They propose a model of probabilistic calculus representing an agent's uncertainty about the interpretation of utterances, within a structured hypothesis space. In other words, in this model "*The posterior probability of some referent is proportional to the product of two terms the likelihood [...] that some words are used to describe a referent and the prior probability [...] that this referent will be the subject of discourse*" (Frank & Goodman, 2014).

According to this theory, listeners and speakers attempt at achieving their communicative goals in a rational fashion, by recursively reasoning about each other's mental states. More specifically, a listener would use Bayesian inference to interpret utterances by reasoning about a cooperative speaker's attempt to inform them, by assuming that speakers choose their utterance so that the listener can recover their intended meaning. Subsequently, expectations of informativeness play a central role in RSA theories.

In short, despite their differences, key theories about the way communication is interpreted and contextually enriched, such as Grice's framework, Relevance theory, and the Rational Speech Act theory imply that expectations about the informativeness of a piece of information may contribute to guide the interpretation of speakers' meanings.

Having found that young children can represent the informativeness of stimuli by two years of age (Article 1) makes it plausible that they may rely on such capacities to interpret novel communicative cues. This hypothesis receives some indirect support by recent data (reviewed below). These recent discoveries suggest that (i) humans interpret communicated information in an inferential and context-sensitive manner from infancy, and that (ii) in some

contexts, young preschoolers evidence a sensitivity to the informativeness of communicated information.

2 Children's early pragmatic abilities

A growing body of evidence suggests that children interpret communicated information not just by extracting pre-established lexical information, but also by drawing inferences in a context-sensitive fashion. In other words, children's pragmatic abilities develop very early. Indeed, infancy onward, children are sensitive to ostensive cues signaling an intention to communicate (Csibra, 2010; Esseily & Fagard, 2013; Gergely & Jacob, 2012). From six-month-old of age, infants seem to understand that speech (novel nonsense words) can communicate information about speakers' intentions (Martin et al., 2012; Vouloumanos et al., 2012, 2014). Thus, from infancy onward, children's interpretation of communicated information goes beyond extracting pre-encoded lexical meanings. Moreover, by early toddlerhood, children interpret differently the exact same communicative action depending on what a speaker knows, can see, or believes (Nurmsoo & Bloom, 2008; Southgate et al., 2010; for a review see Mazzarella & Pouscoulous, 2020). By three years of age, children are already capable of understanding sophisticated forms of figurative language like metaphors and metonyms for instance (Falkum et al., 2017; Pouscoulous & Tomasello, 2020). Such an ability to process figurative language reveals children's capacity to enrich their interpretation of speakers' meaning beyond lexical knowledge. In short, children interpret communicated information in an inferential and context-sensitive manner from infancy onward. Whether such a capacity rests on expectations about the informativeness, and more broadly, on expectations about the cognitive utility of communicated information (as postulated by the Gricean and neo-Gricean approaches reviewed above) remains to be established.

On one hand, a body of work suggests that humans' sensitivity to general communicative principles (such as Grice's maxims) may develop late. In fact, Grice's theory has triggered a lot of experimental investigations, including developmental studies (see Noveck & Reboul, 2008). For instance, Conti and Camras (1984) presented children with a story with two alternative endings. Six- and eight-year-old children succeeded in identifying the ending which violated Grice's conversational maxims of Quantity —they detected underinformative utterances, Quality —they rejected false statements, and Relation —they spotted irrelevant endings. Moreover, Ackerman (1981) found that it was not until eight years of age that children could generate correct explanations for speakers' violations of the maxims of Quantity or Relation. Other studies evaluated children's sensitivity to communicative principles such as the Quantity maxim through the understanding of logical terms. To illustrate, the word "some" can be interpreted as compatible with "some *and* all" in formal logic, while it may mean "some but *not* all" in an ordinary communicative context. Indeed, in daily life, using the scalar "some" to convey its logical meaning may result in being underinformative, which violates the Quantity maxim. Note that the interpretation of "some" either logically or pragmatically doesn't depend on a particular language nor on a number of language one can understand (Dupuy et al., 2019). Crucially, sentences like "Some giraffes have long necks", where "some" is interpreted as compatible with "all", are accepted until seven years of age (Guasti et al., 2005; Katsos & Bishop, 2011; Noveck, 2001; Papafragou & Musolino, 2003). Similarly, seven- and nine-year-old children favor the logical interpretation of the scalar term "or" (e.g., p or q and perhaps both) over the pragmatic one (e.g., p or q but not both; Braine & Romain, 1981). Altogether, these results indicate that children's sensitivity to speakers' informativeness continues to develop into late childhood.

On the other hand, an influential body of work suggests that younger children already take into account properties of communicated information, such as its informativeness, to

evaluate and interpret utterances. For example, in a study by Eskritt, Whalen and Lee (2008) preschoolers played a guessing game where the goal was to find a sticker hidden under one of four containers. The children were familiarized with two puppets who provided them with utterances about the location of the stickers. One of the puppets always adhered to the maxim being tested, while the other always violated it (e.g., in the quantity condition, the Gricean follower provided sufficient information by saying “*it’s under the blue cup*”, while the Gricean flouter did not provide enough information by saying, “*it’s under a cup*”). Next, during the test phase, children had to choose which puppet to ask for help. Four- and five-year-old children chose the puppet that adhered to the Gricean maxims more often than predicted by chance in at least one of the experimental blocks. Thus, by this age, children were sometimes sensitive to violations of the Quantity, Quality and Relation maxims. One reason why children performed better in this study than in other tests of children’s sensitivity to Gricean maxims (such as Conti & Camras, 1984) might be that the procedure of Eskritt and colleagues (2008) measured their implicit evaluation of violations of maxims, rather than asking for an explicit evaluation of someone’s behavior.

Other studies have revealed that humans’ sensitivity to conversational maxims might develop earlier than previously thought. For instance, Pouscoulous and colleagues (2007) provided evidence for four- to five-year-old children’s capacity to use the Quantity maxim to understand the scalar term “some”, translated in a frequently used equivalent in French. Likewise, Matthews, Lieven and Tomasello (2010) revealed a sensitivity to the maxim of Manner by three-year-old, and Pellegrini, Brody, and Stoneman (1987) found that two-year-olds rarely violated the maxims of Quality and Manner when they were producing an utterance themselves. Several studies also provide evidence for children’s capacity to use expectation of informativeness to guide their comprehension of novel labels by three years of age (Bohn, Tessler, Merrick, et al., 2019; Frank & Goodman, 2014) in accordance with the three main

communication theories previously introduced (Grice's theory, the Relevance theory and the RSA theory).

Altogether those results suggest that children's capacity to take into account the cognitive utility of information to interpret the speaker's meaning increases with age. Yet, they also reveal that children's reliance on expectations about the informativeness of communicated information guide their interpretation of meanings by three years of age. Moreover, in our studies of information search, we observed that by two years of age, toddlers can represent and anticipate the cognitive benefits of a stimulus for themselves (see Article 1). Consequently, we hypothesized that by their second birthday, children may be able to use their capacity to prioritize informative interpretations of novel cues in a communicative context. In the second article of this PhD thesis, we directly tested this possibility. This set of studies revealed that toddlers do prioritize interpretations of novel cues that have high cognitive benefits (i.e., that are informative and accurate) and low processing costs. Next, we investigated whether children might interpret novel communicative signals using expectations of informativeness during infancy (Article 3). These studies confirm that young preschoolers rely on expectation of informativeness to interpret novel communicative cues. In contrast, they suggest that at eighteen months, infants' reliance on expectations about the informativeness of speakers is much weaker. It appears to be masked by other word learning strategies, such as tracking co-occurrences between labels and potential referents. The first three articles of this PhD thesis focused on young children's capacity to represent the informativeness for themselves, in non-social and social contexts. The fourth article turned to the representation of what is informative for other people.

Representing information search in others, and interpreting questions

“When will Disneyland reopen?”

– *A Disney fan (2021)*

When communicating, cooperative speakers attempt at conveying relevant information to their audience. Yet, determining what kind of information may be relevant to someone is extremely hard. For instance, determining whether a person wants to know about the reopening date of Disneyland amusement parks is almost impossible to guess before the person asks a question about it. Thus, questions play a crucial role in making it easier to determine what kind of information may be desirable for others. In order for questions to play this role, they must be understood appropriately, which is a challenging task. For instance, depending on who asks the question, there are multiple possible answers to the utterance, *“When will Disneyland reopen?”*. When asked such a question, addressees may want to offer the most appropriate possible answer, i.e., one which is sufficiently relevant to the questioner. To do so, the respondents can consult, among other things, their knowledge of what the questioner already knows (e.g., if the questioner already knows that the amusement parks will reopen at some point in June 2021, answering *“in June 2021”* would not be informative). Thus, replying appropriately to a simple question such as *“When will Disneyland reopen?”* may require identifying over which hypotheses the questioner is uncertain. In other words, representing speakers’ uncertainty, and representing what may be informative for them is crucial to interpret questions. The fourth article of this PhD thesis investigates how humans represent information

search in others, and how these representations guide the interpretation of questions. Here, the word “question” is used to refer to request for information that is conveyed in a communicative manner, typically through interrogative sentences. As we will see, the capacity to communicatively request information supports development from an early age.

1 Children’s capacity to request information

The ability to request information from others and to gather relevant answers is an important mechanism for cognitive development, one that allows children and infants to access information they would have not discovered on their own (Chouinard, 2007; Harris & Koenig, 2006; Tomasello, 1999). By asking questions appropriately, children can gather specific pieces of knowledge precisely when they need them (Baldwin & Moses, 1996; for reviews on children’s capacity to ask relevant questions see Chouinard, 2007; Harris, Bartz, et al., 2017; and Ronfard et al., 2018). Remarkably, there is some evidence that very young children can request information in a communicative context (Begus et al., 2014; Begus & Southgate, 2012; Chouinard, 2007; Kovács et al., 2014; Vaish et al., 2011). By twelve months of age, infants already request information by pointing. For instance, in a study by Kovács and colleagues (2014, experiment 2), twelve-month-old infants were presented with objects that were atypical members of a known category (e.g., a cat wearing boots). An experimenter reacted by labeling the objects when the infants pointed at them. Crucially, the experimenter labeled the atypical objects with a familiar word (“*a kitty*”) in the Sharing condition, or with a novel one (“*a dax*”) in the Informing condition. In this study infants pointed more frequently across trials when the experimenter responded to their pointing by communicating new information (in the informing condition) rather than something that they already knew (in the sharing condition). Furthermore, by their second year of life, children already request information using a variety of interrogative sentences (Callanan & Oakes, 1992; Chouinard, 2007; Kemler Nelson et al., 1995).

Young children do more than requesting information. They seem to have some sensitivity to the appropriateness of answers. To illustrate, eighteen-month-old infants persist more often in asking a question if the answer they receive does not satisfy their expectation than if it provides them with relevant information (Chouinard, 2007; Frazier et al., 2016). Thus, young children seem to ask questions with the goal of obtaining relevant information. Moreover, by the age of five, children's questions are strategically formulated to acquire specific pieces of information efficiently (Chouinard, 2007; Greif et al., 2006; Kemler Nelson & O'Neil, 2005; Mills et al., 2010, 2011; Ruggeri et al., 2017, 2021; Ruggeri, Xu, et al., 2019). Such capacity was evidenced by Ruggeri and colleagues (2021), who used some variant of the 20-question game (Mosher & Hornsby, 1966). In this paradigm, participants had to identify which kind of monster (among 16) activated a machine, by asking as few yes-no questions as possible. Monsters were hierarchically organized in 3 nested categorical levels and children could ask only 10 questions. Children could ask hypothesis-scanning questions (which target an individual monster) or constraint-seeking questions (which target a feature shared by multiple monsters). By five years of age, children were able to strategically choose which kind question they had to ask in order to reduce the overall number questions needed to win the game. Thus, children are able to select questions that are appropriate to collect the specific pieces of information they need.

To put it in a nutshell, requesting information from others by asking questions plays a central role in communication and constitutes an important tool for learning. Even before they can talk, infants successfully request information using non-verbal behaviors, such as pointing. As they grow older, children quickly manage to use verbal questions to learn from others. By five years of age, children's questioning is strategic, and optimizes information gains. While children have some capacity to request information, they also have early developing abilities to detect and answer questions.

2 Children's capacity to answer questions

Infants detect interrogative sentences from an early age. They can use prosodic and syntactic cues to discriminate declarative sentences from interrogative ones. English-learning infants seem to use prosodic rising pitch cues combined with word order to distinguish interrogative sentences such as yes-no question from declarative sentences (Geffen & Mintz, 2011; Soderstrom et al., 2011). Five-month-old learners of European Portuguese distinguish interrogative sentences from declarative ones purely on the basis of prosodic cues and they maintain this sensitivity throughout the first year (Frota et al., 2014). Moreover, English-learning twelve-month-old infants are also able to use the syntax of *wh*-questions to discriminate declarative sentences from interrogative ones (Geffen & Mintz, 2015). By three years of age, children answer appropriately a variety of different types of questions, including questions to be answered by yes or no, and *wh*-questions — starting with what, where, who, etc. (Moradlou et al., 2021).

A few studies also indicate that children can also interpret questions flexibly. Interrogative sentences can serve many different communicative purposes. They can be used to formulate genuine requests for information, but also to raise rhetorical questions (e.g., “*Is this supposed to be some kind of a joke?*”), to ask test questions (questions whose answer is already known to the questioner, used to assess someone’s knowledge e.g., a teacher asking, “*how much is 2 + 3?*” to a pupil) or to make indirect requests (“*Can you pass me the salt?*”). Such studies have revealed that before their third birthday, children already interpret interrogative sentences in a flexible manner. For instance, toddlers distinguish genuine questions from test questions (Grosse & Tomasello, 2012). Interestingly, studies of the context-sensitive interpretation of interrogative sentences have primarily focused on the mechanisms allowing children to determine that interrogative sentences are *not* used to request information.

This thesis takes the opposite stance, by focusing on the mechanisms that are used to interpret interrogative sentences when they are used to convey requests for information.

3 Interpreting question by representing information search in others

In order to interpret requests for information appropriately, one needs to reason about what kind of information others might search for. The simplest strategy to address this issue would be to assume that others search for information that oneself would search for as well. This egocentric strategy may be efficient, up to a point. However, it should fail when the knowledge of the questioner and of the respondent differ (which, in all likelihood, should often be the case, for instance when the respondent actually knows what the questioner is asking for). One study by Nurmsoo and Bloom (2008) suggests that by two years of age, children go beyond such an egocentric strategy: they take into account what is known to an adult when interpreting her questions. In this task, two unfamiliar objects were first visible from both the participant and the experimenter; then, the experimenter placed one of the objects in a location where it was no longer visible from her viewpoint, while remaining visible to the child. Next, the experimenter left the room, and during her absence the second object was hidden by a second experimenter, thus resulting in both objects being accessible visually for the participants and hidden from the experimenter's point of view. During the test phase, the first experimenter came back, and she asked ambiguously for information about the location of one object, using a novel pseudo-word (e.g., saying, "*Where is the dax?*"). Surprisingly, toddlers correctly selected the object whose location was unknown to the experimenter even if they themselves could see both objects. Thus, by two years of age, children do not use a purely egocentric strategy to determine what may be informative for others. Instead, they take into account what people know to interpret their requests for information. However, the nature of the

representations of knowledge and ignorance that guide the representation of information search in others, and the interpretation of questions, is not known.

On the one hand, individuals can only search for a piece of information once they are aware of lacking it. As a result, determining what kind of information others might search could involve tracking people's knowledge of their ignorance, in other words, their Socratic ignorance. Representing what people know that they ignore is far from trivial. It implies forming "second-order" meta-representation i.e., representing representations of representations (such as "*John knows that he ignores that p*", Wimmer & Perner, 1983). If this hypothesis were true, young children would rely on extremely elaborate representations of mental states when interpreting questions and representing information search in others. Alternatively, the interpretation of requests for information may be simplified by merely tracking what other people know or ignore (and not what they know that they ignore). The studies reported in the fourth article of this PhD thesis were designed to judge between these hypotheses by testing toddlers, children and adults.

In short, this PhD thesis investigates how active information-seeking, one of the most central function of cognition is implemented in young humans. It focuses on the capacity to represent the process of learning itself, by tracking the informativeness of stimuli. This ability is crucial because it allows humans to creatively search for information in a flexible manner. The first article of this PhD thesis reports three studies targeting toddlers' capacity to anticipate the informativeness of their own actions. It reveals that toddlers can use representations of informativeness to plan their search for evidence efficiently. Having shown that toddlers can use representations of informativeness to search information for themselves, we test how young children may use this capacity to learn in social contexts. The second and third articles of this PhD thesis test whether representations of informativeness guide the interpretation of novel

communicative cues during toddlerhood and infancy. They reveal that by toddlerhood, young humans prioritize interpretations of novel communicative cues that are sufficiently informative. Having shown that toddlerhood onward, humans rely on representations of informativeness to guide their own individual learning (including in social contexts), we turn toward how they represent what is informative for others, when interpreting requests for information. This last set of studies suggests that there are limits to the complexity of the fast and efficient representations of knowledge that humans use to track what kind of information others might search for.

Part II

Articles

Article 1

Knowledge in sight: Toddlers plan efficient epistemic actions by anticipating the availability and cognitive utility of vision

This research tested the ontogeny of the capacity to anticipate the amount of learning gained from seeing by manipulating whether performing the exact same behavior yielded access to relevant visual data. In Study 1, 14-month-old infants ($N = 72$) were invited to search for a toy hidden inside a container. The participants were faster to attempt at opening a shutter when this action allowed them to see inside the container — they anticipated the availability of sight. In Studies 2-3, two-and-a-half-year-old ($N = 72$) had to locate a character hidden among distractors. The participants were more likely and comparatively faster to engage in actions on the characters when they yielded access to visual data high on informativeness — they anticipated the cognitive utility of sight. These results suggest that cognitive models of learning guide toddlers' search for information. The early developmental onset of the capacity to track and anticipate the availability and cognitive utility of data are crucial bedrocks for active learning.

1 Background

Many species engage in behaviors that support efficient active learning (Kidd & Hayden, 2015). Even relatively simple invertebrates such as worms or bees search for food in ways that yield efficient learning through tradeoffs between exploration and exploitation (Calhoun et al., 2014; Jacqueline Degen et al., 2015). Crucially, efficient active learning can often be achieved through fixed behaviors triggered by the lack of specific information. These information-seeking heuristics do not require learners to anticipate if and when an action will result in learning. In contrast, humans can flexibly discover novel ways to search for information by representing and anticipating the learning outcomes of their actions. This capacity, which is likely to rely on cognitive models of learning, is crucial for (i) searching for information and (ii) teaching others (e.g., Bass et al., 2019; Bridgers et al., 2020; Schulz, 2012; Shafto et al., 2012, 2014). It also supports creative hypothesis testing, a cornerstone of human learning and science. Here, we investigate the early ontogeny of this capacity to anticipate the learning consequences of actions, focusing on the precocious ontogeny of humans' sensitivity to the (i) availability and (ii) cognitive utility of sight.

1.1 Sight as an Intuitive Model of Learning

Sight is associated with knowledge in many cultures (Bloch, 2008), and since Plato and Aristotle, it has been a central model and metaphor for learning in Western philosophy (Synnott, 1992). The importance of sight in naïve and formal epistemology has to do, we suspect, with the central role of vision in human learning, and in humans' core representation of knowledge. In a seminal study by Call and Carpenter (2001), two-and-a-half-year-old had to find a reward hidden in one of three opaque tubes. In some trials they could see in which tube the reward was hidden (seen condition) and in other trials, they could not see it (unseen condition). Most children crouched to look into the tubes before choosing one more frequently in the unseen

condition than in the seen condition (see also Neldner et al., 2015). In addition to human children, all four great ape species and some species of monkeys engage in efficient information-seeking behaviors by trying to see (Beran et al., 2013; Call, 2010; Call & Carpenter, 2001; Marsh & MacDonald, 2012; Rosati & Santos, 2016). In short, children use efficient behaviors to look for visual information, a capacity that is ontogenetically and phylogenetically ancient, and perhaps shared in part with non-human primates. We capitalize on this evidence to test young children's capacity to plan their search for visual information and to anticipate its learning outcomes.

1.2 Cognitive Models of Learning

Infants are sensitive to the amount of learning gained from sight from an early age. They look longer at stimuli that are unexpected (Stahl & Feigenson, 2015), of intermediate complexity (Kidd et al., 2012), or yield maximal learning (Poli et al., 2020). Thus, infants can use the properties of visual data that are already accessible to them to determine whether they should continue looking at a scene (exploit) or should start looking elsewhere (explore). However, in many cases, learners need to assess the learning consequences of future perceptual inputs, before they can access them. This capacity is crucial for planning goal-directed information search, e.g., when deciding what to do in order to access a specific piece of information that one is missing.

The planification of goal-directed search for information is likely to rely on a cognitive model of learning to allow individuals to anticipate the epistemic consequences of actions. This model should (i) be sensitive to the availability of data (e.g., while sight is a basis for learning, it is not always available, for instance, when vision is obstructed by opaque objects), and (ii) aim to maximize the benefits and minimize the costs of processing data by collecting pieces of evidence with high, if not optimal, cognitive utility (e.g., Oaksford & Chater, 1994; Sperber &

Wilson, 1995; Steyvers et al., 2003). Thus, we investigated infants' and toddlers' capacity to anticipate the availability and cognitive utility of sight.

1.3 Anticipating the Availability of Data

Tracking the availability of sight implies detecting the situational factors that specifically enable or impede seeing. For example, sight is influenced by opaque materials, whereas hearing is not. Thus, a sensitivity to the way opaque material might obstruct sight is instrumental to anticipate the availability of visual data. By five years of age, children adjust their information search behaviors to what constraints seeing. In one study, preschoolers had to locate a sticker hidden under an opaque or transparent cup. The participants could observe by peeking while an experimenter placed the sticker for the trial. By five years of age, the children peeked for longer in the opaque than the transparent condition (Iwasaki et al., 2020).

Very little is known about the development of humans' capacity to anticipate the availability of sight prior to five years of age. Yet, infancy research suggests that humans' sensitivity to what constraints seeing emerges early. Young children, infancy onward, are sensitive to what others can see, and use this ability appropriately during social interactions (Choi et al., 2018; Liskowski et al., 2007; Luo & Baillargeon, 2007; Moll & Tomasello, 2006; O'Neill, 1996; Sodian et al., 2007; Southgate et al., 2007). For example, Choi, Mou, and Luo (2018) reported that three-month-old infants differentially processed the reaching actions of an agent depending on what she could see. One-year-old infants begin to take into account opaque barriers when following gaze (D'Entremont & Morgan, 2006; Meltzoff & Brooks, 2008; Moll & Tomasello, 2004). By two years of age, toddlers manipulate others' visual access by hiding objects (Flavell et al., 1978; Mascaro et al., 2017), or making them visible (Mascaro et al., 2019). Furthermore, toddlers develop some sensitivity to the disabling role of opaque materials for their own sight, a capacity that they use to determine what is visible to others (Király et al.,

2018; Meltzoff & Brooks, 2008; Senju et al., 2011). In short, infants and toddlers track what others can see and are sensitive to the opacity of materials. Study 1 capitalizes on these phenomena to investigate infants' sensitivity to the constraints that specifically regulate access to visual data. We probe infants' capacity (i) to treat sight as a source of data for themselves, (ii) to determine whether an action will enable them to see an object (depending on the opacity of a window), and (iii) to adjust their information-seeking behaviors accordingly.

1.4 Anticipating the Cognitive Utility of Data

Although sight is a central basis for learning, seeing does not always lead to knowing. For example, sight is insufficient for discriminating between two distinct individuals who look identical. Thus, the appropriate use of sight in learning must be sensitive to its cognitive utility in a given context. As vision is a central source of learning in primate taxa, acknowledging that sight is not always a relevant source of data is not trivial. In fact, children and adults often overestimate the knowledge that results from gaining visual access to an object (Robinson et al., 1997; Wang et al., 2014).

Yet, previous studies on the ontogeny of learning actions suggest that by four years of age, children anticipate the relevance of data gathered from specific perceptual sources. Four-year-old preschoolers adjust their reliance on specific perceptual sources according to what they want to learn (Fitneva et al., 2013; O'Neill & Chong, 2001; Pillow, 1993; Robinson et al., 2008), and this capacity develops further during preschool years (O'Neill et al., 1992; Perner & Ruffman, 1995; Robinson et al., 1997). To illustrate, when given the choice between looking and asking someone to learn about a character's properties, four-year-olds are more likely to choose looking to learn about the visible properties (e.g., a character's hair color) than to learn about the invisible properties (e.g., what makes a character sick; Fitneva et al., 2013). Thus,

four-year-old are more likely to seek visual information when it is relevant to fill their knowledge gaps.

Studies 2 and 3 build upon this evidence to test comparable abilities in much younger participants, focusing on their capacity to track the cognitive utility of a visual input. We focused on informativeness, a dimension of cognitive utility, defined as the capacity of a stimulus to reduce uncertainty about a set of hypotheses (Frank & Goodman, 2012; Steyvers et al., 2003), uncertainty being quantified using the standard entropy measure from information theory (Shannon, 1948).

1.5 Operationalization Principle

Studies show that children are more likely to engage in information-seeking behavior when they are ignorant rather than knowledgeable about the location of target object that they have to find (e.g., Call & Carpenter, 2001; Ruggeri, Swaboda, et al., 2019). However, it has been suggested that in such experimental paradigms, the participants might be simply retrieving the target object directly when they know where it is, without exploring any other option or engaging in any other behavior. In contrast, when they ignore where the target object is, the participants might be more likely to engage in other behaviors than trying to retrieve the target, including (i) fixed behavioral routines or (ii) general exploratory behaviors (for variants of this argument, see Carruthers, 2008; Crystal & Foote, 2011; Hampton, 2009; Marsh, 2014; Perner, 2012).

Thus, since we wanted to focus on flexible learning, in our experimental conditions, the participants were *always* ignorant about the same piece of information. We modulated the amount of learning benefits resulting from the exact same action across conditions. We measured the latency with which our participants performed this action in order to have an estimate of our participants' capacity to anticipate the learning consequences of future

perceptual inputs. Thus, if our participants use a fixed information-seeking heuristic, they should behave similarly in all conditions. In contrast, if our participants flexibly plan their information search by anticipating the learning outcomes of their actions, they should be faster to engage in a given behavior when it yields learning benefits.

Study 1 investigated infants' capacity to anticipate the availability of sight. The participants enrolled in the experimental group were invited to search for a toy hidden inside a box. In the transparent condition, the participants could see inside the box by opening a shutter covering a transparent window. In the opaque condition, the window behind the shutter was opaque. Thus, in the opaque condition, opening the shutter did not allow infants to see inside the box. We measured the latency with which the participants tried to open the shutter. If infants anticipate the future availability of visual data resulting from opening the shutter, they should be faster to perform this action when it allows them to see inside the box (in the transparent condition) than when it does not (in the opaque condition). Studies 2 and 3 investigated toddlers' capacity to anticipate the cognitive utility of sight. The participants had to locate a target character hidden among others; we assumed that toddlers should be more likely and comparatively faster to engage in actions on the characters when they yielded access to visual data that was sufficiently informative to identify the target.

Data of all Studies and analysis scripts are accessible on an open repository (URL : https://osf.io/9jpmv/?view_only=7e6b6a4b36714fcea6a537f8bc21b557).

2 Study 1

2.1 Method

2.1.1 Participants

Study 1 required the participants to search for an object hidden in a container. Therefore, we chose to test fourteen-month-olds because by this age infants' capacity to adjust their search

behaviors to their beliefs about the presence of one or a few objects hidden in boxes is well established (Cacchione et al., 2013; Feigenson & Carey, 2003). Seventy-two fourteen-month-old infants were enrolled either in the experimental group (transparent condition: $n = 18$; $M = 13.8$ months, $range = 13-15$ months, $SD = 0.86$; opaque condition: $n = 18$; $M = 13.8$ months, $range = 13-15$ months, $SD = 0.68$) or in the control group (transparent condition: $n = 18$; $M = 13.7$ months, $range = 13-15$ months, $SD = 0.70$; opaque condition: $n = 18$; $M = 13.4$ months, $range = 12-14$ months, $SD = 0.62$). Each participant was tested only once, in a single condition. Sixteen additional participants were excluded from the analysis for the following reasons: refusal to cooperate (3), unwillingness to finish the experiment (3), caregiver interference (1), and technical failure (9). For all the Studies (1-3), the participants were recruited by sending an information letter through the participants' daycare centers. The participants lived in a large city area (Lyon, France), and they were of diverse socio-economic backgrounds. We used samples as large as possible, given the recruitment opportunities. A compromise power analysis performed using G*Power (Faul et al., 2007) revealed that the resulting sample sizes ($n = 18$ per group) yielded an implied power equal to .83 for between-group comparisons using Mann-Whitney U test ($d = .8$, $\alpha = .05$).

2.1.2 Materials and Set-up

Infants were tested in a quiet room and were accompanied by a caregiver who was instructed not to influence the participants' choices at any time-point during the test. The participants faced the experimenter across a table on which the testing materials were placed. The participants had to search for a small plush toy (representing a cat) placed in a black box ($31 \times 26 \times 13$ cm). The front face of the box had an opening (14.5×6.5 cm) covered by blue spandex material with a horizontal slit across its width. The back of the box had a second opening that was not visible to the participant and was covered with black fabric. The experimenter used this second opening to remove objects from the box, unbeknownst to the

infants (the box was adapted from Feigenson & Carey, 2003; Starkey, 1992). On the top of the box, there was a “shutter” that could be opened with a handle. Behind the shutter, there was a window made of PVC. In the transparent condition, the PVC was transparent, making it possible for the participants to see the contents of the box through the window. In the opaque condition, the PVC was opaque, making it impossible to see the contents of the box. A camera (temporal resolution = 25 frames per second) recorded the participants’ behavior. The camera was positioned behind the participants, slightly above their head and on their side, in order to record any contact between the participants’ hand and the shutter’s handle.

Familiarization. The experiment began with a familiarization phase, which was identical in all conditions. The experimenter showed the box to the participant, while saying, “*I brought a box with me.*” Then, she opened the shutter located on the top of the box, while saying, “*Look, I can open the window.*” As a result, the participant could see the PVC window (and whether it was transparent or opaque, depending on the opacity condition). Next, the experimenter encouraged the participant to open the shutter by saying, “*Can you open the window?*” The experimenter waited till the participant grabbed the handle and opened the shutter. Next, the experimenter encouraged the participant to reach inside the box and said, “*Look, I can put my hand inside the box.*” while reaching inside the box through the front opening. Then, the experimenter removed her hand and asked, “*Can you put your hand inside the box?*” The experimenter waited till the participant reached inside the box through the front opening. Next, the experimenter showed the toy to the infant while saying, “*Look, I brought a little toy! It is a cat. Do you want to pet it?*” The experimenter allowed the infant to manipulate the toy for a few seconds before taking it back, and announcing, “*Look, I can put it inside the box.*” Then, the experimenter placed the toy inside the box through the front opening and said to the infant, “*Can you give me the cat?*” The experimenter waited till the participant reached

for the cat in the box. During the familiarization phase, the caregivers were allowed to encourage the participants to manipulate the box and to reach for the cat when they were shy.

Test phase. The familiarization phase was followed by a test phase that differed between the groups (control vs. experimental). At the beginning of each test trial, in the experimental group, the experimenter took the box away from the participant, and she inserted the toy into the front opening of the box with her right hand, in full view of the child. Immediately after that, she took the toy out of the box through the secret back opening with her left hand, and she left the toy hidden on her knees, under the table. She encouraged the participant to look for the toy by saying, "*Where is the cat? Can you give me the cat?*" while pushing the box toward the infant, and taking her right hand out of it. The test trial started once the box was positioned, and the experimenter's hand was out of it. During the trial, the experimenter waited for 30 seconds while the participant was left free to search inside the box or to manipulate the shutter. If the participant did not interact with the box until approximately 10 seconds after trial onset, the experimenter repeated the prompt sentence. After 30 seconds, the trial ended. In the experimental condition, to transition to the next test trial, the experimenter placed the toy back in the box through the back opening, unbeknownst to the participants. She reached inside the box through the front opening, retrieved the toy, and showed it to the participant, while saying, "*Look, the cat was there!*" before proceeding to the next test trial. There were three consecutive test trials, each following the same procedure.

In order to assess infants' baseline behaviors when they were not looking for information about the box's contents, we tested a second group of participants in a control condition. In the latter, the test trials followed the same procedure as in the experimental group, except that the experimenter did not place the toy inside the box during the test trial, and asked, "*Did you see my beautiful box?*" (instead of saying, "*Where is the cat? Can you give me the cat?*"). Thus, during each test trial in the control condition, the experimenter simply placed the

box in front of the participant, and said the prompt sentence, “*Did you see my beautiful box?*” before pushing the box toward them. The test trial started from the moment the box was positioned in front of the participant. Moreover, to transition from one test trial to the next in the control condition, the experimenter took the box away from the infant while saying, “*Can I take it back for a moment?*” before proceeding to the next test trial.

2.1.3 Coding

For each test trial, the videotapes were coded offline frame by frame for 30 consecutive seconds. To measure the participant’s anticipation of the information gained by opening the shutter, we coded the delay between the beginning of each test trial and the first time the participant attempted to open the shutter (by touching its handle with any of her fingers). In the opaque condition, opening the shutter did not yield access to any visual information about the contents of the box. In contrast, in the transparent condition, opening the shutter allowed the participant to see inside the box. Thus, we expected participants to be faster to touch the shutter’s handle in the transparent condition than in the opaque condition. When the participants did not interact with the box at all during a test trial (i.e., when they did not touch the handle at all and did not reach inside the box either), we coded the trial as missing data since in those cases the infant showed no interest in participating in the task (12 trials out of 216). For all the Studies reported in this paper, the data were coded first by a primary coder. A second coder, unaware of the hypotheses of the study, coded 50% of the videos. The agreement between the coders was high (average $\rho = .98$, range = .96-1, all $ps < .001$). The statistical analyses were performed on the data from the primary coder for Studies 1-3.

2.1.4 Analysis

All statistical analyses reported in this paper were two-tailed. As our data did not fulfill the assumptions of normality and homoscedasticity required for standard parametric analyses, we conducted omnibus analyses on continuous data by running robust mixed model ANOVAs

implementing Johansen's general formulation of the Welch-James's test with approximate degrees of freedom, trimming of data (per 0.2), and the use of bootstrap (Erceg-Hurn & Mirosevich, 2008; Villacorta, 2017). For all other analyses, we used nonparametric tests. Our analyses were performed with R (v. 3.6.1; R Core Team, 2020), and the R package `welchADF` (v. 0.3.3; Villacorta, 2017).

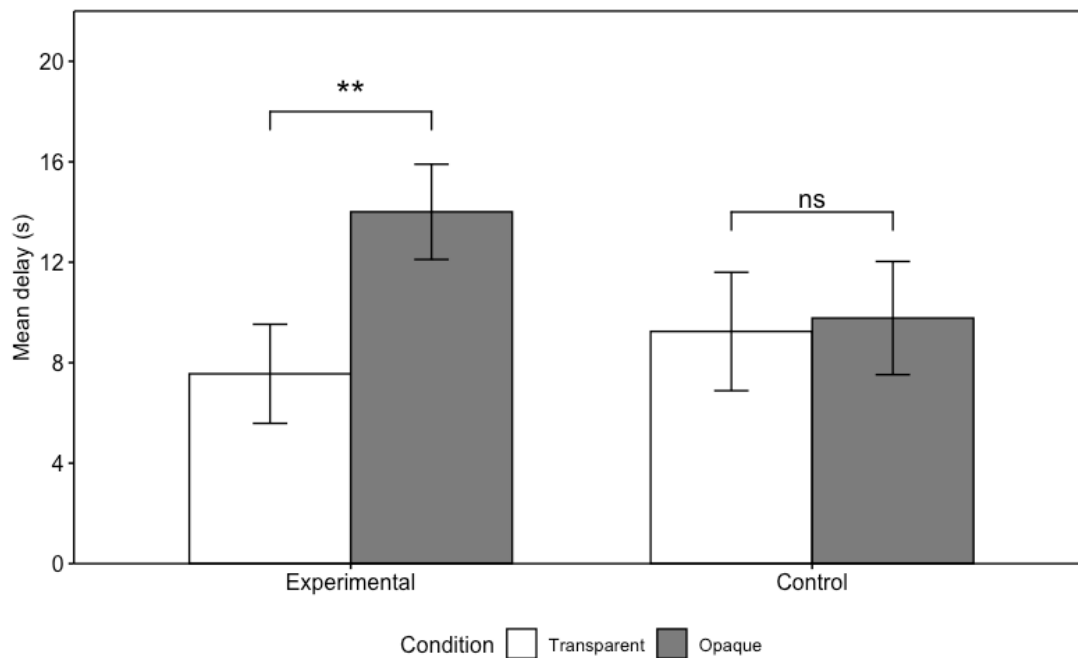
2.2 Results and Discussion

A robust mixed-model ANOVA using the Welch-James ADF procedure on mean delay to reach for the handle with group (control vs. experimental) and condition (opaque vs. transparent) as between-subject factors, and trial (1, 2, or 3) as a within-subject factor revealed an interaction between group and condition ($F(1, 19.67) = 4.12, p = .045$), indicating that the effect of the windows' opacity differed across groups (control vs. experimental). The robust full factorial ANOVA revealed no other significant effect, in particular, no effect of trial ($F(2, 13.82) = .36, p = .698$). Thus, we performed our subsequent analyses on the average value of the delay to reach for the shutter's handle across the three test trials, computed for each participant.

Planned post-hoc analyses revealed that in the experimental group, the participants' average delay to reach for the shutter's handle was significantly shorter in the transparent condition ($M = 7.56, SD = 7.89, M_{dn} = 4.28$) than in the opaque condition ($M = 14.01, SD = 7.58, M_{dn} = 14.06; U = 53.5, p = .005$, Mann-Whitney U test; Figure Article 1.1). Thus, in the experimental group of Study 1, infants were faster at attempting to open a shutter when this action allowed them to gain access to visual data about an object. Since infants' reaching responses were appropriately modulated by the availability of visual information in their environment, their behavior cannot be explained by the use of a fixed information-search strategy.

Figure Article 1.1

Mean Delay to Touch the Shutter's Handle (SEM) per Group, and per Condition.



Note: Stars represent p-values for comparisons between conditions by Mann-Whitney U tests.

ns : not significant, ** : $p < .01$.

Furthermore, in the control group, the opacity of the window had no significant effect on the average delay to reach for the shutters' handle (transparent condition: $M = 9.24$, $SD = 9.43$, $M_{dn} = 5.77$; opaque condition: $M = 9.78$, $SD = 9.02$, $M_{dn} = 6.94$; $U = 121$, $p = .806$, Mann-Whitney U test; Figure Article 1.1). This result confirms that the behavior of the participants assigned to the experimental group cannot be explained by low-level factors, such as a preference to look at transparent rather than opaque materials.

In short, the results from Study 1 suggest that infants treat visual access as a source of information for themselves, and that they adjust their information-search behaviors to the availability of visual access. In Study 2, we investigated whether young children are sensitive

to the fact that seeing does not always lead to knowing. To this end, we manipulated whether seeing yielded cognitive benefits. The participants had to find a target card hidden among distractors. The target and distractors had the same shape and plain flip side, and had symbols on their reverse side. Crucially, in the informative condition, the symbol on the target differed from that on the distractors. In contrast, in the non-informative condition, the target and the distractors all had the same symbols on their reverse side (see Figure Article 1.2). In the test trials in all conditions, the target and distractors were shuffled with their plain flip side visible, so that the participants no longer knew where the target was. We expected that when searching for the target, the participants would be more likely to attempt to see the symbols (by flipping the cards) in the informative condition —where this action yielded cognitive benefits— than in the non-informative condition. Furthermore, we expected that upon being asked to locate the target, the participants would wait for a longer time without knowing what to do in the non-informative condition, since in this case, they had no way of discovering the location of the target. In short, we assumed that if toddlers anticipate the cognitive utility of sight, they should be comparatively faster to attempt at flipping cards in the informative condition than in the non-informative condition.

3 Study 2

3.1 Method

3.1.1 Participants

Study 2 required the participants to memorize the identity of a target character among several others, and to track its displacement while cues of its identity were not visible. Thus, we tested two-and-a-half-year-old toddlers because prior to that age, the capacity to track the invisible displacement of objects may still be fragile (Call & Carpenter, 2001; Collier-Baker & Suddendorf, 2006). Participants were divided into two groups of eighteen toddlers (informative

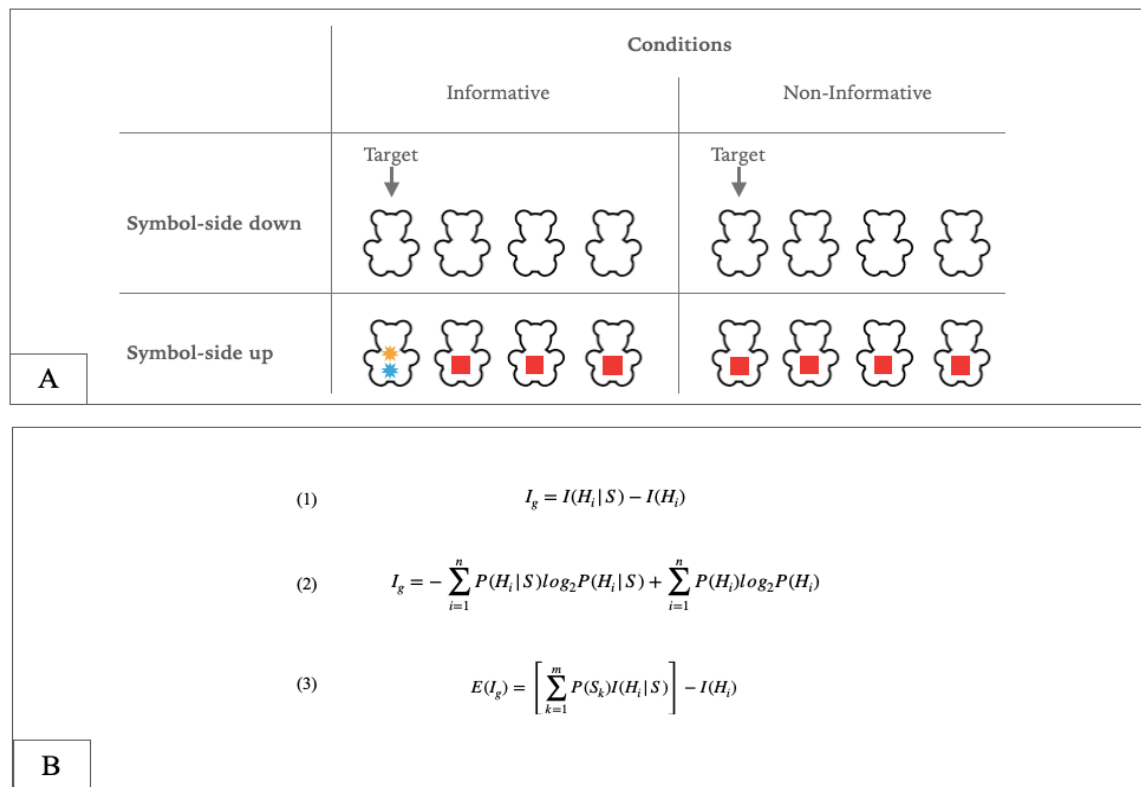
condition: $M = 28.7$ months, $range = 22-35$ months, $SD = 3.83$; non-informative condition: 28.2 months, $range = 22-35$ months, $SD = 4.60$). Each participant was tested only once, in a single condition. Three additional participants were excluded from the analysis because of fussiness (1), total lack of responsiveness (1), and technical failure (1).

3.1.2 Materials and Set-up

The participants were tested in a quiet room at their daycare center. They sat in front of the experimenter, across a child-size table. A familiar caregiver (from the participants' daycare center) was present during the entire experiment. The caregiver was instructed not to influence the participants' choices at any time-point. The participants had to find a character named "Charlie" (henceforth, the "target"), one of four bear-shaped wooden cards of identical shape and size (about $8 \times 9.5 \times 0.5$ cm). There were symbols on the reverse side of each card. We manipulated the informativeness of seeing the symbols across conditions by changing their distribution. In the informative condition, the symbol on the target differed from that on all the other cards. In all other respects, the cards were perceptually identical. In the non-informative condition, all the cards had the same symbol on their reverse side (thus, they were all completely identical, see Figure Article 1.2). Therefore, it was possible to identify the target by looking at the symbol on its reverse side in the informative condition, but not in the non-informative condition. We used two different symbols: a red square and a pair of stars (one blue, one yellow). For both conditions, the symbol on the target was the square for half of the participants and the pair of stars for the other half. The symbol on the other characters varied accordingly.

Figure Article 1.2

Schematic Representation of Study 2's Conditions and Formal Model of Expected Information Gain.



Note: Panel A: Differences Between the Two Conditions of Study 2. The bear shaped cards were all visually identical when their symbol-side was down. When their symbol-side was up, the target card differed visually from the others in the informative condition only. The arrows indicate the target card that the participants had to find. Panel B: A Formal Model of Expected Information Gains (Adapted from Oaksford & Chater, 1994). In this model, learners aim to reduce their uncertainty I over a set of hypotheses H_i (i.e., $I(H_i)$). After seeing a symbol S from flipping a card, the learners revise their uncertainty to $I(H_i|S)$. The information gain (I_g) resulting from seeing a specific symbol S is the reduction of uncertainty (1), where uncertainty is quantified by the standard entropy measure from information theory (2). The learner does not know what the symbol on a card will be before flipping it. Thus, the expected information gain $E(I_g)$ is computed taking into account all the k possible symbols that may be found on a

card (e.g., in Study 2's informative condition, the two possible symbols that may be found on a card). $E(I_g)$ is the uncertainty after flipping a card, weighted by the probability of finding each specific symbol, minus the prior uncertainty (3). According to this model, flipping cards yielded expected information gains only in the informative condition, and not in the uninformative condition.

During each warm-up and test trial, the cards were placed on a cardboard tray (64×27 cm) kept on the child-size table. A rectangular cardboard box (10 x 15 x 3 cm) was used as a "house" in which the participants had to place the target. A camera (temporal resolution = 30 frames per second) recorded the participants' behavior.

Presentation of the game. At the beginning of the session, the experimenter placed the cardboard box on the right side of the table and the cardboard tray in front of her on the table. She announced, "*Look, I brought small bears,*" while placing the cards in a row on the cardboard tray with their symbol side visible. In the informative condition, the experimenter placed the card with a symbol different from the others at the right end of the row (all positions are given from the viewpoint of the experimenter). In the non-informative condition, the procedure was the same as in the informative condition, except that the card placed at the right end of the row was visually identical to the others. The experimenter then told each character's name to the child, by pointing successively toward each of them (moving in the row from left to right) while saying, "*This is Peter. This is John. This is Marc. And this is Charlie.*" After telling the characters' names, the experimenter said, "*We are going to play 'find Charlie,' okay?*" Next, the warm-up trials started.

Warm-up trials. At the beginning of each warm-up trial, the experimenter asked, "*Where is Charlie?*" before pushing the cardboard tray toward the participants to encourage them to select one card. She added, "*Can you put him in his house?*" while holding the

cardboard box and pointing toward it. If the participants did not place any card in the box after approximately 15 seconds, the experimenter prompted them again by asking, “*Where is Charlie? Can you put him in his house?*” Once the participants placed the correct card in the box, the experimenter congratulated them before pulling back the cardboard tray and repositioning the cards for the next trial. When the participants placed the wrong card in the box, they were corrected by the experimenter who said (in a neutral tone of voice), “*That’s not Charlie...*” She then placed the wrong card back to its initial location, and pointed to the correct card, while saying, “*This one here is Charlie!*” before asking again, “*Where is Charlie? Can you put him in his house?*” Two consecutive warm-up trials were conducted. At the end of the first warm-up trial, the experimenter took the target out of the box, and placed it in the second position from the left in the row, before starting the second warm-up trial. The two warm-up trials were followed by a baseline trial.

Baseline trial. The baseline trial unfolded as the warm-up trials, except that when positioning Charlie on the cardboard tray, the experimenter placed the card referred to as “Charlie” symbol-side down, in the third position from the left. The other cards remained symbol-side up, with their symbol visible to the participant, thus making it possible for the participants to locate the target. This baseline trial served to measure the participants’ baseline latency to reach for the character.

Test. At the beginning of each test trial, the experimenter placed all the cards facing down on the cardboard tray, so that the symbols were no longer visible. The experimenter said, “*Let’s mix them up!*” Next, she rearranged the cards by mixing them up quickly on the cardboard tray, thus making it impossible for the participants to track the spatial position of the target. Then, the experimenter positioned the cards in a row on the tray, and asked the participants to locate the target by saying, “*And now, where is Charlie? Can you put him in his house?*” while pushing the tray toward the participant to encourage them to search. The trial

ended once the participants had placed one card in the cardboard box. Four consecutive test trials were conducted, without any feedback to participants on their performance.

3.1.3 Coding and Analysis

We coded the number of cards the participants flipped before placing one in the cardboard box for each of the test trials. In case a participant flipped the same card multiple times, we coded only a single flip, so that the maximum flipped cards were four. In case a participant grasped a card and directly placed it in the box without flipping it, we coded 0 for the number of characters flipped. In order to assess our participants' anticipation of the cognitive utility of sight, we coded the "grasping latency" of the participants by computing the time elapsed from the moment the experimenter finished saying the prompt (i.e., when she pronounced the last syllable of the sentence "*And now, where is Charlie?*"), till the participant grasped one of the cards (i.e., touched it simultaneously with the thumb and any of the other four fingers). We measured the grasping latency for the baseline trial (to have a baseline measure of the participants' motor speed) and for the four test trials. Next, we computed the grasping latency ratios (GLR) to estimate the relative speeding up (or slowing down) of participants during the test trials compared to the baseline. This ratio was computed for each test trial and each participant by dividing the grasping latency during the test trial by the grasping latency during the baseline trial. By performing our analyses on the GLR, a baseline-corrected measure, we reduced the influence of inter-individual differences in grasping speed on our results. In the non-informative condition, flipping the cards to see the symbol on their backside resulted in no information gain. In contrast, in the informative condition, the target could be identified by seeing the symbol on the cards' backside. Thus, we expected that if toddlers anticipate the cognitive utility of seeing symbols in Study 2, they GLR should be lower in the informative condition than in the non-information condition. In the informative condition, we also measured whether the participants found the target card. For each trial, the participants

received a score of 1 when the first card they placed in the cardboard box was the target, and 0 otherwise.

3.2 Results and Discussion

First, we conducted a preliminary analysis to validate that the participants succeeded in finding the target character in the informative condition. Since there were four characters to choose from, chance predicted a mean success ratio of 0.25 in each trial. Across the four test trials in the informative condition, children's mean success ratio in finding the target character was significantly higher than that predicted by chance (0.25) ($M = 0.78$, $SD = 0.34$, $Mdn = 1.00$, $Z = 133.5$, $p < .001$, Wilcoxon signed-rank test). Next, we assessed whether the participants' information search strategies differed across conditions. We first analyzed the participants' number of flips. A Friedman test revealed that trial number had no effect on the number of flips ($\chi^2(3) = 1.98$, $p = .577$, $Kendall's W = .02$). Subsequently, we computed the average number of flips per participant across the four trials, and performed our analyses on this average score. The participants' average number of flipped cards was significantly higher in the informative condition ($M = 1.82$, $SD = 0.86$, $Mdn = 2.00$) than in the non-informative condition ($M = 0.91$, $SD = 0.45$, $Mdn = 1.00$, $U = 275$, $p < .001$, Mann-Whitney U test). Thus, the participants were more likely to flip cards when this action was informative for finding the target than when it was non-informative.

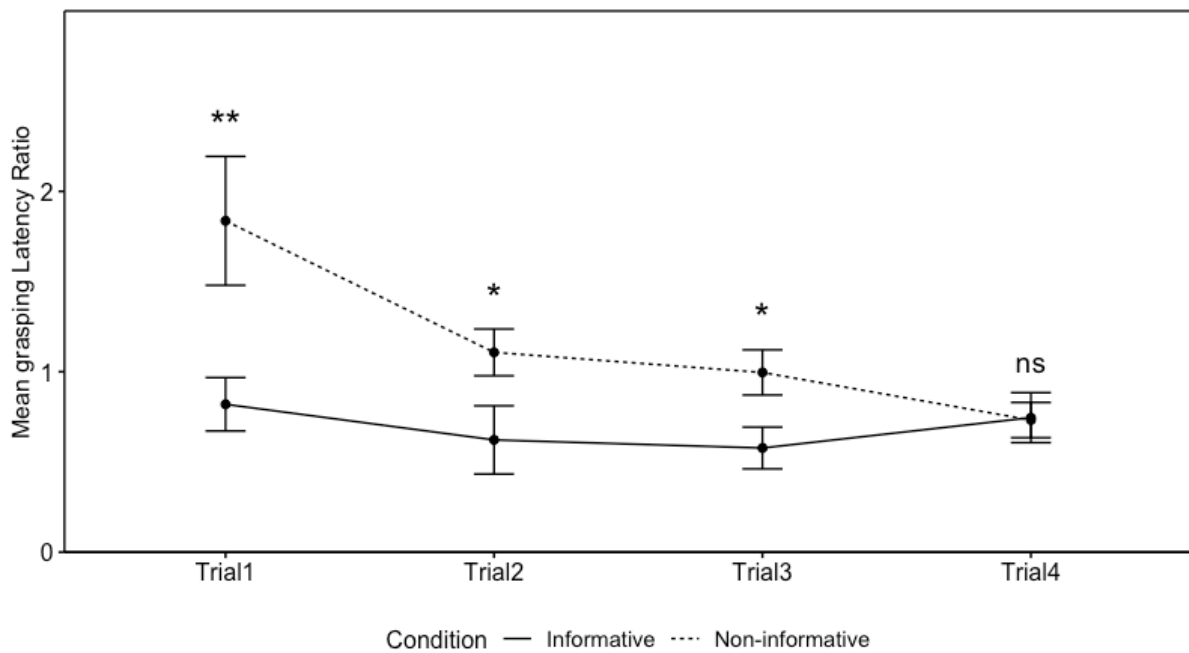
Second, we analyzed the participants' grasping latency ratio (GLR). A robust mixed-model full factorial ANOVA using the Welch-James ADF procedure on mean GLR with condition (informative vs. non-informative) as between-subject factors and Trial (1-4) as a within-subject factor revealed a main effect of condition ($F(1, 20.96) = 8.21$, $p = .008$), indicating that the participants' mean GLR was significantly lower in the informative condition than in the non-informative condition in this condition. The robust ANOVA also revealed a

main effect of trial ($F(3, 17.57) = 5.37, p = .011$) and an interaction between condition and trial ($F(3, 17.57) = 3.34, p = .036$). Planned comparisons revealed that the participants' average GLR was significantly below 1 in the informative condition ($M = 0.69, SD = 0.46, M_{dn} = 0.69, Z = 31, p = .016$, Wilcoxon signed-rank test), indicating that the participants were faster to grasp a card during the test trials than during the baseline trials. In contrast, the participants' average GLR did not differ significantly from 1 in the non-informative condition ($M = 1.17, SD = 0.54, M_{dn} = 1.13, Z = 112, p = .265$, Wilcoxon signed-rank test).

Since the robust ANOVA on the average GLR revealed a main effect of trial and an interaction between trial and condition, we separately analyzed the participants' GLR data for each trial. These analyses confirmed the effect of condition. As Figure Article 1.3 shows, the mean GLR was significantly lower in the informative condition than in the non-informative condition in the first three test trials. In the final test trial, the mean GLR did not differ significantly across conditions (informative vs. non-informative), possibly because the speed at which the participants grasped a card reached the ceiling by the end of the experiment.

Figure Article 1.3

Mean Grasping Latency Ratios for Each Trial (SEM) per Condition.



Note: Stars represent p-values for comparisons between conditions by Mann-Whitney U tests.

ns : not significant, * : $p < .05$, ** : $p < .01$

In a few trials of Study 2, the participants grasped a card and directly placed it in the box without flipping it. As a result, the status of grasping latency as a measure of learning expectation during these trials was ambiguous. Thus, we reanalyzed our results for the GLR after excluding data from these trials (thus considering only the grasping gestures that led to flipping a card). These analyses confirmed our key results by showing an effect of condition on the participants' average GLR, with mean GLR significantly below that predicted by chance in the informative condition, and not significantly different from chance in the non-informative condition (see Supplementary Analysis of Article 1).

Our results suggest that the toddlers anticipated the informativeness of seeing the symbol located at the back of the cards. They did not use a purely confirmatory strategy (e.g.,

collecting evidence confirming their initial hypothesis). If they had done so, the participants' GLRs should have been the smallest in the non-informative condition, in which case the symbol located at the back of the card was guaranteed to confirm their hypothesis. Instead, our participants used an information gain strategy, such that they were more likely and comparatively faster to reach for a target when they had a way to reduce their uncertainty about its location (by flipping it) than when they did not. In Study 2, we manipulated the informativeness of a given source of data (seeing). In Study 3, we sought to conceptually replicate and extend the generalizability of these findings by testing whether toddlers can select the most informative source of data when choosing between two possible actions: flipping a character to see a symbol, or squeezing it to hear the sound it produced.

4 Study 3

4.1 Method

4.1.1 Participants

In Study 3, the participants were divided into two groups of eighteen toddlers (symbol condition: $M = 29.1$ months, $range = 23-34$ months, $SD = 2.36$; sound condition: $M = 30.6$ months, $range = 24-37$ months, $SD = 3.55$). Each participant was tested once, in a single condition. Seven additional participants were removed from the analysis because of fussiness (1) or refusing to play the game (6).







4.1.2 Materials and Set-up

The materials and set-up were identical to those in Study 2, with the following exception. Instead of wooden cards, cushions ($10 \times 10 \times 5.5$ cm) with googly eyes on one side and a symbol sticker on the reverse side served as characters in the game (see Figure Article 1.4). All four characters were of identical shape and size, and were visually identical with the eye-side facing up. One of the characters could be identified by pressing it. When squeezed, it

emitted a loud squeaking noise, while the other three characters produced no sound. A second character could be identified by looking at the symbol placed on its reverse side. This character was the only one with a symbol different from the other characters. For half of the participants, the distinctive symbol placed on the reverse side of this second character was a red circle, while visually identical pairs of triangles were on the reverse side of each of the other characters; for the other half of the participants, we used the opposite pattern. The last two characters were completely identical; they made no sound when pressed, and had the same symbol on their reverse side. A rectangular cardboard box served as a “house” (hereafter referred to as the house-box; 13cm wide x 18cm deep x 7.5cm high). Furthermore, Study 3 also required the use of an opaque paper grocery bag.

Figure Article 1.4

Differences Between the Two Conditions of Study 3.

	Conditions	
	Symbol	Sound
Symbol-side down	Target 	Target 
Symbol-side up		
Sound when squeezed		

Note: The characters were all visually identical when placed symbol side-down, in both conditions. In the symbol condition the target character was the only one with a symbol different from the others. In the sound condition, the target character was the only one producing a loud noise when squeezed. The arrows indicate the target characters.

Presentation of the game. The participants had to find a target character named “*Baptiste*” from among four cushion-shaped characters. At the beginning of the session, the experimenter placed the house-box on her right, at the far end of the board and said, “*Look, I brought little toys to play with.*” Then, she presented the first character to the child by lifting it, holding it eye-side toward the child while saying, “*You see, there is this one here.*” Next, she placed the character eye-side down on the board, thereby revealing the symbol placed on its backside, before pressing on the character to demonstrate whether it squeaked or made no sound. The experimenter repeated this procedure to present the second, third, and fourth characters, lining them up on the board one by one from her right to her left. When presenting the fourth and last character, the experimenter also added, “*This one is named Baptiste*” before placing it in line with the others and pressing on the character. In the sound condition, the target character, which was referred to as “*Baptiste*” was the only one that made a squeaking sound

when pressed. In the symbol condition, the character that was referred to as “Baptiste” was the only one to have a distinctive symbol placed on its reverse side. Apart from this difference, the procedures for the two conditions were identical. After presenting the cushions, the experimenter told the participant, “*We are going to play a game in which you have to find Baptiste, okay?*” and the warm-up trials started.

Warm-up trials. At the beginning of the first warm-up trial, the experimenter asked, “*Where is Baptiste now? Can you put him in his house?*” Next, she pushed the board and the house-box toward the child to indicate that it was the participant’s turn to place a toy into the box. When the participants did not choose the correct cushion, the experimenter corrected them by saying, “*That’s not Baptiste, this one here is Baptiste*” while pointing at the target character before pressing on it, and she repeated the prompt questions. Once the participants chose the target, they were congratulated, and the experimenter brought the materials back to her side of the table. Next, the experimenter positioned the characters on the board, and proceeded with the next warm-up trial. The second and third warm-up trials proceeded just like the first, with two exceptions. First, the position of the target character changed. For the second warm-up trial, the experimenter placed the target symbol side up at the right end of the row of characters. For the third warm-up trial, the experimenter placed the target second from the left end of the row, this time with its eye-side up, and its symbol side down. Second, in order to help the participants remember which character produced a sound when squeezed, the experimenter pressed sequentially on each cushion from left to right at the very beginning of the second and third warm-up trials. After the three warm-up trials, the participants proceeded to the test phase.

Test phase. At the beginning of each test trial, the experimenter placed the four characters into the grocery bag and said, “*Let’s mix them up!*” Next, the experimenter shook the bag and removed the characters two at a time and placed them on the board in front of the

participant, all with their eyes upward (making it impossible for the child to know which character was the target). Next, to help the participants understand that the characters were not in the same position as in the past trials, the experimenter quickly mixed them up, before placing them in a row on the board. All the characters now appeared identical from the viewpoint of the child. Discovering where the target was could only be accomplished by pressing on the characters (in the sound condition), or by flipping them to see the symbols (in the symbol condition). Next, the experimenter asked the prompt questions, “*Where is Baptiste now? Can you put him in his house?*” and she slid the board toward the child. The trial ended when the participant placed one of the characters in the house box, or 1 minute after the experimenter asked the prompt questions in case the participant did not interact at all with any of the cushions. There were four consecutive test trials, without any feedback to participants on their performance.

4.1.3 Coding and Analysis

We coded the following four measures for each test trial: (i) whether the participants succeeded in finding the target character “Baptiste” (coded as 1 when the character the participants placed first in the cardboard box was the target, and 0 otherwise); (ii) the number of characters that the child squeezed; (iii) the number of characters that the child flipped (if a participant performed the same action, that is, flipping or squeezing a toy, on the same cushion multiple times, it was coded only once); and (iv) an estimate of the relative latency with which the participants engaged in flipping or squeezing a toy. We found it difficult to accurately code the exact latency for squeezing a toy. Thus, instead, we coded the first action that the participants performed on the toys (flipping or squeezing a character) for each trial. For the trials in which the participant did not interact with any cushion, we coded 0 for the success in finding the target character, and 0 for the number of characters flipped and squeezed. When the

participants did not flip or squeeze any of the toys before the end of the trial, we coded their first action as missing data.

4.2 Results and Discussion

Friedman tests revealed no main effect of trial on the participants' mean ratio of success in finding the target, the number of flips, and the number of squeezes (all $ps > .659$). Thus, for each of our measures, the participants' scores were averaged across the four trials. We performed subsequent statistical analyses on these average scores.

In a preliminary analysis, we assessed the participants' success in finding the target toy. Since there were four test trials, chance predicted an average success ratio of 0.25. Participants' mean ratio of success in finding the target tended to be higher than predicted by chance (0.25) in the symbol condition ($M = 0.72$, $SD = 0.36$, $M_{dn} = 1.00$, $Z = 146$, $p < .001$, Wilcoxon signed-rank test), and in the sound condition, although in the latter case the statistical tendency was only marginally significant ($M = 0.42$, $SD = 0.35$, $M_{dn} = 0.50$, $Z = 90$, $p = .079$, Wilcoxon signed-rank test). Thus, the participants tended to succeed in finding the target character in the experiment.

Next, we assessed whether the participants' strategy for finding the target differed across conditions. During the test trials, the participants flipped significantly more toys in the symbol condition ($M = 1.92$, $SD = 1.00$, $M_{dn} = 2.25$) than in the sound condition ($M = 0.42$, $SD = 0.73$, $M_{dn} = 0.25$, $U = 282$, $p < .001$, Mann-Whitney U test). Thus, the participants were more likely to flip toys when this action was more informative to discover the location of the target. Conversely, the effect of condition on the participants' tendency to squeeze toys did not reach statistical significance (symbol condition: $M = 0.47$, $SD = 0.66$, $M_{dn} = 0.00$; sound condition: $M = 0.82$, $SD = 0.84$, $M_{dn} = 0.50$, $U = 119.5$, $p = .164$, Mann-Whitney U test). Analyses focusing on the participants' first actions revealed that children flipped a toy first significantly more

often in the symbol condition ($M = 0.93$, $SD = 0.17$, $M_{dn} = 1$) than in the sound condition ($M = 0.43$, $SD = 0.48$, $M_{dn} = 0.13$, $U = 210$, $p = .002$, Mann-Whitney U test). Therefore, the participants were more likely to perform first an action relevant to discovering the location of the target.

Thus, the results of Study 3 confirm that toddlers modulate their search behaviors depending on the informativeness of visual data. Children were more likely to first flip a toy when this action resulted in accessing visual information that was sufficiently informative to locate the target (in the symbol condition), than when it was not (in the sound condition). The evidence suggesting that the participants anticipated the amount of information gained from squeezing the toy was less clear (although the data trended in the expected direction). We speculate that children may have found it harder to track the informativeness of squeezing the toy because they could not be entirely certain that the target toy was the only one producing a sound when squeezed (since the causal mechanism producing the sound within the toys was not directly observable). Furthermore, squeezing toys to make them squeak is likely to be enjoyable in itself for children, thus creating an incentive to squeeze toys in all the conditions. Nevertheless, the results of Study 3 confirm those of Study 2 in suggesting that children can anticipate the informativeness of the data gained from visual access.

5 General Discussion

Mounting evidence suggests that infants monitor the learning benefits resulting from receiving a piece of visual information (Kidd et al., 2012; Poli et al., 2020; Stahl & Feigenson, 2015). Our results indicate that by toddlerhood onward, humans also rely on a model of their own learning from sight to anticipate the epistemic consequences of their actions. This early developing model of learning takes into account both the availability and cognitive utility of sight.

In Study 1, 14-month-old infants were faster to perform an action (opening a shutter) when it allowed them to see an object inside a box, than when it did not. This result adds to previous evidence suggesting that infants monitor what others can and cannot see (e.g., Choi et al., 2018; Liszkowski et al., 2007; Luo & Baillargeon, 2007; Moll & Tomasello, 2006; O'Neill, 1996; Sodian et al., 2007; Southgate et al., 2007). Our results suggest that infants can use their capacity to represent visual access to guide their own search for information. This capacity implies that infants form an epistemic goal (seeing the object inside the box), and select the most appropriate action to achieve it, taking into account the constraints of the situation (in our study, the opacity or transparency of the window). Thus, infants flexibly adjust their information-search behaviors by anticipating the availability of visual data.

In Studies 2 and 3, we found that two-and-a-half-year-old toddlers adjust their information search to the cognitive utility of seeing. In these experiments, the participants were more likely to flip characters in order to see a symbol when this action was informative than when it was not. In Study 2, toddlers' Grasping Latency Ratio before flipping a character was significantly lower when this action was more informative. Similarly, in Study 3, toddlers were more likely to flip a character before performing an alternative action (squeezing a character) when flipping characters was informative. These results suggest that toddlers anticipate the cognitive gains resulting from sight (in our experiments, from seeing a symbol) when planning their search for data. Children's capacity to select and assess learning actions and teaching based on their informativeness has been evidenced in studies of preschoolers' exploratory play (Cook et al., 2011; Ruggeri, Swaboda, et al., 2019; Schulz & Bonawitz, 2007; Van Schijndel et al., 2015), in their assessment of informants (Gweon et al., 2014; Gweon & Asaba, 2018), and in their formulation of questions (Legare et al., 2013; Ruggeri et al., 2017). We demonstrated comparable capacities in the perceptual domain in much younger participants. Instead of expecting that seeing necessarily leads to knowing, toddlers adjusted their behaviors

to the capacity of a visual input to reduce their own uncertainty. Thus, well before they can explicitly talk about sources of knowledge, toddlers do not conceive of seeing as a purely behavioral event (such as merely building an unobstructed line of sight to an object). Instead, they are sensitive to the amount of relevant information carried by a given visual input, and they adjust their information search accordingly.

In its most elaborate form, anticipating the informativeness of a learning action may seem like a very complex task. It may imply, for example, tracking all the possible perceptual events resulting from a learning action, and anticipating the overall reduction of uncertainty resulting from all possible outcomes (as the ideal learner depicted in Figure Article 1.2, panel B). While we do not rule out that toddlers may use such a complex mechanism, they may also rely on simpler procedures that remain effective whilst having a lower cognitive cost. For example, they may simply consider a single or a few hypotheses for the future perceptual event resulting from a learning action (e.g., discovering one specific symbol on a character's backside), and assess the resulting reduction in their uncertainty. These computations can be performed by simply monitoring one's uncertainty, a capacity that may be operational from infancy (Coughlin et al., 2015; Geurten & Bastin, 2019; Goupil et al., 2016; Kim et al., 2020; Poli et al., 2020), and representing future perceptual events (Siegel et al., in press).

In short, even if many species can search for specific pieces of information efficiently, humans stand out in their ability to plan learning actions in creative and flexible ways. The capacity to discover and adjust information-seeking strategies in a contextually sensitive manner requires assessing the learning outcomes of future actions or events. We offer evidence of the early ontogenetic roots of this capacity. Our data indicate that before their third birthday, toddlers plan their epistemic actions by anticipating whether they will result in learning, and adjust them to (i) epistemic constraints and (ii) the cognitive utility of a piece of evidence.

Article 2

Cognitive Costs and Benefits Guide Toddlers' Discovery of Novel Communicative Cues' Meanings: The Cases of Processing Ease, Informativeness and Accuracy

Discovering the meaning of novel communicative cues is challenging and amounts to navigating an unbounded hypothesis space. Several theories posit that the hard problem of discovering novel meanings can be simplified by relying on positive expectations about the cognitive utility of communicated information. These theories imply that learners should prioritize an interpretation whose cost/benefit ratio is high when attempting to discover the meaning of a novel communicative cue. We tested this hypothesis in three studies in which toddlers ($N = 90$) searched for a reward hidden in one of several containers. In all studies, an adult communicated the reward's location with an unfamiliar cue whose meaning was ambiguous. We manipulated the processing costs (operationalized as inferential chain length) and cognitive benefits (operationalized as informativeness) of the possible interpretations of the cues. Toddlers prioritized interpretations with low processing costs (Study 1) and high benefits (Studies 2 and 3) when attempting to discover the meaning of novel cues. More

specifically, they treated novel cues as if they were easy to process, informative, and accurate, even when provided with repeated evidence to the contrary. These results indicate that, from toddlerhood onward, humans prioritize interpretations whose cost/benefit ratio is high when inferring the meaning of novel communicative cues. These data also reveal that toddlers, who are in the process of learning the language and communicative conventions of people around them, exert a pressure favoring cognitive efficiency in communicative systems.

1 Background

Humans are expert communicators. Many animal species use signals to convey information, but humans' communicative practices stand out in their frequency, flexibility, as well as in the scope and nature of the information they convey (Csibra & Gergely, 2009; Harris, 2012; Sperber & Wilson, 1995; Tomasello, 2010). These properties are all the more remarkable given the ambiguity of human communicative means, such as gestures or words. Any communicative action or label could, in principle, carry an infinity of potential meanings (Quine, 1960). As a result, the interpretation of what people communicate amounts to searching through an unbounded hypothesis space. Yet, even infants and toddlers manage to use and interpret communicative cues whose meaning is highly variable, and contextually dependent (e.g., Bohn, Tessler, Merrick, et al., 2019; Falkum et al., 2017; Köder & Falkum, 2020; Mazarella & Pouscoulous, 2020; Pouscoulous & Tomasello, 2020; Stephens & Matthews, 2014).

Many authors have argued that the process of solving the difficult problem of interpreting what others communicate can be guided by presumptions about the cognitive utility of the communicated information (e.g., Clark, 1996; Judith Degen & Tanenhaus, 2019; Frank, 2016; Grice, 1975; Sperber & Wilson, 1995). Relevance theory provides a general characterization of such guidance. It posits that by providing information to their audiences, speakers imply that it is worth processing. As a result, the interpretation of what speakers intend to communicate is guided by a presumption of optimal relevance, defined in terms of cognitive (or contextual) effects, and processing costs. *Ceteris paribus*, the greater the cognitive effects and the smaller the processing costs, the greater the relevance (Sperber & Wilson, 2002). Here, we investigate how cognitive costs and benefits shape toddlers' interpretation of novel communicative cues. Drawing on Gricean and subsequent approaches (Frank, 2016; Grice, 1975; Sperber & Wilson, 1995), we hypothesized that young learners prioritize interpretations

with high cost/benefit ratios when attempting to discover the meaning of novel communicative cues.

1.1 Processing Costs

To test this hypothesis, we first investigated how processing costs shape learners' discovery of novel meanings. Sources of communicative messages attempt to modify the mental states of their audience. This goal is more readily achieved if the sources make the information that they intend to convey easy to access and process. For instance, saying "it is two o'clock" is a more efficient way to convey that it is 2 PM than saying "the number of hours past noon is equal to the square root of four" because the former sentence is much easier to process than the latter. Moreover, by offering information, sources of communicated messages imply that what they convey is worth being processed, and thus, that its cognitive benefits justify its processing costs (Sperber & Wilson, 1995). Indeed, adult speakers make efforts to reduce their audiences' processing costs. For example, individuals wearing digital watches that indicate the exact time are more likely to communicate the time using rounded, not exact, answers when this less precise information is relevant to their audience (Gibbs & Bryant, 2008; Van Der Henst et al., 2002).

Accordingly, processing costs are likely to play a central role in shaping the interpretation of communicated information. Several theories posit that the discovery of speakers' meanings can be guided by expectations about the ease of processing an utterance. Such expectations could originate from a maxim of manner which enjoins speakers to "be perspicuous" (Grice, 1975, p. 46), a presumption of relevance (Sperber & Wilson, 1995), a principle of least joint effort (Clark, 1996), or from speakers' tendency to strategically balance cost and informativeness (Bergen et al., 2016). Despite their differences, all these theories make converging predictions about the role of costs in shaping the interpretation of signals or

utterances. They imply that, *ceteris paribus*, when people try to understand what is communicated to them, they prioritize hypotheses that are easier to process over costlier ones. We tested this prediction empirically by investigating how toddlers interpret the meaning of a novel cue. Several studies have investigated the role of production costs in shaping the interpretation of communicated information by testing whether listeners consider how costly the production of a message is to speakers (e.g., Judith Degen et al., 2013; Rohde et al., 2012). In contrast, there is very little empirical data on the role of processing costs in shaping the interpretation of communicated information.

1.2 Cognitive Benefits

The view that learners prioritize interpretations whose cost/benefit ratio is high when processing novel communicative cues predicts that benefits, and not just costs, shape their discovery of novel meanings. When speakers offer a piece of information to an audience, they imply that this information is worth processing, and thus, should yield some cognitive benefits. Indeed, many theories posit that expectations about positive cognitive effects guide the interpretation of communicated information. These expectations are explicit in Grice's maxims of quality ("Try to make your contribution one that is true") and of quantity ("Make your contribution as informative as is required") (Grice, 1975, p. 45,46). Several theories also postulate that expectations of high cognitive utility guide interpretation (Judith Degen & Tanenhaus, 2019; Frank, 2016; Frank & Goodman, 2012; Franke, 2011; Sperber & Wilson, 1995). In this study, we operationalized benefits in terms of informativeness, defined as the capacity of a stimulus to reduce uncertainty over a set of hypotheses (Frank & Goodman, 2012; Shannon, 1948).

Humans communicate in an informative manner from toddlerhood onward by adjusting their communicative behaviors to what their addressees already know (Liszkowski et al., 2008;

Meng & Hashiya, 2014; O’Neill, 1996; O’Neill & Topolovec, 2001), and to what is expected or unexpected in a given context (Bannard et al., 2017). Moreover, even if toddlers and preschoolers often communicate ambiguously (Davies & Katsos, 2010; Nilsen & Graham, 2009), they can learn to avoid this, when prompted by clarification requests (Bahtiyar & Küntay, 2009; Matthews et al., 2007, 2012). Thus, by two to three years of age, children often adjust the informativeness of their linguistic and non-verbal communication to the needs of their addressees. In short, from toddlerhood onward, children attempt to communicate in an appropriately informative manner.

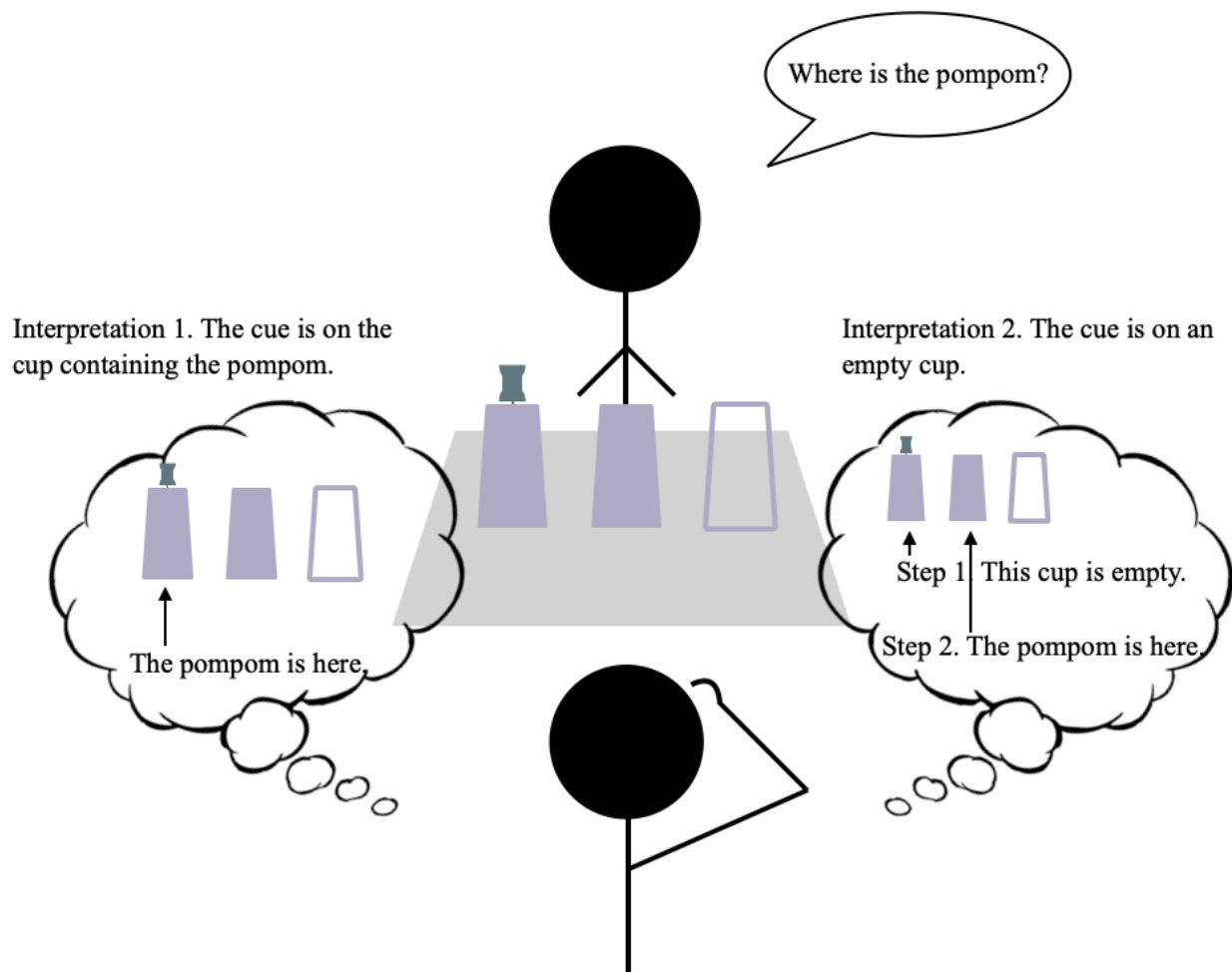
On the reception side, preschoolers can evaluate the informativeness of utterances (Eskritt et al., 2008; Gweon et al., 2018; Gweon & Asaba, 2018; Morisseau et al., 2013); they can also use expectations of informativeness to interpret communicated information, for instance, to discover the meaning of novel labels (Bohn, Tessler, & Frank, 2019; Frank & Goodman, 2014), and to identify the referent of an utterance (Stiller et al., 2015). These data suggest that by preschool age, expectations of high cognitive effects guide children’s interpretation of familiar communicative cues (such as words and pointing). We built on this evidence to investigate how cognitive benefits may guide the interpretation of novel communicative cues during toddlerhood.

In short, we hypothesized that learners prioritize interpretations whose cost/benefit ratios are high, if not optimal, when attempting to discover the meaning of novel cues. We tested this hypothesis by assessing how toddlers’ interpretation of novel cues is shaped by processing costs (Study 1) and benefits (Studies 2 and 3). In Study 1, we operationalized processing costs in terms of the length of the inferential chain required to access a piece of information. The participants had to discover the location of a reward hidden under one of three cups. One of the cups was transparent and could be excluded immediately; the other two were opaque. Before the participants could search for the reward, an experimenter gave them a clue

by placing a marker on top of one of the two opaque cups. This communicative gesture is novel: the child has not observed it before. It is also ambiguous: it might either communicate that the marked cup contains a reward, or that the marked cup is empty. The first interpretation (marked cup = reward) is optimally easy to process (when learning that the reward is in cup A, one directly learns where the reward is). The second interpretation (marked cup = no reward) is sufficient to discover the location of the reward (after excluding the marked cup, the only option left is the other opaque cup). However, it is much harder to process, because it requires the exclusion of one cup. If the reward can be in either cup A or B, upon learning that cup B is empty, one needs first to exclude cup B in order to discover the location of the reward (see Figure Article 2.1). As a matter of fact, in Study 1, the experimenter always placed the marker on the empty cup. However, if cognitive costs guide toddlers' interpretation of novel communicative actions, they should prioritize the less costly interpretation of the cue. Thus, they should keep searching for a reward under the marked cup. The data and analysis scripts of all studies are accessible on an open repository (https://osf.io/k9vwm/?view_only=d4c4ea1af6934e41840257a7625ca1ed).

Figure Article 2.1

The Two Possible Interpretations of the Marker in Study 1.



Note: The grey pin represents the marker placed by the experimenter.

1.3 Ethical considerations

The research reported in this manuscript followed the guidelines of the Declaration of Helsinki. This study was approved by an independent committee for biomedical research (CPP Sud-Est II, IRB: 00009118) and by the local board of the daycare centers involved in the study. The parents of all participants gave their informed written consent prior to their inclusion in any of the studies (1–3).

2 Study 1

2.1 Method

2.1.1 Participants

Eighteen two-year-old toddlers participated in Study 1 ($M_{age} = 27.90$ months, $range = 20\text{--}35$ months, $SD = 4.67$). Five additional participants were excluded from the analysis either because they refused to complete the whole experiment (3), or because they failed to understand the task (i.e., they first chose an empty cup for two or more trials during the warm-up phase) (2). In Study 1 and in subsequent studies, our sample size was set to 18 participants per group. In previous studies in which 2.5-year-olds had to discover the location of a hidden object using a novel cue (a marker), children discovered the object more often than predicted by chance, with effect sizes ranging from .902 to 1.998 (Tomasello, 2009; Zlatev et al., 2013). Assuming comparable effect sizes in our studies, a sample size of 18 was sufficient to reach a power ranging from .94 to 1 to compare the participants' choices of cups against chance (analyses performed with G-Power 3.1, Faul et al., 2007; with $\alpha = .05$).

2.1.2 Materials

In all the studies, the participants were seated in front of the experimenter across a child-sized table, in a quiet room at their daycare center. A caregiver familiar to the participants was present throughout the experiment. The caregiver was instructed not to influence the participants' choices at any time point during the experiment. In Study 1, the participants had to find a blue pompom (5 cm in diameter) hidden under one of the three upside-down plastic cups. The three cups had the same shape and size (diameter: 6.5 cm, height: 11.5 cm); two cups were opaque (an orange one and a purple one); and the third cup was transparent. To communicate the location of the pompom, the experimenter used a "marker"—a plastic disc with a little protruding handle (5 cm in diameter and 1 cm tall). During each warm-up and test trial, the cups were placed on a cardboard tray (64 cm \times 27 cm) positioned on the child-sized

table. The experimenter also used a large opaque screen made of white cardboard (45 cm x 48 cm x 9.5 cm) to occlude herself and the cups from the participants when she was hiding the pompom. A camera recorded the participants' behaviors (temporal resolution = 30 frames per second).

2.1.3 Procedure

Warm-up phase. At the beginning of the session, the experimenter showed three cups and a pompom to the participants. She explained that they would play a game in which they had to find out where the pompom was hidden. Next, the participants were enrolled in three warm-up trials. At the beginning of each warm-up trial, the experimenter placed a rectangular cardboard tray on the table in front of her. She arranged the three cups in a row on the tray, approximately 15 cm apart. Next, she placed the pompom under one of the cups in full view of the child. She asked, "*Where is the pompom?*" before pushing the tray toward the participant to encourage them to search for the reward. The experimenter let the participant search for the pompom and congratulated them once they found it. Three consecutive warm-up trials were conducted. During each of them, the pompom was placed under a different cup and at a different location (to the left of the child, in front, or to the right). We assumed that the participants who chose an empty cup during two warm-up trials or more did not understand the task, and were, therefore, excluded from the data analysis. Following the warm-up phase, participants were enrolled in nine consecutive test trials.

Test phase. The test trials were identical to the warm-up trials, with the following exceptions. First, the experimenter did not show the participants where she hid the pompom. Instead, before hiding the pompom, the experimenter placed the large cardboard screen on the table between the cups and the participant. The screen was large enough to prevent the participant from seeing where the pompom was placed. The experimenter always hid the pompom under one of the two opaque cups. After hiding the pompom, the experimenter

removed the screen from the test table, and asked, “*Where is the pompom?*” Next, she held up the marker and said, “*Look,*” before placing it on top of the empty opaque cup (Figure Article 2.2). Subsequently, the experimenter pushed the tray toward the participant and allowed them to search for the pompom. When the participant did not select the cup with the pompom first, they were given a second opportunity to find it. These second choices were coded separately from the participant’s first choices. Nine consecutive test trials were conducted in Study 1. The location of each cup, of the baited cup, and of the cup on top of which the marker was placed (to the left of the child, in front, or to the right) were counterbalanced across trials for each participant. The color of the opaque cup under which the pompom was hidden (orange or purple) was randomized across trials.

2.1.4 Coding

For each trial, we coded two distinct measures: the participant’s first choice of cup, and (in case they did not find the pompom in the first attempt), their second choice of cup. For each of these measures, we coded which cup the participant lifted first above the table. When the participant found the pompom in the first attempt, we coded their second attempt as missing data. All the data were double-coded by the experimenter and by a second coder, who was unaware of the hypotheses of the study. There was a high correlation between the two raters’ evaluations of whether the participant selected the marked cup during their first or second attempts (Spearman’s $\rho = .99, p < .001$). Disagreements were resolved through discussion.

2.1.5 Analyses

Statistical analyses were performed in the same manner for all studies (1–3). They were always two-tailed and computed using R (v. 4.0.3; R Core Team, 2020) with the following packages: rcompanion (v. 2.3.27; Mangiafico, 2021), lme4 (version 1.1-26; Bates et al., 2015), and lmerTest (version 3.1-3; Kuznetsova et al., 2017). For all studies, when reported, the Wilcoxon signed-rank effect size refers to the matched rank biserial correlation of the

“rcompanion” package. Moreover, for null results of main interest, we conducted Bayesian tests with a Cauchy Prior Distribution set to the default value (.707) with Jasp (version 0.14.1; JASP Team, 2020). When conducting the Bayesian Wilcoxon signed-rank test, we used a data algorithm with five chains of 1000 iterations. In all of the studies, we assessed the effect of our factors using generalized linear mixed models (GLMMs) with the selection of a specific container (e.g., the cup with the marker) as a binary repeated measure (binomial distribution, logit link). In all of our models, we included subject identity as a random intercept. The likelihood ratio test (LRT) was used to compare the overall fit of distinct models. In order to compare the participants’ performance to what was predicted by chance, we used nonparametric tests, given the discontinuous nature of our data.

2.2 Results

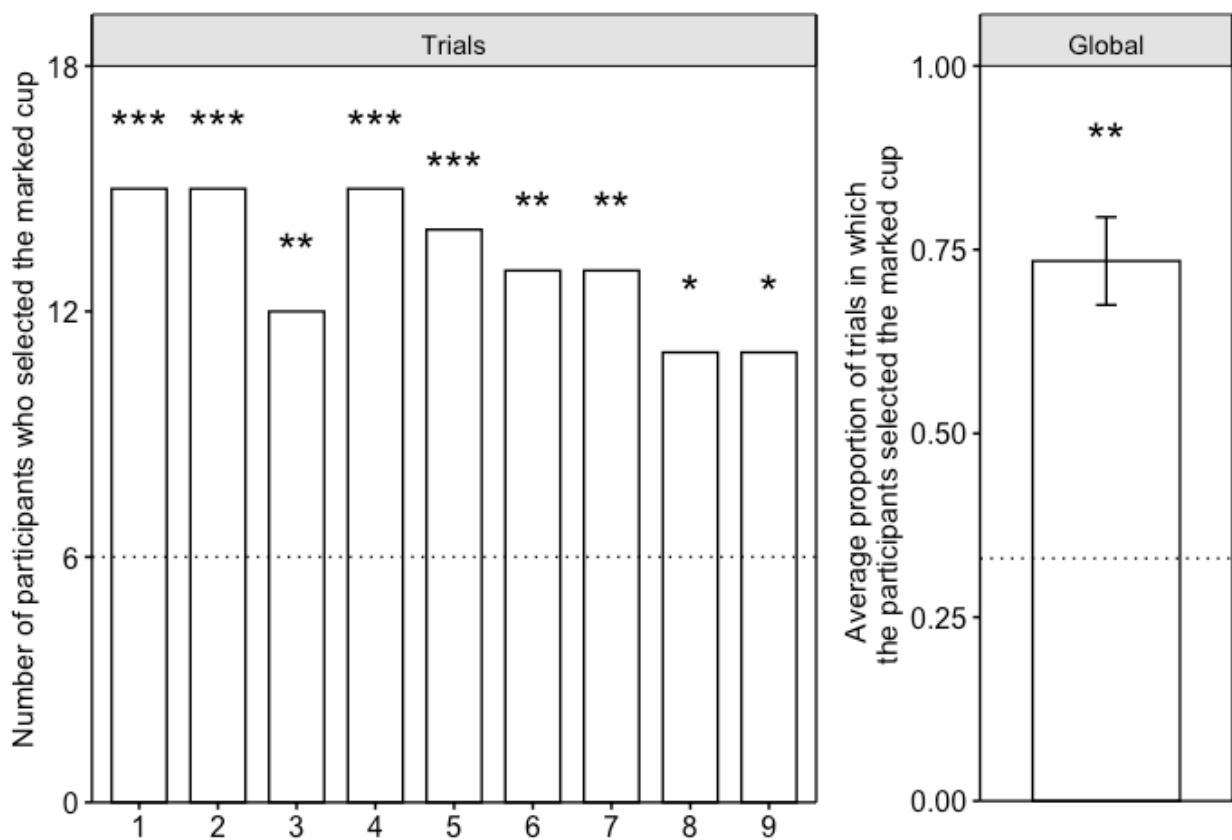
First choice of cup. When analyzing the participants’ first choice of cup, we first assessed the effect of trial by running GLMMs on the selection of the marked cup as a binary repeated measure. We fitted (1) a null model, which included only subject identity as a random intercept, and (2) an exploratory model, which added the fixed effect of Trial number (1–9) to the null model. Comparing the null model to the exploratory model revealed that adding the fixed effect of trial number to the null model significantly improved its goodness of fit by an LRT ($\chi^2(1) = 4.9, p = .027$). The exploratory model revealed a significant effect of trial number ($\beta = -.18, SE = .08, z\text{-value} = -2.14, p = .032$). Thus, the participants’ tendency to select a marked cup decreased significantly across trials in our experiment.

Next, we performed analyses on the proportion of test trials in which each participant had selected the marked cup during their first attempt. We compared the likelihood of participants selecting the marked cup first to what was predicted by chance—1/3, since there were three cups to choose from. As shown in Figure Article 2.2, the mean proportion of trials

in which the participants selected the marked cup as their first choice was significantly higher than that predicted by chance ($M = 0.74$, $M_{dn} = 0.78$, $SD = 0.25$, $Z = 168$, $p = .004$, $r = .78$, Wilcoxon signed-rank test). This result was confirmed by a trial-by-trial analysis (see Figure Article 2.2).

Figure Article 2.2

Performance During the Test Trials of Study 1.



Note: Left graph: Number of participants selecting the marked cup for each trial. Right graph: average proportion of trials in which participants selected the marked cup (error bars indicate the SEM). The dotted lines represent the level of performance predicted by chance (i.e., 1/3). Comparisons against chance by three-choice binomial tests (left graph) and Wilcoxon signed rank test (right graph).

*: $p < .05$, **: $p < .01$, ***: $p < .001$.

Second choice of cup. We did not run GLMMs to assess the effect of trial number on the participants' second attempt because they sometimes found the pompom on their first attempt, thus resulting in missing data for their second choice in multiple trials. The mean proportion of trials in which the participants selected the marked cup on the second attempt was significantly lower than that predicted by chance ($M = 0.068$, $M_{dn} = 0.056$, $SD = 0.078$, $Z = 0$, $p < .001$, $r = -1$, Wilcoxon signed-rank test). Thus, Study 1's participants had no difficulty excluding the marked cup once they had discovered that it was empty.

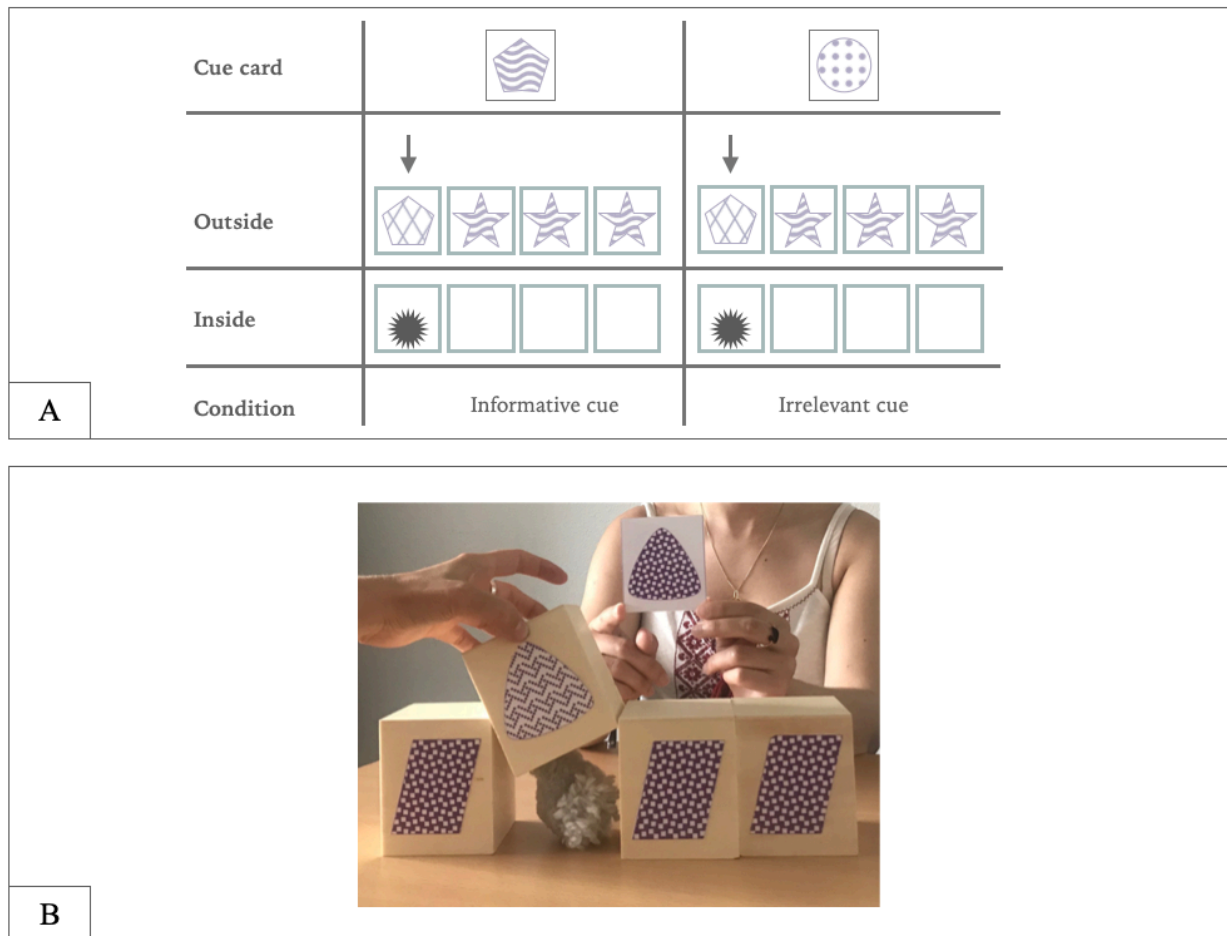
Complementary analysis. In the analyses reported above, we assumed that for each trial of Study 1, the probability of selecting the marked cup predicted by chance was 1/3 (which corresponds to randomly choosing one of the three cups). However, in Study 1, one cup was fully transparent. Thus, if children randomly chose one of the two opaque cups (while avoiding the transparent cup), the probability of them selecting the marked cup was 1/2. Subsequently, we performed additional analyses to compare the likelihood of selecting the marker to 1/2. These analyses showed the same pattern of statistically significant results as the ones reported above (see the Supplementary Materials of Article 2 for details).

2.3 Discussion

In Study 1, the novel cue used to communicate the location of the reward was ambiguous. It could be interpreted as indicating the location of the baited cup either directly (by marking it) or indirectly (by marking the empty opaque cup that needed to be excluded). Crucially, the latter interpretation was more difficult to process than the former. Although the experimenter consistently placed the marker on the empty cup, toddlers had a strong initial tendency to search for the reward under the marked cup. Thus, toddlers strongly favored the interpretation of the marker that was easier to process. This result is all the more remarkable given that our participants' second choices indicate that they could easily locate the reward by

excluding the marked cup, once they discovered that it was empty (in line with data from Gautam et al., 2021; Hill et al., 2012; Mody & Carey, 2016). In short, Study 1 suggests that by two years of age, toddlers prioritize interpretations of novel communicative cues that are less costly to process.

Study 2 tested how cognitive benefits (the second component of cost/benefit ratios) shape toddlers' interpretation of novel communicative cues. In Study 2, cognitive benefits were operationalized in terms of informativeness. In the "informative cue" condition, the participants had to find a reward hidden in one of four boxes on which symbols were glued (see Figure Article 2.3). The same symbol was glued to three of the boxes (henceforth, the repeated symbol), and a second symbol was glued to the fourth box (henceforth, the unique symbol). Before the participants could search for the reward, the experimenter showed them a cue card. The cue card shared one feature with the unique symbol and another feature with the repeated symbol. Thus, the cue card could be taken as an indicator that the reward was in the specific box marked with the unique symbol—an interpretation that maximally reduced the participants' uncertainty about the reward's location. Alternatively, the cue card could be assumed to indicate that the reward was in one of the three boxes marked with the repeated symbol—a less informative interpretation. We anticipated that toddlers would prioritize the most informative interpretation of the cue card, and thus search for the reward inside the box with the unique symbol. Furthermore, to test whether our participants answered on the basis of the cue card in our informative-cue condition, we also used an irrelevant cue control condition. In the latter, the experimenter communicated with a cue card whose symbol shared no common feature with any of the symbols on the boxes. Thus, in the irrelevant cue condition, the cue card carried no relevant information about the location of the reward. Accordingly, in this second condition, we anticipated that toddlers would be no more likely than chance would predict to search for the reward inside the box with the unique symbol.

Figure Article 2.3*Study 2's Stimuli.*

Note: Panel A: Schematic representation of the stimuli in Study 2. The gray arrows indicate the locations of the pompom. Panel B: Picture of actual experimental materials.

3 Study 2**3.1 Method****3.1.1 Participants**

In Study 2, the participants were divided into two groups of 18 two-year-old toddlers (informative cue condition: $M_{age} = 28.94$ months, $range = 24-37$ months, $SD = 3.83$; irrelevant cue condition: $M_{age} = 28.83$ months, $range = 24-36$ months, $SD = 4.00$). Each participant was tested once in a single condition. Ten additional participants were excluded from the analysis

for the following reasons: refusal to complete the whole experiment (5), failing to understand the task, that is, choosing an empty box for two or more trials during the warm-up phase (3), and technical issues (2).

3.1.2 Materials and set-up

The materials used in Study 2 were the same as those used in Study 1, with the following changes. Instead of searching for the reward inside the cups, the participants had to find the pompom in one out of four upside-down wooden boxes of identical size and shape (8 cm × 8 cm × 10 cm each). During the warm-up phase, plain boxes without symbols were used. During the test phase, each box had a symbol glued on its front face, and the experimenter communicated with the child using cue cards (7 cm × 8 cm) on which symbols had been drawn. Each symbol had a shape and was filled with a colored pattern. To create all the symbols used in the experiment, we used eight different shapes (circle, crescent, parallelogram, pentagon, rhombus, rounded-corner triangle, square, and star) and eight different patterns (small confetti, colored dots, diamonds, Scottish tartan, waves, interweaved patterns, white diagonal bricks, white dots on a dark background).

3.1.3 Procedure

Warm-up phase. The warm-up phase procedure was the same for all conditions. This was identical to the warm-up phase of Study 1, with the following exceptions. First, there were four warm-up trials (instead of three). Second, the experimenter did not hide the reward under the cups, but under one of four identical plain boxes (without symbols on their front side). The location of the box containing the pompom on the cardboard tray (outer left, central left, central right, or outer right position) was counterbalanced across trials within participants. The warm-up phase was followed by a test phase.

Test phase. Eight consecutive test trials were divided into two blocks of four trials. The test trials were identical to the warm-up trials, with the following exceptions.

First, during the test phase, symbols were glued to the front face of the boxes used to hide the reward. The front face of the boxes was turned toward the participant throughout the test phase. For each test trial, one symbol—repeated symbol—was glued to three of the boxes. A different symbol—the unique symbol—was glued to the fourth box (see Figure Article 2.3). The shape and pattern of the unique and repeated symbols varied from trial to trial. For each participant, we used four different unique symbols and four different repeated symbols in each of the two blocks of test trials. Each symbol glued on the boxes was used as a unique symbol for half of the participants, and as a repeated symbol for the other half. In each test trial, all the symbols glued on the boxes were of the same color (green, blue, purple, or orange).

Second, during Study 2's test phase, the experimenter did not show the participant where she hid the pompom. Instead, before hiding the pompom, the experimenter placed the large cardboard screen on the table between the cups and the participant. In all conditions, the experimenter always hid the pompom under the box with the unique symbol. We randomized across trials the location of the box with the unique symbol on the cardboard tray (outer left, central left, central right, or outer right position). After hiding the pompom, the experimenter removed the screen from the test table and asked, "*Where is the pompom?*" Next, she communicated with the child by holding up a cue card and saying, "*Hey, look!*" while pointing at the symbol on the card.

The pairings between the cue cards and boxes differed across conditions. In the test trials of the informative cue condition, the symbol on the cue card was ambiguous because it shared a different common feature with the unique symbol and with the repeated symbols on the boxes. For each participant, in half of the trials, the symbol on the cue card had the same shape as the unique symbol, and the same filling pattern as the repeated symbols; in the other half of the trials, the opposite was true. Thus, in the informative condition, the symbol on the cue card could be used to refer either to the box with a unique symbol, or to the three boxes

with repeated symbols. However, the most informative interpretation of the cue card was that it referred to the unique symbol, which resulted in a maximal reduction of the participants' uncertainty about the location of the reward (Figure Article 2.3).

In each test trial of the irrelevant cue condition, the symbol on the cue card had no common feature with the symbols glued on the boxes, that is, its shape and filling pattern were different from those of the unique and repeated symbols. Thus, in the irrelevant cue condition, the cue card provided no information about the location of the reward. To achieve this result, we used the same sets of boxes and cue cards as in the informative condition, and simply modified which cue card was paired with each given set of boxes.

In all conditions, after showing the cue card to the participant, the experimenter pushed the cardboard tray toward them, while asking again, "*Where is the pompom?*" Next, the participant was left to freely search inside the boxes until they found the pompom. At that point the trial ended.

3.1.4 Coding

For each trial, we coded which box the participants chose first, that is, which box they lifted first above the table. The participants received a score of 1 for each trial in which they selected the box with a unique symbol and 0 otherwise. All the data were coded by the first author, and a second coder, who was unaware of the hypotheses of the study, double-coded 50% of the videos. There was a high correlation between the two raters' evaluations of whether the participants had selected the box with the unique symbol (Spearman's $\rho = .98, p < .001$). Disagreements were resolved through discussion.

3.2 Results

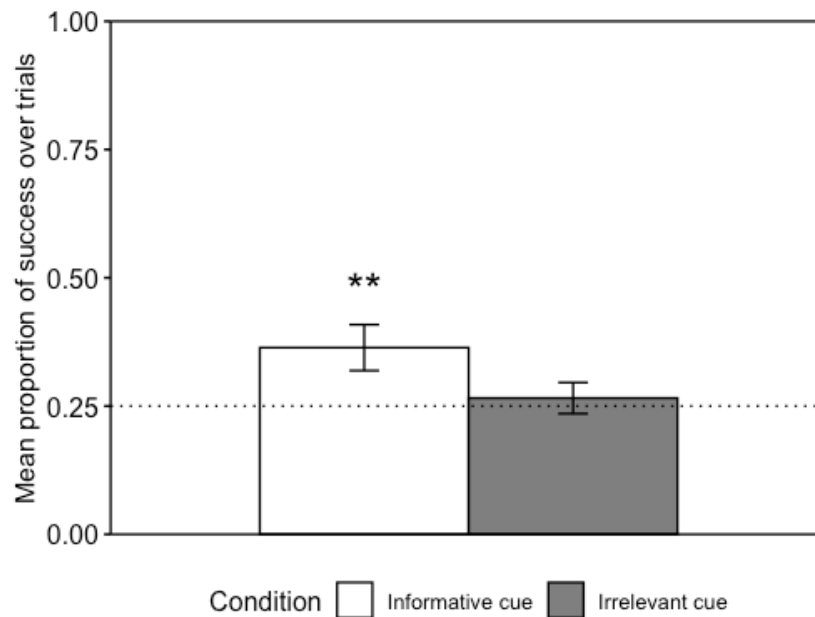
To assess the respective effects of condition and trial number, we ran GLMMs with the participants' choice of the container with the unique symbol as a binary repeated dependent

measure. We fitted (1) a null model, which included only subject identity as a random intercept; (2) a test model, which added the fixed effect of Condition (informative-cue vs. irrelevant-cue) to the null model; and (3) an exploratory model, which added the fixed effect of Trial number (1–9) to the test model. Comparing the null model to the test model revealed that adding Condition (Informative vs. Irrelevant cue) to the null model improved its goodness of fit by a LRT in a marginally significant manner ($\chi^2(1) = 3.17, p = .075$). The goodness of fit of the exhaustive model tended to be better than the test model's goodness of fit in a marginally significant manner ($\chi^2(1) = 3.40, p = .065$), thus indicating that the effect of trial number on participants' performance was marginally significant in Study 2. The exhaustive model revealed a marginally significant main effect of Condition ($\beta = -.46, SE = .26, z\text{-value} = -1.79, p = .074$) showing that children tended to select the box with the unique symbol more often in the informative cue-condition than in the irrelevant cue condition. The exhaustive model also revealed a marginally significant main effect of Trial number ($\beta = .10, SE = .06, z\text{-value} = 1.83, p = .067$) suggesting that children's tendency to select the box with the unique symbol tended to increase across trials.

Next, we performed subsequent analyses on the proportion of test trials in which each participant selected the box with the unique symbol during their first attempt. As shown in Figure Article 2.4, the average proportion of trials in which the participants first chose the box with the unique symbol was significantly higher than predicted by chance (1/4), since there were four boxes to choose from in the informative-cue condition ($M = 0.36, SD = 0.19, M_{dn} = 0.38, Z = 121, p = .006, r = .78$, Wilcoxon signed-rank test), and it did not differ significantly from what was predicted by chance in the irrelevant-cue condition ($M = 0.27, SD = 0.13, M_{dn} = 0.25, Z = 28, p = .55, r = .24$, Wilcoxon signed-rank test; $BF_{01} = 3.23$, Bayesian Wilcoxon signed-rank test).

Figure Article 2.4

Performance During the Test Trials of Study 2 per Condition (Informative cue and Irrelevant cue Conditions).



Note: Mean proportion of success in all trials (error bars indicate the SEM). The dotted lines represent the level of performance predicted by chance (1/4). Comparisons against chance by Wilcoxon-signed rank tests.

†: $p < .10$, *: $p < .05$, **: $p < .01$

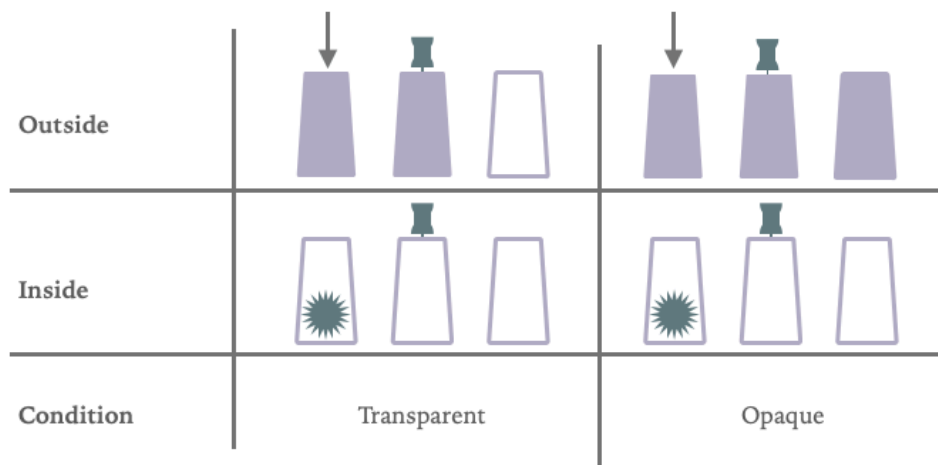
3.3 Discussion

The results of Study 2's informative cue condition suggest that toddlers prioritized the most informative interpretation of the ambiguous novel cue, that is, the one that maximized their reduction of uncertainty about the location of the toy. It is likely that the children's choice of the box with the unique symbol in the informative cue condition was guided by the cue card. Indeed, in the irrelevant cue condition, the participants did not select the box with the unique symbol more often than what is predicted by chance. However, the effect of condition on children's performance was only marginally significant ($p = .074$), thus calling for caution when interpreting our data.

We addressed this issue in Study 3 by testing the effects of cognitive benefits in a different paradigm. In Study 3, the participants were enrolled in a hiding game comparable to that of Study 1, with two main changes. First, we added a familiarization phase to help the participants overcome their tendency to select the marked cup (since Study 1 evidenced a very strong influence of cognitive costs that resulted in toddlers' near-systematic selection of the marked cup). Second, the participants were enrolled in one of two conditions, the transparent condition or the opaque condition (see Figure Article 2.5). In the test phase of the "transparent condition" two of the cups used to hide the reward were opaque, while the third one was transparent. The experimenter placed the marker on top of the empty opaque cup. Thus, in the transparent condition, assuming that the marker was placed on an empty cup was sufficiently informative to discover the location of the reward (by excluding the marked cup). In contrast, in the "opaque condition," the three cups used for hiding were opaque. In this case, assuming that the marker was placed on an empty cup was not sufficiently informative to discover the location of the reward (after excluding the marked cup, there were still two possible locations left for the reward). Subsequently, if toddlers prioritize interpretations of the marker that are informative enough to discover the location of the reward, they should be less likely to assume that the marker indicates the empty location in the opaque condition than in the transparent condition.

Figure Article 2.5

Schematic Representation of Study 3's Stimuli per Condition.



Note: The gray arrow indicates the location of the pompom. The gray pin represents the marker placed by the experimenter.

4 Study 3

4.1 Method

4.1.1 Participants

In Study 3, the participants were divided into two groups of 18 two-year-old toddlers (transparent condition: $M = 29.22$ months, $range = 23\text{--}35$ months, $SD = 2.92$; opaque condition: $M = 29.22$ months, $range = 23\text{--}37$ months, $SD = 4.11$). Each participant was tested once in a single condition. Four additional participants were excluded from the analysis because they refused to complete the experiment.

4.1.2 Materials

The materials used in Study 3 were the same as those used in Study 1, with the following changes. All the opaque cups were of the same color (purple) and had a transparent window ($4\text{ cm} \times 4\text{ cm}$) on their side, thus making it possible for the participants to see the contents of a cup when the window was facing them. In the transparent condition we used a

fully transparent cup and two opaque ones, and in the opaque condition we used three opaque cups (Figure Article 2.5).

4.1.3 Procedure

Warm-up phase. The warm-up trials of Study 3 followed the same procedure as in Study 1 (after hiding the pompom in full view of the participant, the experimenter encouraged them to search for it). During the warm-up phase, the cups' transparent windows were turned away from the participant. The warm-up phase was followed by a familiarization phase.

Familiarization phase. The familiarization trials of Study 3 followed the same procedure as the test trials of Study 1, except that the cups' transparent windows were turned toward the participant, thus making it possible for them to see the cups' contents. Therefore, in each familiarization trial, the experimenter hid the pompom under one of the opaque cups, while an opaque cardboard screen prevented the participant from seeing where the pompom was placed. Next, the experimenter removed the screen from the test table and placed the marker on an empty opaque cup before encouraging the participant to search for the pompom. Crucially, during the familiarization trials, the participant could see the contents of the cups through the transparent windows. Three consecutive familiarization trials were conducted, followed by the test phase.

Test phase. The test trials of Study 3 followed the same procedure as Study 3's familiarization trials, except that the opaque cups' transparent windows were turned away from the participant, thus making it impossible for them to see inside these cups. Nine consecutive test trials were conducted.

During the warm-up, familiarization, and test phases of all the conditions, we counterbalanced the locations of the baited cup and of the cup on top of which the marker was placed (to the left of, in front of, or to the right of the child) across trials for each participant. During the warm-up, familiarization, and test phases of the transparent condition, we also

counterbalanced the location of the fully transparent cup (to the left of, in front of, or to the right of the child) across trials for each participant.

4.1.4 Coding

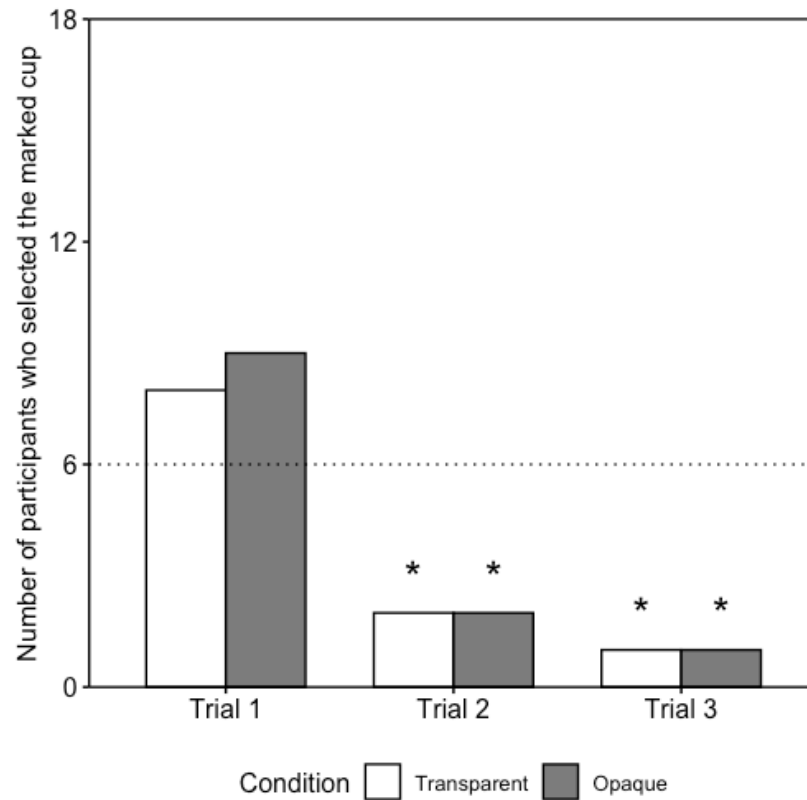
We coded the participant's first choice (i.e., which cup they lifted first) for all familiarization and test trials. For the test trials, we also coded the participant's second choice of cup when they did not discover the reward in the cup that they chose first. For the familiarization trials, we did not code the participants' second choice, since during the familiarization phase, the participants found the reward very often from their first choice. All the data were coded by the first author and a second coder, who was unaware of the hypotheses of the study, double-coded 50% of the videos. There was a high correlation between the two raters' evaluations of whether the participants selected the marked cup during their first and second choices (Spearman's $\rho = .99, p < .001$).

4.2 Results

Familiarization phase. As shown in Figure Article 2.6, from the second familiarization trial onward, in both conditions, the participants selected the marked cup significantly less often than what is predicted by chance. Thus, by the end of the familiarization phase, the participants managed to exclude the cup on which the marker was placed.

Figure Article 2.6

Number of Participants who Selected the Marked Cup for Each Trial of Study 3's Familiarization per Condition.



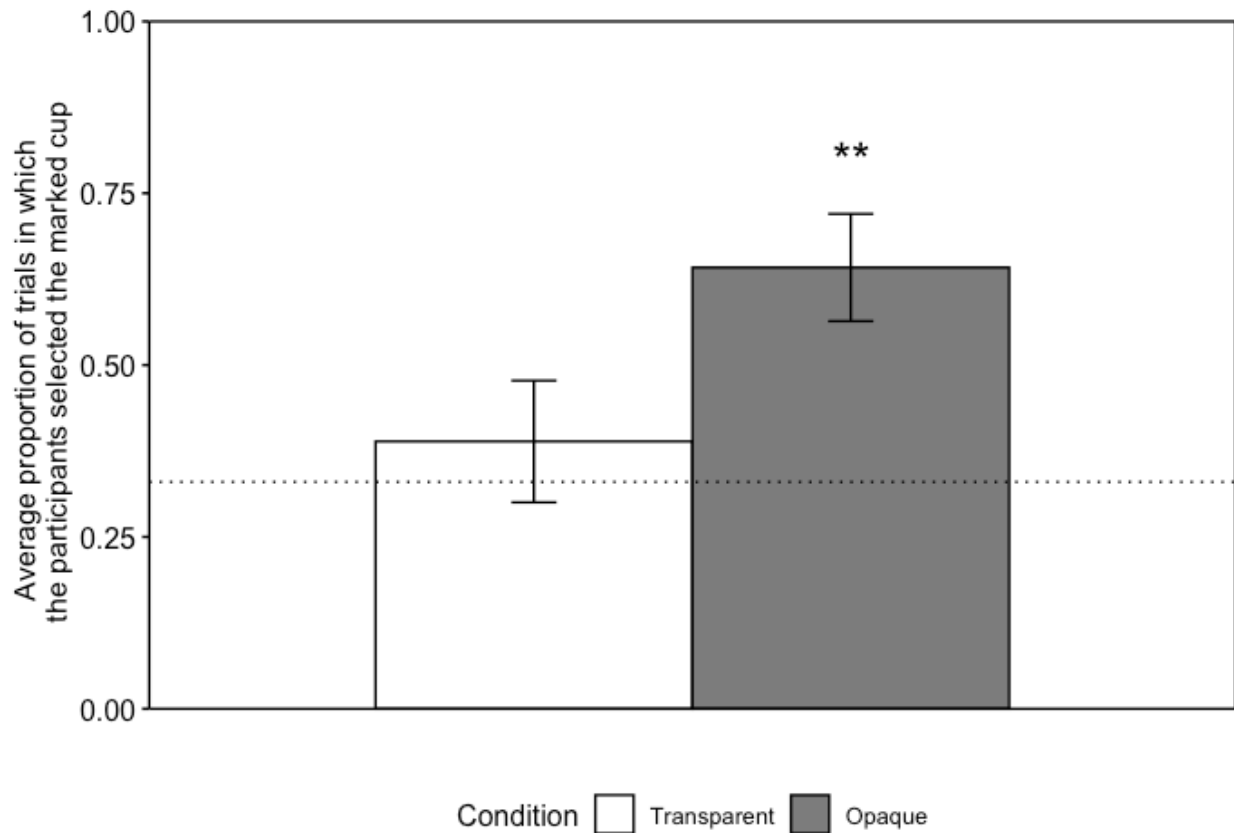
Note: The dotted lines represent the level of performance predicted by chance (i.e., 1/3). Comparisons against chance using four-choice binomial tests.

*: $p < .05$.

Test phase - First choice. We assessed the effect of our factors by running GLMMs on the participants' first choice as a binary repeated dependent measure. We fitted (1) a null model, which included only subject identity as a random intercept, (2) a test model, which added the fixed effect of Condition (transparent vs. opaque) to the null model, and (3) an exploratory model, which added the fixed effect of Trial number (1–9) to the test model. Comparing the null model to the test model revealed that adding the fixed effect of Condition to the null model improved significantly its goodness of fit by a LRT ($\chi^2(1) = 4.09, p = .043$). The resulting test

model revealed a significant main effect of Condition, indicating that the participants were less likely to select the marked cup in the transparent condition than in the opaque condition ($\beta = 1.79$, $SE = 0.86$, $z\text{-value} = 2.08$, $p = .038$). The goodness of fit of the exploratory model did not differ from that of the test model ($\chi^2(1) = 0.36$, $p = .55$), thus revealing no statistically significant effect of Trial number on the participants' performance.

Next, we performed analyses on the proportion of test trials in which each participant had selected the marked cup during their first choice. As shown in Figure Article 2.7, during Study 3's test phase, the average proportion of trials in which the participants first selected the marked cup was significantly higher than predicted by chance in the opaque condition ($M = 0.64$, $SD = 0.33$, $M_{dn} = 72$, $Z = 155$, $p = .003$, $r = .81$, Wilcoxon signed-rank test), but not in the transparent condition ($M = 0.39$, $SD = 0.38$, $M_{dn} = 0.33$, $Z = 95$, $p = .694$, $r = .11$, Wilcoxon signed-rank test; $BF_{01} = 3.10$, Bayesian Wilcoxon signed-rank test).

Figure Article 2.7*Performance During the Test Trials of Study 3.*

Note: Average proportion of trials in which the participants selected the marked cup per condition (error bars indicate the SEM). The dotted lines represent the level of performance predicted by chance (i.e., 1/3). Comparisons against chance by Wilcoxon-signed rank tests

*: $p < .05$, **: $p < .01$, ***: $p < .001$

In the transparent condition, the average proportion of trials in which the participants first selected the marked cup did not differ significantly from what was predicted by chance. Yet, children did not behave randomly in this condition. In fact, in the transparent condition, participants tended to use systematic strategies. One could consider that in Study 3's transparent condition, the participants used a systematic strategy if they selected one specific cup (e.g., the marked cup, or the unmarked opaque cup) more often than chance would predict, that is, for eight or more trials out of nine. More participants selected the marked cup

systematically, in this sense, than what is predicted by chance (four participants out of 18, $p < .001$, $g = -0.28$, binomial test, with a proportion predicted by chance equal to .00097). Similarly, more participants selected the unmarked opaque cup systematically than what is predicted by chance (seven participants out of 18, $p < .001$, $g = -0.11$, binomial test with a proportion predicted by chance equal to .00097). Finally, we assessed the proportion of participants who did not systematically avoid or select the marked cup (i.e., selected the marked cup in at least two trials, or seven trials at most). This proportion was significantly lower than that predicted by chance (seven participants out of 18, $p < .001$, $g = -0.11$, binomial test, a proportion predicted by chance equal to .86). Thus, in Study 3's transparent condition, children tended to use one of two strategies: either systematically selecting the marked cup or systematically selecting the unmarked opaque cup.

Test phase - Second choice. As in Study 1, we did not run GLMMs on the participants' second choice of cup because of missing data for the trials whose participant found the reward during their first choice. In Study 3, the proportion of trials whose participant selected the marked cup as their second choice was significantly lower than that predicted by chance in both conditions (transparent: $M = 0.0086$, $SD = 0.031$, $M_{dn} = 0$, $Z = 0$, $p < .001$, $r = -1$; opaque: $M = 0.072$, $SD = 0.11$, $M_{dn} = 0$, $Z = 0$, $p < .001$, $r = -1$; Wilcoxon signed-rank tests), thus confirming that participants could exclude the marked cup once they had discovered that it was empty.

Complementary Analysis. As in Study 1, in Study 3's transparent condition, if children randomly chose one of the two opaque cups (while avoiding the transparent cup), they should have selected the marked cup with a probability of 1/2. Subsequently, we performed additional analyses on the data from Study 3's transparent condition, while comparing the proportion of participants' choice of the marked cup to 1/2. These analyses showed the same

pattern of statistically significant results as the analyses reported above (see the Supplementary Materials of Article 2 for details).

5 General Discussion

Our data suggest that toddlers prioritize interpretations whose cost/benefit ratios are high, when processing unfamiliar communicative cues. In all three studies, children had to interpret a novel cue in order to locate a reward hidden under one of several containers.

Study 1 provides evidence of the effect of costs on toddlers' interpretations. In Study 1, the experimenter always placed an unfamiliar communicative cue (a marker) on one of the two opaque cups. This communicative gesture could receive a large number of possible interpretations, two of which contradicted each other and differed in ease of processing. The marker could be interpreted as directly indicating the location of the cup containing the reward (by being placed on top of it). An alternative and costlier interpretation of the marker was that it indicated the location of the empty opaque cup, thereby allowing the participants to discover the location of the reward (by excluding the marked cup). Among these two possible interpretations, children favored the one that was less costly, despite receiving repeated feedback showing that the marker was always placed on the empty opaque cup. Thus, Study 1 provides evidence for toddlers' tendency to resist assigning meanings that are comparatively harder to process when alternative, easier to process interpretations are available.

Studies 2 and 3 provide evidence for the effect of cognitive benefits on toddlers' interpretations. In Study 2, participants had to choose between two interpretations of a visual symbol, which could be taken to refer either to the pattern or to the shape of the image placed on the container containing the reward. Overall, toddlers were more likely to choose the most informative interpretation of the symbol, that is, the interpretation that reduced their uncertainty about the location of the reward. In Study 3, toddlers participated in a hiding game in which a

marker was placed on an empty cup. Importantly, interpreting the marker as an indicator of the empty location was less informative in the opaque condition than in the transparent condition. Accordingly, participants were more likely to keep searching for the reward under the marked cup in the opaque condition compared to the transparent condition. Thus, Study 3's results suggest that toddlers are less likely to discover the meaning of novel cues when these are used in an insufficiently informative manner. The data of Studies 2 and 3 dovetail with results showing that preschoolers assign meanings to labels by assuming that speakers are informative (Bohn, Tessler, Merrick, et al., 2019; Frank & Goodman, 2014). Here, we provide evidence for a comparable learning strategy in younger children (toddlers) when discovering the meaning of novel non-verbal cues. These results also indicate that the expectations of informativeness, found for labels, can be extended to other types of ostensive communication, including unfamiliar ones.

Interestingly, Studies 1 and 3 provide further evidence for toddlers' tendency to treat novel communicative cues as if they were accurate (a property that contributes to the cognitive benefits of a piece of information). In Study 1, and in the opaque condition of Study 3, toddlers kept searching for the reward under the marked cup throughout the whole experiment, even though it was always empty. These results are all the more remarkable given that the same participants successfully excluded the marked cup in their second choice. Thus, Studies 1 and 3 provide strong evidence for the fact that toddlers expected the marker, an unfamiliar cue, to be accurate. Previous studies have shown that, by preschool age, children expect information conveyed by familiar means to be accurate. On the production side, three-year-old children show a robust disposition to communicate accurately, which is mostly evidenced by their difficulty in lying. For example, in Mascaro, Morin, and Sperber (2017), three-year-olds demonstrated the ability to hide information and attempted to create false beliefs in others in a simple competitive setting; however, they communicated honestly in the same competitive

situation, when given an opportunity to do so, to the point of masking their deceptive abilities. On the reception side, young preschoolers find it hard not to trust familiar communicative cues, such as pointing and testimony, even if the informant is misleading (Heyman et al., 2013; Jaswal et al., 2010; Mascaro & Sperber, 2009; Vanderbilt et al., 2011). Here, we provide evidence suggesting that expectations of accuracy guide the processing of novel communicative cues, from toddlerhood onward. Thus, Studies 1 and 3 provide additional evidence for the role of cognitive benefits in shaping toddlers' interpretation of novel cues, since the accuracy of a piece of information is one of the factors that contributes to its cognitive benefits. In short, our results suggest that toddlers prioritize interpretations of novel cues (i) whose processing costs are low, and (ii) whose cognitive benefits are high.

Our findings can be explained by two types of processes (not mutually exclusive). First, they may arise as a consequence of cognitive systems' tendency to be geared toward efficiency. *Ceteris paribus*, minds should be built to prioritize processes that yield important effects, while reducing the associated costs (Chater & Vitányi, 2003; Sperber & Wilson, 1995). As a result, the cognitive system should prioritize simpler hypotheses over more complex ones when attempting to discover the meaning of a novel cue. More generally, a preference for simplicity may characterize cognition at large, such that individuals first generate simpler hypotheses (Chater & Vitányi, 2003). Thus, a preference for simplicity should lead toddlers to consider first, or to give more weight to the hypotheses about the interpretation of the marker that is easier to process.

Similarly, cognitive systems might prioritize hypotheses about cues' meanings, when the putative cognitive benefits of hypotheses are high, rather than low. We found that toddlers interpreted novel cues as if they were accurate (Studies 1 and 3) and informative (Studies 2 and 3). Some degree of accuracy is a basic property of cues (a completely inaccurate cue is not a cue at all). Likewise, hypothesis generation and hypothesis testing should favor considering

and testing first hypotheses that, if proven true, might reduce one's uncertainty. In short, minds should be built to detect cognitively useful regularities before other regularities, and to rely upon those regularities above others. Cognitively useful regularities yield important effects while having reduced costs. This general property of minds could explain toddlers' tendency to prioritize interpretations of novel cues whose cognitive benefits are high.

Second, toddlers' tendency to prioritize cognitively useful interpretations of novel cues may result from communication-specific processes. By offering information, sources of communication imply that the information they provide is cognitively useful (Frank, 2016; Sperber & Wilson, 1995). For this reason, the detection of communicative intentions may trigger specific expectations about the cognitive utility of communicated information. Such expectations should lead learners to interpret communicative means as if their cost/benefit ratios were high. Our studies were not designed to adjudicate between the role of general cognitive factors and that of communication-specific factors in shaping toddlers' interpretations of novel cues. In fact, we believe that both a general tendency to be geared toward cognitive efficiency and communication-specific expectations may jointly contribute to guiding the interpretation of novel meanings.

By favoring cognitively useful interpretations of communicative cues, learners exert pressure on communicative systems that, in turn, contribute to ensuring that their expectations of cognitive utility are warranted. In the wake of Zipf's (1935) seminal work, many studies suggest that emitters of communicative messages balance the constraint of minimizing their own efforts with the requirement to fulfill their audience's needs (Caplan et al., 2020; Maryia Fedzechkina et al., 2017; Masha Fedzechkina & Jaeger, 2020; Kanwal et al., 2017; Piantadosi et al., 2011; Zipf, 1935). The optimization of communication at the interaction level has cascading consequences on the cultural dynamics at a populational level. It is likely to lead to the emergence and stabilization of communicatively efficient systems, which are informative,

easy to process, and easy to produce (Maryia Fedzechkina et al., 2018; Gibson et al., 2019; Mahowald et al., 2018).

Our data provide direct evidence for the mechanisms that may support the emergence of efficient communicative systems, by demonstrating that learners exert pressure on communicative efficiency. First, we found that toddlers have great difficulties discovering the meaning of cues that are either too costly (because they are difficult to process, Study 1), or not beneficial enough (because they are insufficiently informative, Study 3). As a result, suboptimal uses of communicative cues are less likely to be understood by toddlers, compared to optimal ones. Second, toddlers did not just resist assigning meaning to the cues that were used inefficiently; instead, they readily reinterpreted them as if they were used efficiently. In both Study 1 and Study 3, toddlers kept assuming that the novel cue directly indicated the cup containing the reward across nine consecutive trials, and despite systematic evidence to the contrary. Thus, toddlers assigned a meaning to the cue that was consistent with it having a high cost/benefit ratio.

Therefore, our data indicate that by toddlerhood, learners shape communicative systems in at least two ways: by discovering the meaning of communicative cues more easily when they are cognitively useful, and by reinterpreting communicative cues whose cognitive utility is suboptimal. Across multiple learners and multiple generations, these two phenomena should give an advantage to the cultural transmission, diffusion, and stabilization of efficient uses of communicative cues over inefficient ones.

Article 3

The early ontogeny of expectations about speakers' informativeness

By preschool age, children interpret what is communicated to them on the assumption that speakers are appropriately informative (Frank & Goodman, 2014). Here, we investigate the nature and early development of this expectation. We tested preschoolers ($n = 73$) and toddlers ($n = 40$) in a word learning paradigm. After a familiarization phase, a speaker produced a novel label while pointing ambiguously toward a set of unfamiliar objects: one unique exemplar of a first type of object and many identical exemplars of another type of object. Thus, participants could infer that the speaker was referring to the unique exemplar by assuming that she was informative enough to allow her audience to identify what she referred to. Results reveal that expectations about speakers' informativeness develops during the first years of life. Whereas preschoolers assumed that the novel label referred to the unique exemplar (thereby demonstrating that they expected the speaker to be informative), toddlers assumed that the novel label referred to the object type present in multiple exemplars (a strategy that is consistent with tracking co-occurrence between labels and potential referents). In an additional condition, we also demonstrate that toddlers and preschoolers rely on the distribution of potential referents from the speaker's viewpoint, rather than from their own egocentric viewpoint. Altogether, the

results suggest that expectations about speakers' informativeness change greatly during early childhood, and are based on social, not perceptual, salience from the outset.

1 Background

From a very early age, infants are interested in words and they quickly learn a remarkable number of new labels (Bergelson & Swingley, 2012, 2015; Oviatt, 1980; Tincoff & Jusczyk, 1999; Werker et al., 1998; Werker & Yeung, 2005; Woodward et al., 1994). Yet, learning new labels and extracting their meaning is an extraordinarily difficult task, because any label has an infinite number of potential referents. To modify a classic example (Quine, 1960), imagine a learner who hears someone shouting “Gavagai”, while pointing toward a rabbit running away. From the learner’s viewpoint, this word could refer to the rabbit itself, or the action of running away, its tail, the color of its fur, to the events that caused the rabbit to run, and so on. Thus, discovering the meaning of words requires that learners use efficient strategies to navigate large hypothesis spaces. One of these strategies consists in drawing contextually guided inferences about what speakers intend to communicate, in other words, pragmatic inferences (Frank & Goodman, 2014; Goodman & Frank, 2016; Grice, 1989; Sperber & Wilson, 1995). Another of type of word learning strategy consists in monitoring the co-occurrence between labels and potential referents: the more often a label and a potential referent entity co-occur, the more likely it is that the label refers to that entity (Fazly et al., 2010; Siskind, 1996; Yu & Smith, 2007). Most of the time, those strategies complement one another, and toddlers probably use them both. Yet, in some cases, those strategies conflict, and the question of resolving this conflict arises. Here, we investigate how these two types of strategies interact during early development, focusing on learners’ sensitivity to speakers’ informativeness.

1.1 Pragmatic inferences

One way to take advantage of contextual information in order to discover the meaning of a novel label, consists in relying on expectations about the intentions of communicative

agents, and about the type of information that they intend to communicate. Grice, for example, famously suggested that inferences about speakers' meaning can be guided by a general expectation of cooperativeness and of speakers' adherence to a set of conversational maxims. More generally, many pragmatic theories posit that the discovery of speakers' meaning is guided by a set of appropriate expectations about the way people communicate, and about the type of information they convey. Several theories posit, for instance, that speakers are expected to be appropriately informative. This expectation is explicitly phrased in Grice's first quantity maxim which enjoins speakers to make their contribution, "as informative as is required (for the current purpose of the exchange)" (Grice, 1989). Similarly, for relevance theory, the interpretation of communicated information is guided by a presumption of optimal relevance. In this theory, "relevance" is defined in a technical way, as function of the processing costs and the cognitive effects of an utterance. The lower the processing costs, and the higher the cognitive effects, the higher the relevance of a stimulus (Sperber & Wilson, 1995; D. Wilson & Carston, 2007; D. Wilson & Sperber, 2012). Since the informativeness of a stimulus can contribute to its cognitive effects, relevance theory implies that speakers should be appropriately informative. Rational Speech Act theory, building on information theory, provides a computational framework to quantify expectations of informativeness, defined as the capacity of a stimulus to reduce uncertainty over a set of hypotheses (Goodman & Frank, 2016). For Rational Speech Act theory, listeners expect speakers to produce utterances that are helpful yet parsimonious, relative to some particular topic or goal. As a result, listeners interpret utterances by inferring what such a putatively helpful speaker might have meant, via Bayesian updating (Frank, 2016; Goodman & Frank, 2016; Goodman & Stuhlmüller, 2013; Kao et al., 2014). Despite their differences, all these theories posit that listeners will expect speakers to be appropriately informative and will use this expectation to infer the meaning of utterances.

Expecting speakers to be appropriately informative can guide a learner's discovery of an utterance's meaning (Bohn, Tessler, & Frank, 2019; Frank & Goodman, 2014; Martin et al., 2012; Stiller et al., 2015; Vouloumanos et al., 2012, 2014), by assuming that when producing an utterance or a new label, an informative speaker will intend to reduce the hearer's uncertainty regarding the new label's meaning. Such inferences guide children's word learning from preschool age. For example, Frank and Goodman (2014) created an ambiguous situation, where a speaker referred to "a dinosaur with a dax," while two dinosaurs were visible: (i) one with a bandanna, (ii) the other one with both a headband and a bandanna. Given the context the novel label "dax" could refer to the headband or to the bandanna. Yet, if the speaker would have intended to mean bandanna by saying "dax", he would not have been informative enough to enable the listener to discriminate between both dinosaur and to identify the dax. Thus, by applying an expectation of informativeness, learners could infer that the new label referred to the headband – the object uniquely present in this scene. Other studies such as Horowitz and Frank (2016), showed that children are able to infer properties based on speaker's production choices (e.g., saying "small zib" implies zib are usually bigger than this one). Recent studies also highlight the capacity of children and adults to combine common ground information with expectations about speaker informativeness when learning a new word (Bohn, Tessler, & Frank, 2019; Bohn, Tessler, Merrick, et al., 2019).

1.2 Relying on co-occurrences

Another way to take advantage contextual information to learn the labels' meanings consists in relying on co-occurrences between labels, and their potential referent. Quite simply put, the more often a given entity co-occurs with the use of a label, the more likely it is that the label refers to this entity (Fazly et al., 2010; Siskind, 1996; Yu & Smith, 2007). Evidence for such a sensitivity to statistical regularities comes from studies showing that adults and children

are capable to rapidly learn multiple word-referent pairs by accruing statistical evidence across and between multiple and individually ambiguous word-scene pairings (Akhtar & Montague, 1999; Smith et al., 2014; Smith & Yu, 2008; Suanda et al., 2014; Vlach & Johnson, 2013; Vouloumanos & Werker, 2009; Yu & Smith, 2007). For instance, Smith and Yu (2008) used a preferential looking paradigm to examine cross-situational word learning in 12- and 14-month-olds. Infants were presented on each trial with two unfamiliar pseudo-words (e.g., “bosa” and “gasser”) and two potential referents (e.g., two different unfamiliar shapes) without any information about which word went with which referent in a given trial. Although word-referent pairings were ambiguous within individual trials, they were regularities in the association between labels and shapes across trials (e.g., a star shape was always present on the screen when the label “bosa” was uttered). During this study, infants learned to look significantly longer at the shape that co-occurred more often with a given label. This work suggests that young infants’ word learning is influenced by regularities in the co-occurrences between objects, and labels. Additional studies suggest that statistical aggregation might influence new label’s learning, even in naturalistic contexts (Raz et al., 2019; Yurovsky et al., 2013; Zhang et al., 2020; Zhang & Yu, 2016).

Perhaps surprisingly, co-occurrences between labels and objects can also influence hypothesis testing processes, even when they involve very limited abilities to represent cross-situational regularities. For example, the Propose-but-verify hypothesis posits that after encountering a new label, learners form a single explicit hypothesis about its meaning. This hypothesis is then carried forward unless disconfirmed later (Berens et al., 2018; Medina et al., 2011; Trueswell et al., 2013; Woodard et al., 2016). For comparable models involving a ranking of a small set of hypotheses, see also (Dautriche & Chemla, 2014; Koehne et al., 2013; Roembke & McMurray, 2016; Stevens et al., 2017; Yurovsky et al., 2014). Even such a hypothesis testing process can be influenced by co-occurrences between labels and objects. For

example, imagine a learner hearing a novel label while surrounded by two types of novel objects, one being present in many more exemplars than the other. Assuming that the learner has no priors about the novel label's meaning, she should be more likely to hypothesize that the label refers to the object type present in more exemplars.

In short, several processes might result in an influence of statistical regularities between the occurrence of a label and potential referents on word learning. Such a sensitivity to statistical regularities when learning the meaning of novel words emerges in early infancy (for a review see Smith et al., 2014; Zhang et al., 2019).

1.3 Dealing with conflicts between pragmatic inferences, and statistical regularities

It seems plausible that young humans use a variety of strategies to discover the meaning of labels, including pragmatic inferences and tracking statistical regularities. Importantly, tracking co-occurrences, and pragmatic inferences may sometimes yield conflicting results. This type of conflict is manifest for inferences guided by expectations of informativeness. For example, when a learner hears “dax” while seeing one dinosaur with a bandanna and another dinosaur with both a headband and a bandanna, the word dax co-occurs with more instances of the category bandanna than with instances of the category headband. Thus, tracking co-occurrences should suggest that the novel label is more likely to mean refer to members of the category bandanna than to members of the category headband. Now, as we have seen, pragmatic inferences suggest just the opposite. Here, we investigate how young learners solve this conflict.

1.4 Operationalization principle

We tested how children handle conflicts between pragmatic inferences and reliance on statistical regularities in the “visible condition” of our Studies. We familiarized the participants

with videos in which an adult used a novel label while pointing ambiguously toward a row of unfamiliar objects. One object (henceforth, the unique object) differed from all the others. All of the other unfamiliar objects looked identical (henceforth, the duplicated objects). The speaker pointed ambiguously between the unique object, and a neighboring duplicated object, and uttered a novel label. The ambiguity of the speaker's point could be resolved by assuming that she was informative enough to allow her audience to identify what she referred to. Indeed, if the speaker had wanted to convey information about one of the duplicated objects, she could have pointed toward one of the duplicated objects that were far away from the unique object. As a result, expecting the speaker to be informative should have led preschoolers to assume that the speaker was more likely to refer to the unique object. In contrast, relying on co-occurrences should result in assuming that the novel label refers to the most frequent object type (since it is visually present five times in the scene $P(\text{duplicated}) = 5/6$ vs. $P(\text{unique}) = 1/6$, see Figure Article 3.1 panel A). Thus, pragmatic processes based on expectations of informativeness, and reliance on co-occurrences yielded conflicting inferences about the meaning of the novel label in the visible condition of our experiments.

We also used a "hidden condition" to assess whether children's sensitivity to informativeness takes into account what speakers can see. This condition builds on the early development of humans' sensitivity to gaze direction in a word learning context (Baldwin, 1991, 1993), and on the ability to track what speakers saw and/or missed disambiguating an ambiguous utterance (Bloom, 2002; Bohn & Köymen, 2018; Grosse & Tomasello, 2012; Kampa & Papafragou, 2020a; Khu et al., 2020; Mazzarella & Pouscoulous, 2020; Nadig & Sedivy, 2002; Nilsen & Graham, 2009; Nurmsoo & Bloom, 2008; Papafragou et al., 2017; Southgate et al., 2010). In this hidden condition, the speaker could only see one exemplar of each of the two object types. The other exemplars of the duplicated object type were hidden from the speaker behind an occluder, while remaining visible to the participant. If children take

into account what the speaker can see, they should assume that the novel label is equally likely to refer to any of the two object types in this hidden condition.

In all of our conditions, we assessed participants' word learning in a lexical decision test, in which the participants had to identify the referent of the novel label. We tested preschoolers (Study 1), and 18-month-old toddlers (Study 2)

1.5 Ethical statement

The research reported in this manuscript followed the guidelines of the declaration of Helsinki and was approved by the local board of preschools and by an independent ethical committee for biomedical research (CPP Sud-Ouest et Outremer III, protocol number 2018-A02157-48). The parents of all participants gave their informed written consent prior to their inclusion in the studies.

2 Study 1 - Preschoolers

2.1 Methods

2.1.1 Participants

We tested three- to five-year-old native French speakers from diverse socio-economic backgrounds. Within each age group, each participant was only tested once, in a single condition. We tested as many available participants as possible within our age range in the preschools participating in the project, thus resulting in a total sample size of seventy-nine participants (visible condition: 21 girls, 19 boys; $M_{age} = 52$ months; $SD = 7.23$ months; *age range*: 39-65 months; hidden condition: 16 girls, 23 boys; $M_{age} = 52.4$ months; $SD = 8.68$ months; *age range*: 41-70 months). Two additional participants were excluded from the analysis because of they refused to talk with the experimenter. The participants were recruited by sending an information letter through the participants' preschool. A compromise power

analysis performed using G*Power (Faul et al., 2007) revealed that the resulting sample sizes ($n > 38$ per group) yielded an implied power superior to .98 for comparisons against chance with one sample two-tailed Wilcoxon signed-rank test ($d = .8, \alpha = .05$).

2.1.2 Materials and Procedure

Preschoolers were tested in a quiet room. They sat in front of the experimenter across a child table. A tablet (10.5" 25.06x17.41x0.61 cm) was used to show the video stimuli. The participants saw four times a warm-up video followed by a label learning video.

Warm-up videos. The warm-up videos were identical in all conditions. They were used to familiarize the participants with the label learning situation, and with the fact that the speaker did not use any determiner while referring to the objects in the scene. In the warm-up videos an actress named objects placed on a table in front of her. At the beginning of each warm-up video, a red curtain rose to reveal the actress and five objects placed on a table: a ball, a shoe, a cat plush toy, a spoon, and an unfamiliar object (a green round shape object with spikes and a black sort of handle). The actress greeted the viewer and looked at the objects while saying, "*Hello! Look at all those toys!*". Then, she named the objects one by one while pointing at them one by one: "*Ball, shoe, cat, spoon, nuve*". We included an unfamiliar object (referred by the pseudo-word "nuve") to familiarize the participants with the possibility that the actress might use novel labels. At the end of the warm-up video, the red curtain was lowered so as to hide the actress, and the objects disappeared from the table. After each warm-up video, the participants saw a label learning video.

Label learning videos. At the beginning of all labels learning videos, the curtain was lowered, thus hiding the actress. The next parts of the label learning videos differed across conditions. In the visible condition, a horizontal row of six unfamiliar objects appeared all at once on the table. Five of the unfamiliar objects were visually identical (henceforth the duplicated objects). Another, different unfamiliar object was placed at one end of the row

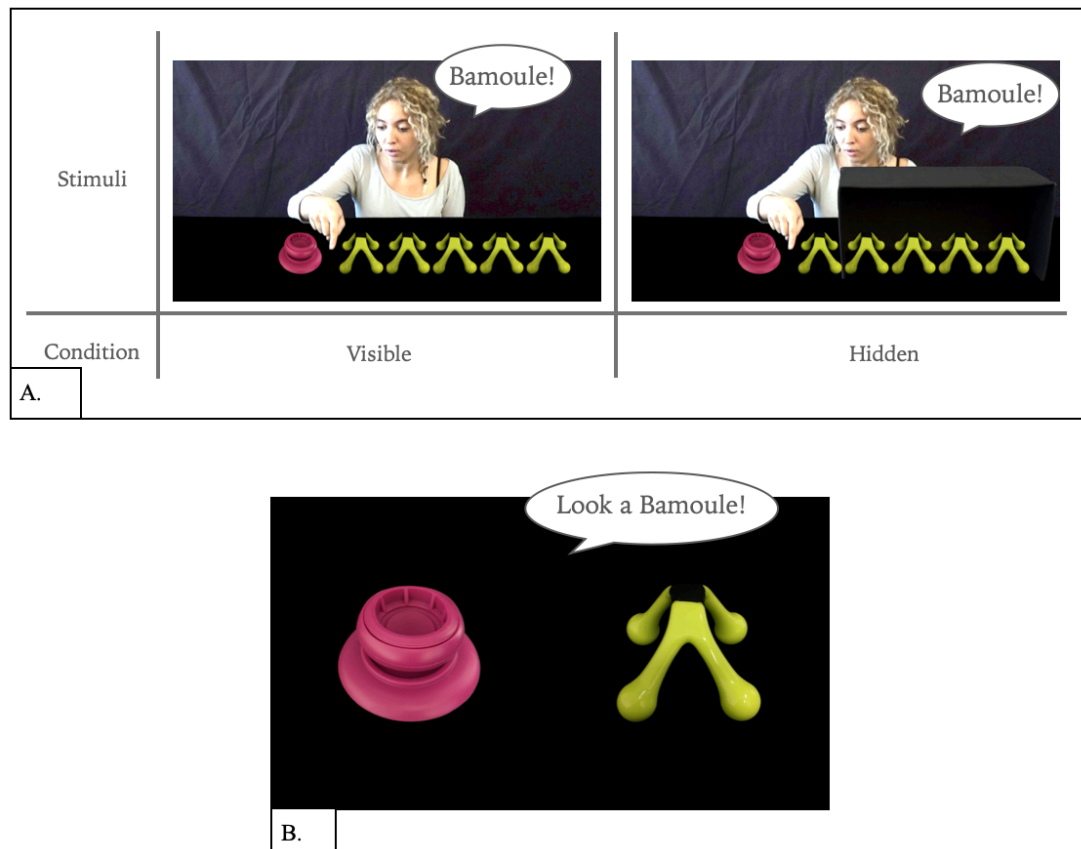
(henceforth, the unique object). Next, the curtain was raised, revealing the actress. The actress looked toward the objects, and she expressed surprise at seeing the objects by raising her eyebrows, and by saying, “Oh!”. Next, she pointed ambiguously in between the unique object, and the neighboring duplicated object (see Figure Article 3.1, panel A), and she uttered a pseudo-word “*Bamoule!*” (this novel label was selected because it sounds like a French word, see Havron et al., 2019). Next, she kept pointing while looking toward the viewer while repeating again, “*Bamoule!*”. Last, she looked in the direction of her point, and repeated once more “*Bamoule!*” (See Figure Article 3.1 panel A). At the end of the label learning videos, the red curtain was lowered so as to hide the actress, and the objects disappeared from the table.

In the hidden condition, the label learning videos were the same as in the visible condition, except that an occluding screen appeared on the table, right before the curtain was raised. The occluding screen hid all the identical objects from the actress, apart from the one that was located next to the unique object (see Figure Article 3.1, panel A). Thus, from her viewpoint, the actress could see only two objects: one of the duplicated objects, and the identical object. All the objects remained visible from the participants’ viewpoint.

In both conditions, we used two unfamiliar objects in the label learning videos: a green plastic object with four legs and a pink silicone oval shaped object. For half of the participants the green object was duplicated, and the pink one was unique. For the other half of the participants, we used the opposite pattern. We also counterbalanced between subjects the side of the screen on which the unique object was located (right vs. left).

Figure Article 3.1

Critical Events of Studies 1 and 2.



Note: Panel A: Schematic representation of the two conditions of Studies 1 and 2. Panel B: Picture from the test phase.

Test phase. After seeing four warm-up videos each followed by a label learning video, the participant was enrolled in the test phase, which consisted of a two Alternative Forced Choice (2AFC) task. The test phase was identical in all conditions. In each of the test trials, the participants saw one exemplar of the duplicated and of the unique objects, each of them on one side of the tablet's screen, on a black background (see Figure Article 3.1 panel B). The experimenter invited the participant to point at the object that was referred to by the novel label by asking a test question (e.g., “*Where is the bamoule?*”). A trial ended once the participant answered the test question (if needed the experimenter repeated the test question till the participant answered). Next, the subsequent test trial started. There were four consecutive test

trials, thus resulting in four measures (one after each test question). The test questions differed from trial to trial and were the following: “*Can you show me the bamoule?*” (trials 1 and 3), and “*Where is the bamoule?*” (trials 2 and 4). During the test phase, we counterbalanced the side of the screen (right or left) on which each of the two unfamiliar objects appeared across trials.

2.1.3 Data Analysis

For each test trial, we coded whether participants pointed at the unique object (coded as 1) or at the duplicated object (coded as 0). For each participant, we summed the binary scores from each of the four test trials, thus resulting in a global score ranging from 0 to 4.

Data were coded by the first author. A second coder unaware of the hypotheses of the study double coded 100% of videos in each condition. Inter-rater agreement was maximal (*Cohen's k* = 1, 100% of agreement). All the statistical analyses reported in this paper were two-tailed. Frequentist statistics were computed using R (v. 4.0.3; R Core Team, 2020). We assessed the effect of Age using generalized linear mixed model regression analysis (GLMM) performed in R with the package lme4 (version 1.1-26; Bates et al., 2015). When reported, the Wilcoxon signed-rank tests' and Mann Whitney U-tests' effect size refer to the matched rank biserial correlation of the rcompanion package (v. 2.3.27; Mangiafico, 2021). When we found null results, we conducted Bayesian tests with Jasp (version 0.14.1; JASP Team, 2020), with a Cauchy Prior Distribution set to the default value (.707). When conducting Bayesian Wilcoxon signed-rank test we used a data algorithm with 5 chains of 1000 iterations. For these analyses, we report the bayes factors expressing support for the null hypothesis over the alternative hypothesis (BF_{01}). Any value of BF_{01} larger than 3 is typically interpreted as meaningful evidence for the null hypothesis.

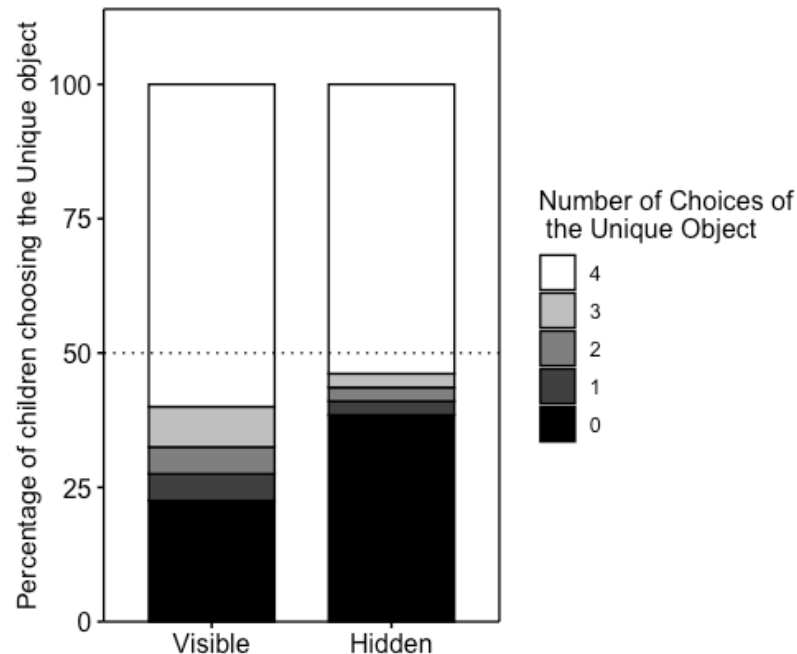
2.2 Results and Discussion

First, we tested the effect of Age on participants' score. We ran a generalized linear mixed model (binomial distribution, logit link) with the binary participant's success score as the dependent variable, including participant's identity as a random intercept, and fixed effect of Age (in month). This model revealed no main effect of Age ($Estimate = 0.059$, $SE = 0.12$, $z\text{-value} = 0.50$, $p = .62$).

The participants were enrolled in four test trials, thus resulting in a theoretical score of 2 predicted by chance. In the visible condition, preschoolers pointed toward the unique object more often than predicted by chance ($M = 2.78$, $M_d = 4$, $SD = 1.70$, $Z = 537$, $p = .009$, $r = .45$; Wilcoxon signed-rank test). In contrast, in the hidden condition, the participants' level of performance did not differ significantly from what was predicted by chance ($M = 2.31$, $M_d = 4$, $SD = 1.94$, $Z = 432$, $p = .32$, $r = .17$; Wilcoxon signed-rank test; $BF_{01} = 3.58$, Bayesian Wilcoxon signed-rank test). Yet, there was no significant statistical effect of condition (visible vs. hidden, $U = 692$, $p = 0.33$, $r = -.11$, Mann-Whitney U-test ; $BF_{01} = 3.12$, Bayesian Mann-Whitney U-test; see Figure Article 3.2).

Figure Article 3.2

Number of Selections of the Unique Object During the Test Phase per Percentage of Participant and per Condition.



Note: Comparisons against chance by one-sample Wilcoxon tests.

** $p < .01$

In the visible condition of Study 1, the actress uttered a novel label while performing an ambiguous communicative action that could refer to one of two types of novel objects. Crucially, if the speaker had wanted to refer to the category of the duplicated object, she could have been more informative by pointing toward one of the duplicated objects that were far away from the unique object. Thus, expecting the speaker to be informative should have led preschoolers to assume that the speaker referred to the unique object. Results from the visible condition confirmed this hypothesis. This evidence dovetails with previous results from Frank and Goodman (2014), and validate our stimuli. Results from the hidden condition indicate that when only two alternative objects are visible from the actress viewpoint, preschoolers no longer assume that the speaker refers to the unique object. Importantly, since there was no significant

difference in performance between the visible and the hidden condition, our data do not tell whether preschoolers' sensitivity to informativeness is modulated by what speakers can see. In Study 2, we build upon these results to test how younger participants resolve the conflict between pragmatic processes based on an expectation of informativeness, and co-occurrence tracking. To this end, we adapted our task to collect participants' non-verbal responses. We chose to test eighteen-month-olds, because by this age, infants are already capable of using contextual information to infer the meaning of novel words (Briganti & Cohen, 2011; Woodward et al., 1994).

3 Study 2 - Toddlers

3.1 Methods

3.1.1 Participants

We tested eighteen-month-old native French speakers from diverse socio-economic backgrounds. Each participant was only tested once, in a single condition. Forty participants were retained in the analysis (Visible condition: 11 girls, 9 boys; $M_{age} = 567$ days; $SD = 8.83$ days; *age range*: 551-581 days; Hidden condition: 7 girls, 13 boys; $M_{age} = 567$ days; $SD = 8.41$ days; *age range*: 555-584 days). Eighteen additional participants were excluded from the analysis because the participants cried (4), and because of technical failure (4) or incomplete eye-tracking data resulting in more than two trials with 50% of missing data (10). A compromise power analysis performed using G*Power (Faul et al., 2007) revealed that the resulting sample sizes ($n = 20$ per group) yielded an implied power equal to .94 for comparison against chance with one-sample two-tailed t-test ($d = .8$, $\alpha = .05$).

3.1.2 Materials and Procedure

Study 2 followed the same procedure as Study 1, with the following exceptions. First, the participants did not see the stimuli on a tablet. Instead, the videos were shown on an eye-

tracker's screen. Toddlers sat on their parents' knees in a soundproofed booth, 60 cm from the eye-tracking screen (Tobii Pro Spectrum 150, set in 60 Hz). We used Psychopy (v.3.0.4; Peirce et al., 2019) for stimuli presentation (associated to python v.2.7) and the Tobii Pro SDK package v.1.7. A five-points calibration adapted from the psychopy-tobii controller package was performed for each participant, prior to the presentation of the experimental stimuli.

Second, during the test phase of Study 2, we collected data about the participants' gaze behaviors. In each of test trial, the participants saw the two unfamiliar objects from the label learning videos, each of them on one side of the screen, on a black background. A voice-over invited the participant to look at the object that was referred to by the novel label by asking a prompt question (e.g., "*Did you see the bamoule?*") followed by five seconds of silence. Next, the subsequent test trial started. The side where the objects were located were switched in between test trials. There were four consecutive test trials, thus resulting in four measures (one after each prompt question). The prompt questions differed from trial to trial and were the following: "*Look! A bamoule!*" (trials 1 and 3), and "*Did you see the bamoule?*" (trials 2 and 4).

3.1.3 Data Analysis

We pre-processed the eye-tracking data with R (v. 4.0.3; R Core Team, 2020), using the package *eyetrackingR* (v. 0.1.8; Dink & Ferguson, 2015). When we found null results, we conducted Bayesian tests with Jasp (version 0.14.1; JASP Team, 2020) with a Cauchy Prior Distribution set to the default value (.707).

We analyzed the eye-tracking data collected in the test phase, during the silence period following the prompts from the voice-over (e.g. "*Did you see the bamoule?*"). We restricted our analysis to a predefined time window classically used in Two-Alternative Forced-Choice tasks, from 367 ms to 2000 ms after the onset of the novel label ("Bamoule"). Gaze behaviors

occurring outside this time window are typically assumed to be unrelated to the processing of the target label (Swingley, 2007; Swingley & Aslin, 2000).

To analyze the eye tracking data, we divided the screen centrally in two regions of 960 x 1080 pixels (i.e., the left and right side of the entire screen). For each participant, we computed the proportion of looks toward the unique object type for each 20 ms time bin by summing the time spent looking to the side of the unique object type and dividing it by the total time spent looking at the entire screen over that time bin. Next, for each participant, we averaged these proportions across all trials for each time bin, and next, across all time bins. We excluded the data from test trials for which we missed more than 50% of the data (6 trials out of 160 - 2 in the visible condition, and 4 in the hidden condition). After exclusions, each participant contributed an average of 3.9 ($SD = 0.31$) out of 4 test trials in the without occluder condition, 3.8 ($SD = 0.41$) out of 4 test trials in the with occluder condition.

We ran a cluster-based permutation analysis on the proportion of looks toward the unique object type to look for time windows revealing a significant difference between Conditions (for examples of comparable analyses see Dautriche et al., 2015; de Carvalho et al., 2019; Havron et al., 2019; for a formal presentation of the analysis itself see Maris & Oostenveld, 2007). For each 20 ms time sample, we ran a two-tailed independent t-test on the arcsin-transformed proportion of looks toward the unique object type to test for the effect of Condition (With and Without occluder). Adjacent time samples were grouped in a cluster when their t-value were be greater than a threshold corresponding to a statistically significant difference ($t = 2.06$). The size of each cluster was measured by computing the sum of all t-values within that cluster. In order to evaluate the probability that a cluster existed by chance, we ran 1000 simulations where Condition was randomly assigned for each trial. For each simulation, we computed the size of the largest cluster, just like for the real data (sum of all the t-values within a cluster of significant t-values). Clusters found in the real data were considered

meaningful if the probability of observing a cluster of the same size or bigger in the simulations was smaller than 5%, i.e., a threshold equivalent to a p-value of 0.05.

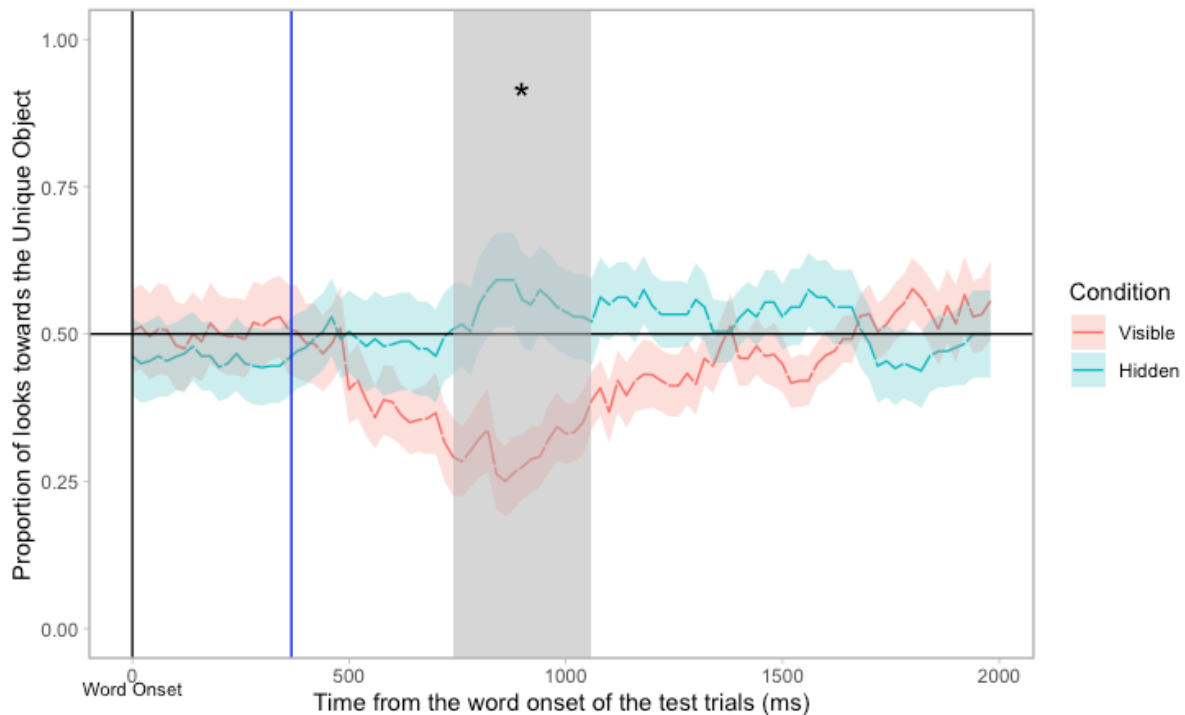
Then, we compared aggregated proportions of looks toward the Unique object type and averaged across trials, to chance level (i.e., 0.5) for both the aggregated data to the time windows revealed by the cluster-based permutation analysis.

3.2 Results and Discussion

The cluster-based permutation analysis revealed a significant time window where the proportion of looks toward the Unique object type was significantly different between conditions (Visible vs. Hidden condition, see Figure Article 3.3). This time window goes from 740 ms to 1060 ms after the onset of the novel label ($p = .018$). During this time window, the participants' mean proportion of looks toward the unique object was lower than predicted by chance in the visible condition only ($M = 0.32$, $SD = 0.23$, $t(19) = -3.54$, $p = .002$, $d = 1.42$; One Sample t-test), while it did not differ from chance in the hidden condition ($M = 0.55$, $SD = 0.32$, $t(19) = 0.70$, $p = .49$, $d = 1.71$; One Sample t-test; $BF_{01} = 3.45$, error % = .021, Bayesian One Sample t-test).

Figure Article 3.3

Proportion of Looks Toward the Unique Object During the Test Trials of Study 2 per Condition.



Note: Data are time-locked from 367 ms after the onset of the novel label (blue vertical line). Colored shading represents ± 1 SEM. A cluster-based permutation test indicates that performance differed between the visible and hidden conditions from 740 till 1060 ms (dark grey windows).

*: $p < 0.05$

In the visible condition of Study 2, toddlers looked at the duplicated object when asked to search for the referent of the novel label. Thus, they relied more on a strategy of co-occurrence tracking than on inferences based upon expecting speakers to be informative. Moreover, toddlers took into account what the speaker could see, as indicated by the effect of condition (visible vs. hidden). This result indicates that, toddlerhood onward, strategies of co-occurrence tracking are not necessarily ego-centric, and can discount object that are hidden from speakers' viewpoint.

4 General Discussion

We investigated the developmental trajectory of expectations of informativeness guiding the interpretation of communicated information in two studies testing preschoolers and toddlers. We highlighted that in word learning contexts, pragmatic inferences based on expectations of informativeness can conflict with other word learning strategies, such as co-occurrence tracking. We investigated how children deal with this conflict across development. First, we found evidence that in a context in which pragmatic inferences based on expectations of informativeness and co-occurrence tracking yielded conflicting results, three- to four-year-old preschoolers relied on pragmatic inferences to discover the meaning of an ambiguous novel label (Study 1). Thus, by three years of age, children are sensitive to expectation of informativeness in communication. These data confirm results found in previous works Frank and Goodman (2014). In contrast, 18-month-old toddlers showed the opposite pattern of results, suggesting that they relied more on co-occurrence tracking (Study 2). In short, we observed a switch in the use of expectations of informativeness expectation from toddlerhood to preschool age. These data dovetail with those of Ramscar, Dye and Klein (2013), which suggest that toddlers might rely more strongly on statistical regularities (taking into account background rates) than older children and adults when assigning meanings to novel labels.

Interestingly, our data do not necessarily show that toddlers are unable to use expectation of informativeness to engage in pragmatic inference. Toddlers' tendency to rely more on co-occurrence tracking in our study could be accounted by difficulties to engage in informativeness driven pragmatic inference. Yet, it could also be explained by weak expectations about the informativeness of speakers, or by a strong disposition to rely on co-occurrence tracking in word learning contexts.

In Study 1, the manipulation of speakers' visual access had mixed results on preschoolers' performance. When only two objects were visible from speaker's viewpoint,

preschoolers no longer selected the unique object as the referent of the novel label. Yet, they did not behave in a significantly different manner when the speaker could see all the objects (in the visible condition), or only two of them (in the hidden condition). In short, Study 1's results are compatible with the view that preschoolers can use what speakers see when engaging in pragmatic inferences. Yet, it does not provide conclusive evidence in support of this claim.

In Study 2, the effect of condition (visible vs. hidden) reached significance. This result suggests that by eighteen-month-old infants take into account what speakers can see when learning novel labels. This result dovetails with data from Nurmsoo and Bloom (2008), who showed that 2.5 and 4-year-olds take into account not just gaze direction, but also what is visible or hidden for speakers in word learning contexts. Young infants' capacity to register and use what speakers can see makes sense, given their sensitivity to what is visible for others, which develops from the first months of life onward (Choi et al., 2018; Liszkowski et al., 2007; Luo & Baillargeon, 2007; Moll & Tomasello, 2006; O'Neill, 1996; Sodian et al., 2007). Importantly, our study suggests that what is visible to others can have an impact on co-occurrence tracking. By monitoring what speakers can see when learning novel labels, toddlers can restrict the range of potential referents for novel labels, thus contributing to make word learning a much more tractable problem.

Our results open perspectives for future research. We identified a developmental switch from co-occurrence tracking to informativeness driven pragmatic inferences. Future work should identify precisely at what age this switch occurs and explore how it may be related to other developmental changes in word learning.

Article 4

How do we interpret requests for
information?

Simplified representations of knowledge
guide humans' interpretation of
information requests

This paper investigates the cognitive mechanisms supporting humans' interpretation of requests for information. Learners can only search for a piece of information if they know that they are ignorant about it. Thus, in principle, the interpretation of requests for information could be guided by representations of Socratic ignorance (tracking what people know that they do not know). Alternatively, the interpretation of requests for information could be simplified by relying primarily on simple knowledge tracking (i.e., merely tracking what people know). We judged these hypotheses by testing two-and-a-half-year-old toddlers ($N = 18$), five- to seven-year-old children ($N = 72$), and adults ($N = 384$). In our experiments, a speaker asked a question that could be disambiguated by tracking her state of knowledge. We manipulated the speakers' visuals to modulate the complexity of the ignorance representation required to disambiguate their questions. Toddlers showed no tendency to appeal to representations of Socratic ignorance when disambiguating questions (Study S1). Five- to seven-year-olds exhibited a similar pattern

of results, and they performed better when information requests could be disambiguated using simple knowledge tracking (Studies 1a-1b). Adults used representations of Socratic ignorance to interpret questions, but were more confident when simple knowledge tracking was sufficient to disambiguate information requests (Studies 2-3). Moreover, adults disambiguated questions as if speakers could request information about things that they were ignorant of, even when speakers had no reason to know about their ignorance (Studies 3-4). Thus, the interpretation of requests for information rests primarily on simple knowledge tracking—and not on representations of Socratic ignorance—a heuristic that reduces processing costs.

1 Background

Humans have a remarkable disposition to ask questions and devote cognitive resources to determine what others want to learn. Even children request information by pointing, in infancy (Begus et al., 2014; Begus & Southgate, 2012; Kovács et al., 2014), and by asking appropriate questions, toddlerhood onward (Chouinard, 2007; Kurkul & Corriveau, 2018; Ronfard et al., 2018). The capacity to formulate and interpret requests for information expands extraordinarily humans' ability to communicate cognitively useful information. This competence allows us to identify precisely others' specific informational needs, and thus, to address them. Significantly, for requests for information to play an efficient role in learning, they must be understood accurately. In this study, we investigated the nature and ontogeny of cognitive capacities supporting the interpretation of requests for information, with a particular focus on representations of ignorance. We studied the interpretation of interrogative sentences that are used to request information, referred to as "questions" (Bach & Harnish, 1979; Groenendijk & Stokhof, 1984; Karttunen, 1977; Searle, 1969).

1.1 Simple knowledge tracking and Socratic Ignorance

Humans are quite efficient in tracking what others can see, have experienced, or are aware of. This capacity develops very early during infancy (Kampis et al., 2015; Liskowski et al., 2007; Luo & Baillargeon, 2007; Moll & Tomasello, 2006; O'Neill, 1996; Sodian et al., 2007), and often operates quickly and spontaneously (Beck et al., 2018; Furlanetto et al., 2016; O'Grady et al., 2020; Samson et al., 2010). From early childhood, humans rely on their ability to track what speakers know to disambiguate their meanings (Bohn & Köymen, 2018; Grosse & Tomasello, 2012; Kampa & Papafragou, 2020; Khu et al., 2020; Mazzarella & Pouscoulous, 2020; Nadig & Sedivy, 2002; Nilsen & Graham, 2009; Nurmsoo & Bloom, 2008). Thus,

humans have well established and early developing capacities to track what someone saw, experienced or is aware of; we will refer to this capacity as “simple knowledge tracking”.

Importantly, simple knowledge tracking is not sufficient to build a full-blown representation of information search. Indeed, learners will not look for a piece of information unless they detect that they lack it (e.g., if John believes his cell phone is at home, when it has actually been stolen, he will not search for it even though he does not know where it is, quite simply because he does not know that he is ignorant about his cell phone’s location). Thus, building a full-blown representation of what triggers information search requires more than tracking what people do not know. It also requires determining what kind of information others are aware of lacking.

The detection of a lack of information is a basic component of information search (Bromberger, 1992; Loewenstein, 1994). Yet, monitoring the detection of a lack of information in others is far from trivial. For human adults, representing someone’s awareness of lacking a piece of information can be achieved by tracking what they know that they do not know (henceforth, “Socratic ignorance”, named as such after the Greek philosopher Socrates, who famously emphasized the importance of knowing what one is ignorant about). Representations of Socratic ignorance imply the capacity to attribute complex mental states about mental states; for example, representing, “John knows that he does not know where his cell phone is.” Thus, to represent Socratic ignorance, one needs to attribute “second-order” mental states, i.e., mental states about mental states about reality (Perner & Wimmer, 1985).

The representation of information search differs depending on whether it is achieved with simple knowledge tracking or with Socratic ignorance attribution mechanisms. To illustrate, imagine that John has left his laptop on his kitchen table and his cell phone inside the drawer of the same table. Later on, while John is absent, his friend Melissa stores both his laptop and his cell phone in John’s room, unbeknownst to him. Upon returning to the kitchen,

John can see that his laptop has disappeared (it is no longer on the table); he does not see that his cell phone has moved (since he left it inside a drawer). John asks Melissa: “*Where is it?*”. If Melissa relies on simple knowledge tracking to interpret John’s question, she will assume that John is equally likely to refer to his laptop or to his cell phone (since he is ignorant about the location of both). In contrast, if Melissa relies on representations of Socratic ignorance to interpret John’s question, she will assume that John is referring specifically to his laptop (since John knows only about his ignorance about his laptop’s location).

Thus, in principle, humans could use either simple knowledge tracking or representations of Socratic ignorance to interpret requests for information. These two mechanisms differ in complexity and accuracy. Simple knowledge tracking is arguably less complex than representations of Socratic ignorance. Yet, it can only support simplified representations of information search (it does not take into account people’s knowledge of their ignorance). The monitoring of Socratic ignorance is more complex (it involves embedded representations of knowledge about someone’s ignorance); yet, it is necessary to build a full-blown representation of information search. We tested which of these two representations of knowledge states guides the interpretation of requests for information, capitalizing on adults’ and children’s sensitivity to what people ignore when interpreting questions (Brown-Schmidt et al., 2008; Brown-Schmidt & Fraundorf, 2015; Grosse & Tomasello, 2012; Nurmsoo & Bloom, 2008). We outlined three hypotheses about the processes supporting the interpretation of requests for information, each of which makes distinct developmental predictions.

1.2 Hypothesis 1. Developmental continuity—Early use of Socratic ignorance attributions

Complex recursive reasoning about mental states is often involved in social interactions (Grueneisen et al., 2015; Siposova et al., 2021). Thus, the first hypothesis is that humans appeal

primarily to early developing representations of Socratic ignorance when interpreting information requests. The capacity to form verbal representations of Socratic ignorance appears to develop during late childhood (Miller, 2009; Perner & Wimmer, 1985; Sullivan et al., 1994). Yet, a few studies indicate that children might be able to manipulate complex second-order representations of representations at a relatively young age. For instance, four-year-old children recognize the involutive nature of falsity ascriptions — i.e., inferring « p » from « It is not true that it is not true that p » (Mascaro & Morin, 2015).

Moreover, the interpretation of requests for information might very well rest on implicit representations of Socratic ignorance, which could develop quite early. The capacity to represent what other people have seen or experienced emerges well before young children can manipulate verbal representations of knowledge and ignorance. For instance, children can answer questions about other individuals' knowledge from three years of age onward (Pratt & Bryant, 1990). Yet, humans' sensitivity to what others have seen or experienced is observed at a much earlier age, during infancy, when children's capacities are tested implicitly (Kampis et al., 2015; Liszkowski et al., 2007; Luo & Baillargeon, 2007; O'Neill, 1996; Phillips et al., 2020). Such a sensitivity to what people have seen or experienced guides the interpretation of communicated information from toddlerhood onward (e.g., Carpenter et al., 2002; Grosse et al., 2010; Grosse & Tomasello, 2012; Liebal et al., 2009; Nurmsoo & Bloom, 2008; for a review see Mazzarella & Pouscoulous, 2020). In principle, a similar discrepancy between verbally accessible representations and implicit capacities might be observed for representations of Socratic ignorance. If this were the case, young children would be able to manipulate implicit representations of Socratic ignorance well before they can talk about them, and might use them to interpret requests for information (Hypothesis 1). Validating this hypothesis would suggest that children, who answer questions from infancy onward, can form representations of second-order mental states much earlier than previously thought.

1.3 Hypothesis 2. Developmental discontinuity—From simple knowledge tracking to attributions of Socratic ignorance

A second hypothesis is that during ontogeny children start by using simple knowledge tracking to interpret requests for information, and later on shift to using attributions of Socratic ignorance when they become able to manipulate them explicitly. This hypothesis predicts that children's use of Socratic ignorance to interpret questions should appear along with their capacity to manipulate explicit verbal representations of second-order mental states, between five and seven years of age (Miller, 2009; Perner & Wimmer, 1985; Sullivan et al., 1994). Validating this hypothesis would reveal that the way humans interpret questions changes dramatically during development, and involves simple knowledge tracking, initially, and later on, attributions of Socratic ignorance, six years of age onward.

1.4 Hypothesis 3. Developmental continuity—Simple knowledge tracking

The third hypothesis is that the interpretation of information requests rests primarily on simple knowledge tracking, rather than on attributions of Socratic ignorance, both in children and adults. In order to request a piece of information that one lacks, one needs to detect that one is ignorant about that piece of information. Thus, attributions of Socratic ignorance are critical to building a full-blown representation of others' information search. However, in many cases, simple knowledge tracking is sufficient for interpreting information requests. Furthermore, tracking Socratic ignorance is costly and difficult (e.g., Arslan et al., 2017). Simply put, representing "A knows that A does not know p" is more complex than representing, "A does not know p." Thus, the interpretation of requests for information can be simplified by using simple knowledge tracking rather than representing Socratic ignorance. This heuristic should be efficient because it reduces the cognitive costs associated with processing questions. Furthermore, it should result only in infrequent mistakes that can be clarified in conversation,

and that are mostly harmless; if a speaker requests for a piece of information, and the listener replies by providing the speaker with a relevant piece of information that the speaker lacks (yet, was not aware of not knowing), the speaker still learns something useful. Thus, there are reasons to believe that the interpretation of questions may rest primarily on simple knowledge tracking. If this hypothesis is correct, even populations that can represent second-order mental states might prioritize simple knowledge tracking over representations of Socratic ignorance to interpret requests for information. Validating this hypothesis would reveal that humans appeal to a simplification heuristic when interpreting questions.

To summarize, we outlined three possible hypotheses about the interpretation of information requests. Since learners can only request a piece of information when they realize that that they lack it, the interpretation of requests for information may rely primarily on representations of Socratic ignorance. These representations could develop early and operate throughout the learner's lifespan (Hypothesis 1: Developmental continuity—early use of Socratic ignorance attributions), or they may emerge late, along with the capacity to reason explicitly about second-order mental states (Hypothesis 2: Developmental discontinuity—from simple knowledge tracking to attributions of Socratic ignorance). Alternatively, the interpretation of requests for information may rest primarily on simple knowledge tracking, a heuristic that reduces processing costs (Hypothesis 3: Developmental continuity—simple knowledge tracking).

1.5 Operationalization principle

First, we tested two-and-a-half-year-old toddlers in a live interactive paradigm testing their sensitivity to Socratic ignorance (Study S1, reported in the supplementary materials). In this initial study, toddlers showed no sensitivity to a speaker's Socratic ignorance when interpreting her questions. In subsequent studies, we investigated systematically the

mechanisms used by humans to interpret questions by testing children (Studies 1a-1b) and adults (Studies 2-4). In Studies 1a and 1b, we assessed whether the use of Socratic ignorance to interpret questions emerges along with changes in the capacity to manipulate explicit representations of second-order mental states. Thus, we tested five- to seven-year-old participants, i.e., over an age span during which the capacity to manipulate explicit representations of second-order mental states typically increases (Miller, 2009). We relied on second-order false belief tasks to assess our participants' capacity to manipulate explicit representations of second-order mental states (Perner & Wimmer, 1985; Sullivan et al., 1994).

To judge our hypotheses, we used scenarios in which adult speakers asked questions about the location of an object using a label. In all question tests, the label could refer to one of two different objects. This ambiguity could be resolved by tracking the speakers' state of knowledge. In the first-order question test, the speakers were ignorant about the location of only one of the two objects. Thus, it was possible to disambiguate what the speakers wanted to learn by using simple knowledge tracking. In the second-order question test, the speakers were ignorant about the location of both the objects; notably, the speakers knew about their ignorance of the location of only one of the two objects. Thus, it was possible to disambiguate what the speakers wanted to learn, by tracking what they knew that they did not know, but not merely by tracking what they did not know. In both the first-order and second-order question tests, we assessed participants' interpretations of the ambiguous information request.

In Study 1a, we tested five- to seven-year-olds on a first-order question test in which they could determine the meaning of a request for information by using simple knowledge tracking. Thus, Study 1a served to validate our stimuli and our data analysis procedure, and to estimate the sample sizes required for testing children's sensitivity to Socratic ignorance in Study 1b (as a result, Study 1a was tested before Study 1b, and is reported first). In Study 1b, we tested five- and seven-year-old children on the second-order question test and second-order

false belief tasks. In Studies 1a-1b, we collected both eye-tracking data and answers to explicit questions because both of these measures are suitable for five- to seven-year-old children. Had we found positive evidence for five-year-olds' use of Socratic ignorance in Studies 1a-1b, our eye-tracking paradigm would have allowed us to test much younger children to determine how early the capacity to track Socratic ignorance develops. Moreover, gaze behaviors sometimes reveal abilities at an earlier age than explicit answers (e.g., Bergelson & Swingley, 2012; Dautriche et al., 2021; Köder & Falkum, 2020). Thus, collecting both eye-tracking data and explicit answers allowed us to probe whether there was dissociation, or some consistency, between children's explicit choices and their gaze behaviors.

Studies 1a and 1b allow us to evaluate our three hypotheses. If, from a young age, children primarily use attributions of Socratic ignorance to interpret questions, then all groups will succeed in the second-order question test of Study 1b, even five-year-old children and children who fail at explicit second-order false belief tasks (Hypothesis 1). We will observe a different pattern if children's reliance on attributions of Socratic ignorance to interpret questions emerges along with explicit verbal representations of second-order mental states. In that case, performance on the second-order question test will increase between five and seven years of age, and it will be positively related to performance in second-order false belief tasks (Hypothesis 2). If the interpretation of questions rests primarily on simple knowledge tracking, then children's performance will be better in the first-order test than in the second-order test (Hypothesis 3).

Data, stimuli samples, and analysis scripts of all Studies are accessible on an open repository (URL : https://osf.io/dneqm/?view_only=d3b3fcfa894b49d99e18b50801d337fb).

1.6 Ethics

This project was approved by an independent ethical committee for biomedical research (CPP Sud-Ouest et Outre-Mer III, Bordeaux, France). All adult participants and the parents of all toddlers and child participants provided written informed consent, prior to their inclusion in the study.

2 Study 1a

2.1 Methods

2.1.1 Participants

We tested sixteen five- to seven-year-olds ($M_{age} = 77.9$ months; $SD = 12.2$; age range: 61–95 months). The participants were all native French speakers recruited from a large French city (/MASKED FOR BLIND REVIEW/). Children were recruited by sending letters to a randomly selected sample of children born in the area. A priori, we planned to exclude participants for the following reasons: refusal to complete the whole procedure, technical failure, low-quality data (more than two test sequences with 50% or more of the eye-tracking data missing), and parental interference. In Study 1a, no participant was excluded from the analysis. The sample size of Study 1a was set a priori to be large enough while limiting recruitment efforts.

2.1.2 Materials and Procedure

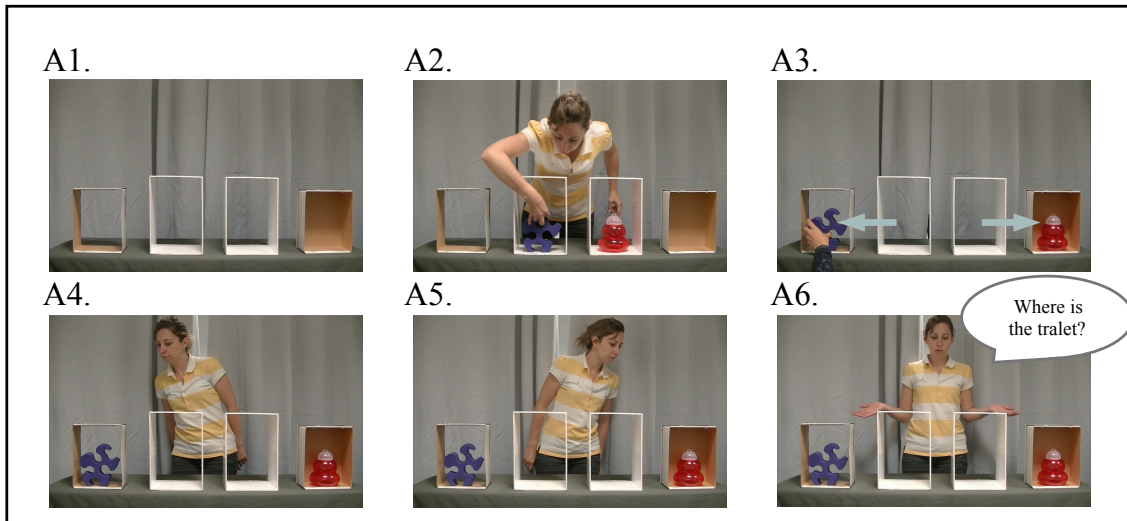
Eye-tracking Experiment. The study started with an eye-tracking experiment that took place in a soundproof booth. The participants sat approximately 60 cm away from the eye tracker's monitor on which the stimuli were presented (Tobii Pro Spectrum 150, sampling frequency: 60 Hz, screen diagonal: 23.8", resolution: 1920×1080 pixels). For stimuli presentation and data collection, we used Psychopy v.3.0.4, (Peirce et al., 2019) associated with

Python v.2.7, and Tobii Pro SDK package v.1.7. We used a five-point calibration method, repeated until it was complete. The participants typically required only one calibration.

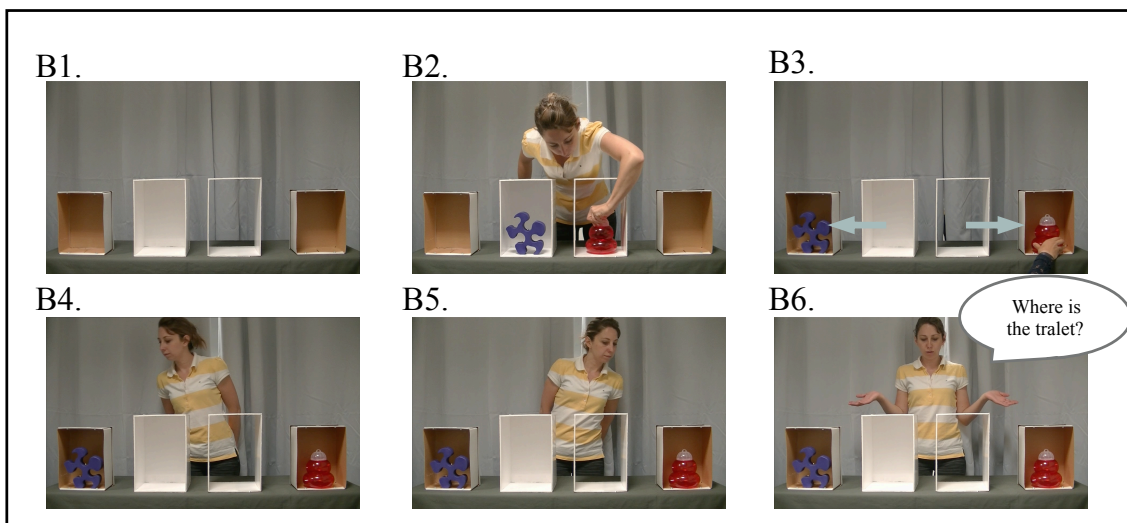
Figure Article 4.1

Critical Events of Studies 1a and 1b.

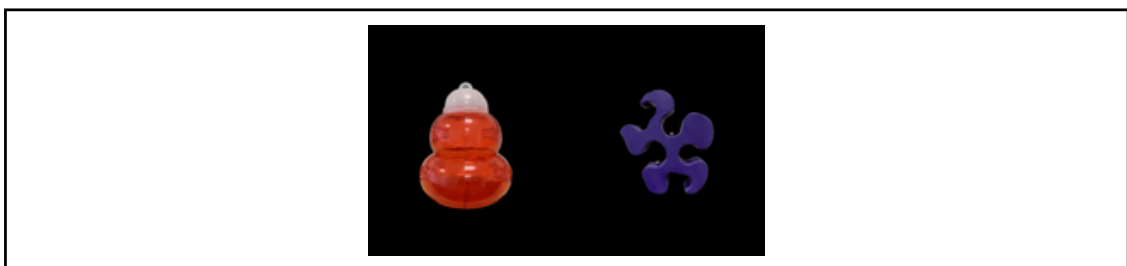
A. First-order test (Study 1a)



B. Second-order test (Study 1b)



C. Test phase



Note: Panels A (A1–6): Photographs from the familiarization of the first-order test condition (Study 1a). Panels B (B1–6): Photographs from the familiarization of the second-order condition (Study 1b). Panel C: Photograph from the two-alternative forced choice test.

The eye-tracking experiment was initiated after the calibration phase. First, the participants saw a familiarization video that lasted 50 seconds (see Video S1 in the Supplementary Materials), twice. In this video, there were four boxes made of opaque cardboard, placed in a row on a table: two larger central boxes in the central part of the table, and two peripheral smaller boxes located next to the edges of the table. The boxes had no front side, so that the participants could see their content at all times. One of the peripheral boxes had an opaque backside; thus, it was impossible for anyone facing the participant across the table to see its contents (see Figure S3 panel A in the Supplementary Materials). The other three boxes had no backsides. At the beginning of the video, all boxes were empty (see Figure 4.1, panel A1). Next, a female actor entered the scene through an opening at the center of the opaque curtains located in the background. She carried two unfamiliar objects: a purple wooden structure ornamented with silver balls and a transparent, round, red plastic structure with a white top. She placed the objects one after the other in each of the two central boxes (see Figure 4.1, panel A2). Following this, the female actor returned behind the curtains. While she was away, a hand appeared from the bottom of the screen, and displaced each of the two unfamiliar objects one by one, each time from the central box where the object was initially located to the outer box located on the same side (see Figure 4.1, panel A3). When the female actor returned through the opening in the curtains, she pretended to search for an object (first, looking toward the center of the table, second, looking across the whole table from one side to another, and third, looking back toward the center again). From her perspective, she could not see the object placed in the box with an opaque backside (we call this object the “target” when reporting the

analysis and results of Study 1a), whereas she could see the other object (see Figure 4.1, panels A4 and A5). Next, she flipped the palms of her hands upward and out to the side, and she asked for the location of one of the objects, using a novel label (the nonsense word “tralet”): She looked toward the center of the table, and said, “*Where is the tralet?... Where did the tralet go?... Where is the tralet?*” (See Figure 4.1, panel A6).

After watching the familiarization movie, the participants were enrolled in the test phase, which consisted of four test sequences using a two alternative forced-choice (2AFC) task. The participants saw the two unfamiliar objects from the familiarization videos, each of them on one side of the screen, on a black background (see Figure 4.1, panel C). During each of the test sequences, a voice-over invited the participant to look at the object that was referred to by the novel label by asking a prompt question (e.g., “*Did you see the tralet?*”) followed by five seconds of silence. After this, the subsequent test sequence began. The sides where the objects were located were switched between test sequences. There were four consecutive test sequences, resulting in four measures (one after each prompt question). The prompt questions differed from one test sequence to the next, and were as follows, “*Where is the tralet?*” (test sequences 1 and 3), and “*Did you see the tralet?*” (test sequences 2 and 4), respectively.

The same label (“tralet”) was always used to refer to the object that the female actor was searching for. During the familiarization phase, we counterbalanced the following factors across participants: the side of each unfamiliar object (right or left), the side of the box with the opaque backside (right or left), the side toward which the female actor looked first when searching for the object across the table (right or left), and the identity of the target (purple or red object). During the test phase, we counterbalanced within subjects the side of the screen on which each unfamiliar object appeared across test sequences (right or left).

Explicit Identification Test. After completing the eye-tracking experiment, the participants were enrolled in an explicit identification test outside the soundproof booth. The experimenter showed one picture of each of the unfamiliar objects, side by side on a single sheet of paper. She asked the participant to explicitly identify the target by saying, “*Which one is the target?*” The side of the sheet (left/right) occupied by the picture representing the object that was in the box with an opaque backside during the familiarization phase was counterbalanced across participants.

Standard Second-order False Belief Tasks. The child participants sat in front of the experimenter, across a child-sized table, and were enrolled in two classic standard second-order false belief tasks while being filmed with a camera (temporal resolution = 30 frames per second). There were two tasks: one about a birthday puppy and one about a chocolate bar (adapted from Sullivan et al., 1994; and illustrated with vignettes from Avik Kumar Maitra, see Arslan et al., 2020). In the birthday puppy task, a mother deliberately misinforms her son about what he will receive for his birthday, so as to surprise him. Yet, the child actually discovers the true birthday present, unbeknownst to his mother. Later, the child's grandmother asks the mother whether the child knows what he is getting for his birthday (second-order knowledge question), and then what the child thinks he is getting (second-order belief question). In the chocolate bar task, a sister displaces her brother's chocolate bar, to hide it from him. Unbeknownst to the sister, the brother sees her displacing the chocolate bar in the new location. Later, the participants were asked whether the sister knows that her brother knows where the chocolate bar is (second-order knowledge question), and where the sister thinks that her brother believes the chocolate bar is (second-order belief question). After each of the second-order knowledge and second-order belief questions, the participants were asked to justify their answers (follow-up justification questions). The scripts for each of these tasks are detailed in

the Supplementary Materials. The order of presentation of the two second-order false belief tasks (chocolate bar and birthday puppy) was counterbalanced across participants.

2.1.3 Pre-processing and Coding

Eye-tracking Experiment. We pre-processed the eye-tracking data (v. 4.0.3; R Core Team, 2020) using the package *eyetrackingR* (v. 0.1.8; Dink & Ferguson, 2015). We analyzed the eye-tracking data collected in the test phase during the silence period following the prompt questions (e.g., “*Did you see the tralet?*”). We restricted our analysis to a predefined time window classically used in two alternative forced-choice tasks, from 367 ms to 2000 ms after the onset of the target label (“tralet”). Gaze behaviors occurring outside this time window are typically assumed to be unrelated to the processing of the target label (Swingley, 2007; Swingley & Aslin, 2000).

To analyze the eye-tracking data, we divided the screen centrally into two sides of 960×1080 pixels (i.e., the left and right sides of the entire screen). For each participant, we computed the proportion of looking toward the target for each 20 ms time interval by summing up the time spent looking at the side of the target object and dividing it by the total time spent looking at the entire screen over that time bin. Following this, for each participant, we computed the average of these proportions, across all test sequences for each time bin, and then, across all time bins. We excluded the data from test sequences, in which we missed more than 50% of the data (2 test sequences out of 64). In total, each participant contributed an average of 3.81 ($SD = 0.54$) of 4 test sequences.

Explicit Identification Test. For the explicit identification test, the participants received a score of 1 if they appropriately answered by selecting the target object, and a score of 0 otherwise.

Standard Second-order False Belief Tasks. For the standard false belief tasks, the participants received a score of 1 for each correct answer on a test question (second-order

knowledge and second-order belief questions), and for each correct answer on the corresponding follow-up justification question, thus resulting in a score ranging from 0 to 4 for both second-order knowledge questions and second-order false belief questions (see the Supplementary Materials for more details).

2.1.4 Data Analysis

All statistical analyses reported in this paper were two-tailed. Unless specified otherwise, they were performed using R (v. 4.0.3; R Core Team, 2020) with the following packages: lme4 (v. 1.1.26; Bates et al., 2015), lmerTest (v. 3.1.3; Kuznetsova et al., 2017), logistf (v. 1.24; Heinze et al., 2020) and rcompanion (v. 2.3.27; Mangiafico, 2021). In all studies of this paper, the confidence intervals reported for binomial tests are obtained by a procedure first given in Clopper and Pearson (1934). In Study 1a, to better approximate a normal distribution, we transformed the proportion of looks toward the target prior to data analysis using an angular transformation (arcsin of squared root data). For ease of reading, we reported untransformed data in the text and figures. Where applicable, we also reported nonparametric statistics of untransformed eye-tracking data.

We assessed the effect of the factors in the following manner. For the eye-tracking data, we ran linear models with the transformed proportion of looks toward the target as the dependent variable. For the data from the explicit identification test, we ran generalized linear models (binomial distribution and logit link) with the binary success score as the dependent variable. In case of complete or quasi-complete separation of the data, we used logistic regression models using Firth's bias reduction method. Age was entered in months (mean-centered) when it was included in the statistical model.

2.2 Results

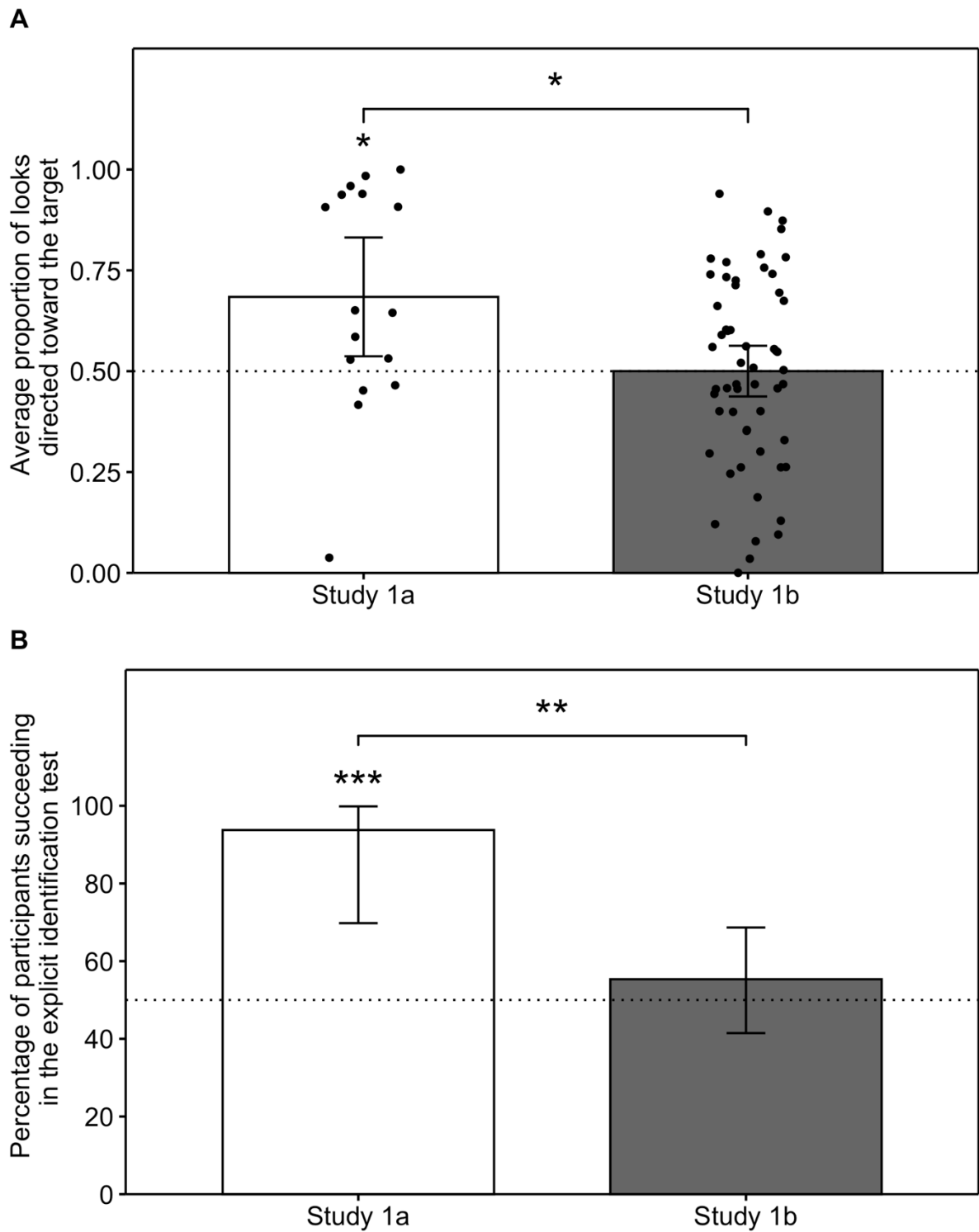
We assessed the respective effects of the variables on participants' performance in the eye-tracking test and in the explicit identification test. Since age, second-order knowledge scores, and second-order false belief scores were all positively correlated ($M_{rho} = .60$; range = .45 - .81), we assessed their contribution separately to avoid collinearity issues. Thus, we fitted the following series of models: (1) the age model (with the fixed effect of Age), (2) the ignorance model (with the fixed effect of second-order knowledge score), and (3) the false belief model (with the fixed effect of second-order false belief scores). None of the three models revealed any main effect for the eye-tracking experiment or for the explicit identification test (see Table S1 and Table S2 in the Supplemental Materials for details). Thus, there was no evidence for an effect of age or scores on second-order false belief tasks on the participants' interpretation of questions in Study 1a.

Following this, we compared the performance of the participants with what was predicted by chance. The descriptive statistics are reported in Figure 4.2 (panel A : eye-tracking experiment; panel B: explicit identification test). In Study 1a, the participants' performance was significantly higher than what was predicted by chance in the eye-tracking experiment (average proportion of looks toward the target: $M = 0.68$, $SD = 0.28$; $t(15) = 2.58$, $p = .021$, $d = .65$, one-sample t-test; $Z = 110$, $p = .029$, $r = .62$, Wilcoxon signed-rank test on untransformed data) and in the explicit identification test (15 successes out of 16; $p < .001$, $g = .44$, binomial test).

Figure Article 4.2

Results of Studies 1a and 1b; Panel A: Average Proportion of Looks Directed Toward the Target

Object; Panel B: Percentage of Participants Successful in the Explicit Identification Test.



Note: The dotted lines represent the level of performance predicted by chance (i.e., 0.5 in panel A and 50% in panel B). Error bars represent 95% CI. Panel A: Comparisons against chance by one-sample Wilcoxon tests and Comparison between studies by Mann-Whitney U test. Panel B: Comparisons against chance by binomial tests and comparison between studies by Fisher's exact test.

*: $p < .05$, **: $p < .01$, ***: $p < .001$.

2.3 Discussion

In Study 1a, children succeeded in appropriately identifying the referent of the novel label, both in the implicit and explicit identification tests. Thus, children tracked what the adult knew based on what she could and could not see, and used this information to interpret her questions. These results validate our stimuli and data processing procedures. In particular, they revealed that when watching the familiarization videos, the participants spontaneously used information about the female actor's knowledge to interpret her requests for information. In Study 1b, we built upon these results to investigate the role of representations of Socratic ignorance in the interpretation of questions.

3 Study 1b

3.1 Methods

3.1.1 Participants

We computed the sample size required for Study 1b using G*power (v. 3.1; Faul et al., 2007). These analyses revealed that assuming effect sizes identical to those observed in Study 1a, a sample size of twenty-eight participants per group was sufficient to achieve a power of .90 ($\alpha = .05$) for comparisons against chance (see Table S3 in the Supplementary Materials). Thus, we tested twenty-eight participants for each age group, i.e., five-year-old children ($M_{age} = 64.5$

months; $SD = 3.58$; age range: 60–71 months) and seven-year-old children ($M_{age} = 89.2$ months; $SD = 4.09$; age range: 84–95 months). The exclusion criteria were the same as in Study 1a. We excluded seven participants for the following reasons: refusal to complete the whole procedure (1), technical failure (5), low-quality data (1). None of the children who participated in Study 1b had participated in Study 1a.

3.1.2 Materials and Procedure

Study 1b followed the same procedure as Study 1a, except for changes in familiarization movies. In the familiarization movies of Study 1b (see video S2 in the Supplementary Materials), only one of the central boxes had no backside. The three other boxes had opaque backsides (the second central box, and the two peripheral boxes, see Figure 4.1 panel B1). Thus, when the female actor stood behind the table, she could only see inside the box with no backside. After placing the two unfamiliar objects inside the central boxes, the female actor left the scene, and the objects were displaced, as in Study 1a (Figure 4.1 panels B2 and B3). Thus, when the female actor returned after the displacement of the unfamiliar objects, she was ignorant of the location of the two unfamiliar objects (since she could not see them, see Figure S3 panel B in the Supplementary Materials). Notably, she could see that the object initially placed in the central box with no backside was no longer there, thus making her knowledgeable about her ignorance of this object's location (we call this object the “target” while providing details regarding the analyses planned for Study 1b). Conversely, the female actor could not see that the object that she placed initially in the central box with a backside was no longer there, thus making her unaware of her ignorance of the object's location (Figure 4.1 panels B4, B5, and B6). In Study 1b, we counterbalanced the same factors as in Study 1a, except that instead of counterbalancing the side of the box with no backside, we counterbalanced the side of the box with an opaque backside across participants.

3.1.3 Data Analysis

The data of Study 1b were pre-processed and coded as in Study 1a. In the eye-tracking experiment, we excluded the data from test sequences for which we missed more than 50% of the data (26 test sequences out of 224). In total, each participant contributed an average of 3.57 ($SD = 0.74$) out of four test sequences in the five-year-old children's group, 3.79 ($SD = 0.57$) out of four test sequences in the seven-year-old children's group.

We used the same data analysis procedure and software as in Study 1a, with the following additions: When analyzing the eye-tracking data, we used likelihood ratio tests (LRTs) to compare the models. Due to the complete separation of data, when analyzing performance in the explicit identification test, we fitted logistic regression models using Firth's bias reduction method, and compared models using penalized LRTs.

Moreover, for the null results of the main interest, we conducted Bayesian tests with Jasp (v. 0.14.1; JASP Team, 2020), with a Cauchy Prior Distribution set to the default value (.707). When conducting the Bayesian Wilcoxon signed-rank test, we used a data algorithm with five chains of 1000 iterations. We report the Bayes factors expressing support for the null hypothesis over the alternative hypothesis (BF_{01}). Any value of BF_{01} larger than 3 is typically interpreted as meaningful evidence for the null hypothesis.

3.2 Results

First, we analyzed the results of Study 1b. We fitted the following series of models: (1) the age model (with the fixed effect of age), (2) the ignorance model (with the fixed effect of second-order knowledge score), and (3) the false belief model (with the fixed effect of second-order false belief score). None of these models revealed any main effect either for the eye-tracking experiment, or for the explicit identification test (see Table S1 and Table S2 in the

Supplemental Materials for details). Thus, there was no evidence for an effect of age or scores on second-order false belief tasks on the participants' interpretation of questions in Study 1b.

As shown in Figure 4.2, in Study 1b, participants' performance did not differ significantly from what was predicted by chance, either in the eye-tracking experiment (proportion of looks toward the target: $M = 0.50$, $SD = 0.24$, $t(55) = -0.17$, $p = .86$, $d = -.02$, one-sample t-test; $Z = 830$, $p = .80$, $r = .04$, Wilcoxon signed-rank test on untransformed data), or in the explicit identification test (31 successes out of 56; $p = .50$, $g = .05$, binomial test). Complementary Bayesian analyses of Study 1b's results provided evidence for the null hypothesis in the eye-tracking experiment ($BF_{01} = 6.77$, error % < .001, Bayesian one-Sample t-tests; $BF_{01} = 6.85$, Bayesian Wilcoxon signed-rank test on untransformed data), and in the explicit identification test ($BF_{01} = 4.41$, Bayesian binomial test).

In a subsequent analysis, we wanted to determine whether children with established capacities to represent second-order mental states would still fail in the second-order question test. Thus, we focused on the performance of the participants whose scores on the explicit second-order false belief tasks were high (i.e., who reached a cumulative score of 7 or more out of 8, for their answers on the second-order knowledge and second-order belief questions; $n = 17$; $M_{age} = 85.2$ months; $SD = 11.0$; age range: 64–95 months). The performance of participants with high scores on second-order false belief tasks did not differ significantly from what was predicted by chance, either in the eye-tracking experiment (proportion of looks toward the target: $M = 0.47$, $SD = 0.24$; $t(16) = -0.52$, $p = .61$, $d = -.13$, one-sample t-test; $Z = 66$, $p = .64$, $r = -.14$, Wilcoxon signed-rank test on untransformed data; $BF_{01} = 3.56$, error % = .006, Bayesian one-sample t-test on transformed data; $BF_{01} = 3.43$, Bayesian Wilcoxon signed-rank test on untransformed data), or in the explicit identification test (9 successes out of 17, $p = 1$, $g = .03$, binomial test; $BF_{01} = 3.34$, Bayesian binomial test). Thus, even the

participants with a high score on the second-order false belief tasks showed no evidence of relying on the attribution of Socratic ignorance to interpret questions.

Finally, we assessed whether participants performed better when information requests could be disambiguated using simple knowledge tracking (Study 1a), than when representations of Socratic ignorance were required (Study 1b). We pooled the data from Studies 1a and 1b, and ran omnibus analyses to assess the respective effects of the variables on the participants' performance in the eye-tracking and explicit identification tests. We fitted the following series of models: (1) a test model, which included only the fixed effect of the studies (1a vs. 1b); (2) the age model (with the fixed effects of study, age, and their interaction); (3) the ignorance model (with the fixed effects of study, second-order knowledge score, and their interaction); and (4) the false belief model (with the fixed effects of study, second-order false belief scores, and their interaction).

The goodness of fit of the age, ignorance, and false belief models did not differ significantly from the goodness of fit of the test model, either for the eye-tracking test or for the explicit identification test. Thus, we retained the test model as the final model. The latter revealed a main effect of study, with hits more likely to occur in Study 1a than in Study 1b, both in the eye-tracking experiment ($F(1,70) = 8.31, p = .0052$, and in the explicit identification test ($\beta = -2.12, SE = 0.92, Wald's \chi^2 = -8.56, p = .003$). We also confirmed the effect of the study on children's behaviors in the eye-tracking experiment in a cluster-mass test analysis, which made no a priori hypothesis on the time window of the effect (see the Supplementary Materials).

3.3 Discussion

Studies 1a-b revealed a consistent pattern of results across measurements (eye-tracking and explicit questions). Children participants successfully interpreted questions when simple

knowledge tracking was sufficient to disambiguate them (Study 1a). Conversely, children showed no evidence for using representations of Socratic ignorance to disambiguate the meaning of requests for information, with data supporting the null hypothesis (Study 1b). Moreover, success in tasks requiring participants' use of Socratic ignorance to interpret questions was unrelated to participants' capacity to answer explicit questions about second-order mental states. In fact, even children who were proficient in manipulating representations of second-order mental states in second-order false belief tasks did not seem to use representations of Socratic ignorance to interpret questions.

In addition, participants performed better in Study 1a than in Study 1b, and thus were much more proficient at using simple knowledge tracking than at using representations of Socratic ignorance when interpreting requests for information. These results suggest that even when children possess the capacity to manipulate explicit representations of second-order mental states (such as representations of Socratic ignorance), their interpretation of requests for information relies primarily on simple knowledge tracking (Hypothesis 3). In Study 2, we tested whether this phenomenon remains valid in adulthood. If this is the case, adults will be less confident in their interpretation of a question's meaning when accessing it requires the use of representations of Socratic ignorance, instead of simple knowledge tracking. In Studies 1a-b, there was no dissociation between participants' performance on the explicit identification test, and in the eye-tracking task. Thus, we used only explicit identification tests in subsequent studies.

4 Study 2

4.1 Methods

4.1.1 Participants

In Study 2, two groups of sixty-four adults French-speaking participants were randomly assigned to one of two conditions (first-order condition: $M_{age} = 26.0$ years; $SD = 4.83$; age range: 18–35 years, second-order condition: $M_{age} = 25.1$ years; $SD = 4.64$; age range: 18–35 years). The participants were recruited using the online platform Prolific (<https://www.prolific.co>). We chose to test adults online (i) because of the COVID pandemic, which made it impossible to host participants in our laboratory, and (ii) because online testing makes it possible to recruit large samples of participants. In order to be included, the participants needed to fulfill the following criteria: (i) be between 18 and 35 years of age, (ii) speak French as their first language, (iii) be of French nationality, and (iv) possess a tablet or regular computer device. We had intended to exclude participants for the following reasons: refusal to complete the entire procedure and failure on an attention check. None of the participants were excluded from the analysis in Study 2. The sample sizes were set a priori to achieve a high power. Analyses conducted with G*power ($\alpha = .05$) indicated that assuming effect sizes equal to those observed in the explicit identification test of Study 1a, our sample size (64 participants per group) yielded a power of 1 for comparisons against chance.

4.1.2 Materials and Procedure

The study was run online on Qualtrics (<https://www.qualtrics.com/>), using a survey template compatible with tablets and regular computers. The participants were randomly assigned to the first-order or second-order conditions.

At the beginning of the experiment, the participants were told that they would see a video with the following written message, “*You will see the same video twice to ensure that you can process it fully. The video will begin automatically. In this video, you will see two new*”

objects and a person asking questions using a new word. Please do not forget to switch ON your sound.” Next, in the familiarization phase, the participants saw a familiarization video lasting 52 seconds, twice. We used the videos of Study 1a in the first-order condition and the videos of Study 1b in the second-order condition. After seeing the familiarization videos, the participants were enrolled in the test phase. In the latter, the participants were asked, “*Which object is the tralet?*” (identification question). They could answer by selecting the picture of one of the two unfamiliar objects from the familiarization videos, each of them shown against a black background (see Figure S4 panel A in Supplementary Materials). Next, the participants were asked to drag a slider to indicate how certain they were about their answer (using a continuous scale ranging from 0/completely uncertain to 100/completely certain; see Figure S4 panel B in Supplementary Materials). We collected certainty scores in adults because we anticipated that they would perform at the ceiling when identifying the referent of the novel label in all conditions. By asking them to rate how certain they were about their answers, we aimed to collect a more fine-grained measure of their confidence. We did not collect certainty scores in the Studies with children (S1, 1a and 1b) because this type of measure is not easy to use with young participants.

During the familiarization phase, we counterbalanced the same factors as in Study 1a.

The same novel label (the nonsense word “tralet”) was always used to refer to the object that the female actor was searching for. During the familiarization phase, we counterbalanced the same factors as in Studies 1a and 1b. During the test phase, the two unfamiliar objects were presented in a fixed manner (i.e., the red object in the first position and the purple object in the second position).

After the experiment, the participants were tested on an attention check question (see Supplementary Materials for procedural details). The participants who failed in the attention check question were excluded from the analysis.

4.1.3 Data Analysis

The statistical tests of Study 2 used the same software and followed the same general analysis procedure as in Studies 1a and 1b.

4.2 Results and Discussion

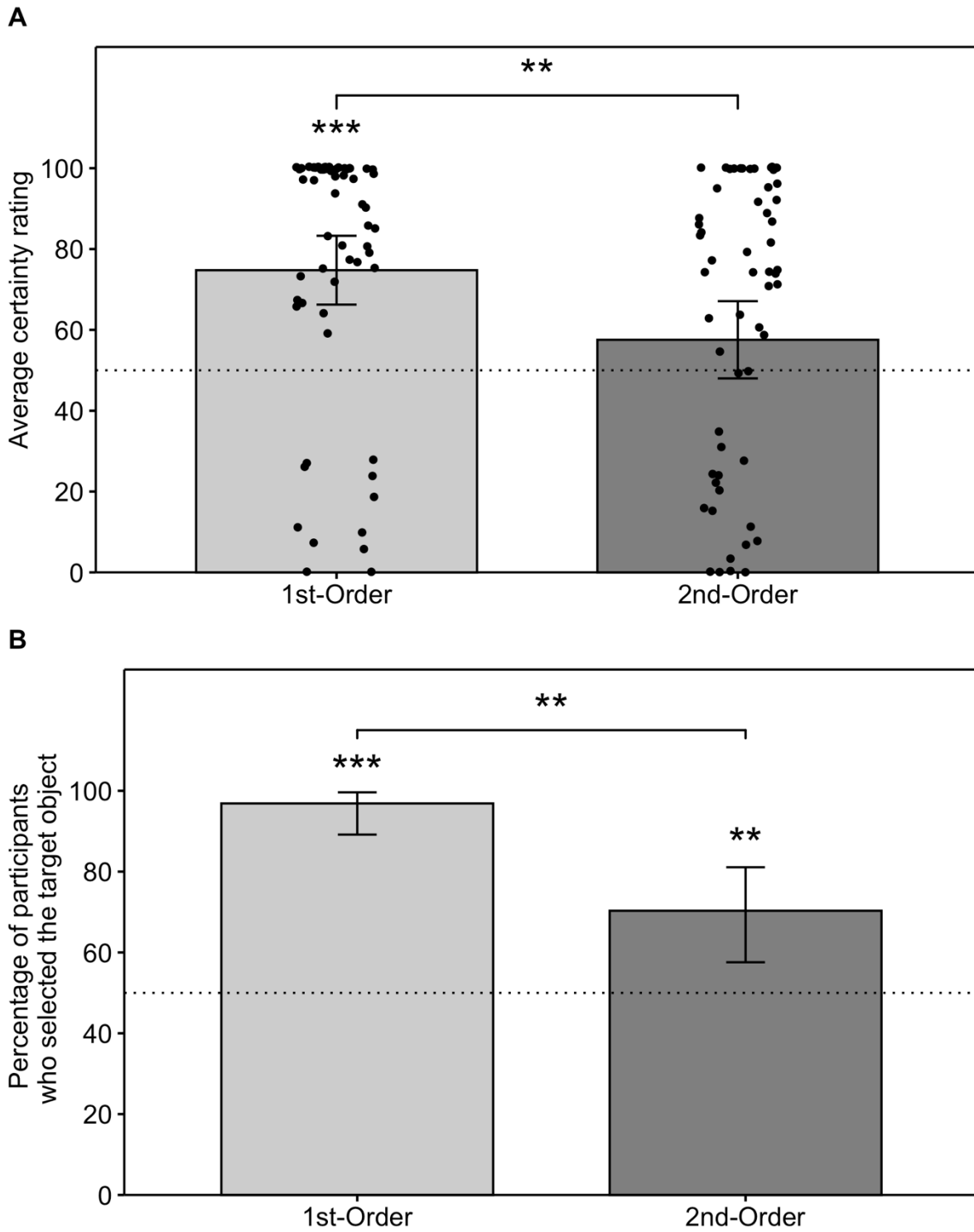
In Study 2, the participants were more likely to select the target than predicted by chance in both conditions (first-order condition: 62 successes out of 64, $p < .001$, $g = .47$; second-order condition: 45 successes out of 64, $p = .0015$, $g = .20$, binomial tests see Figure 4.3 panel B). However, the performance of the participants was significantly better in the first-order condition than in the second-order condition ($p < .001$, Fisher's exact test).

The average certainty score predicted by chance was 50 (since the participants could assign a certainty score ranging from 0 to 100). As Figure 4.3 panel A shows, the participants' average certainty score was significantly higher than that predicted by chance only in the first-order condition ($M = 74.8$, $SD = 34.1$, $Z = 1719$, $p < .001$, $r = .65$, Wilcoxon signed-rank test), but not in the second-order condition ($M = 57.5$, $SD = 38.3$, $Z = 1198$, $p = .19$, $r = .19$, Wilcoxon signed-rank test; $BF_{01} = 3.69$, Bayesian Wilcoxon signed-rank test). In fact, the participants' certainty scores were significantly lower in the second-order condition than in the first-order condition ($U = 2641$, $p = .0042$, $r = .29$, Mann-Whitney U-test).

In Study 2, the performance of adult participants on the second-order test suggests that they can use representations of Socratic ignorance to interpret requests for information. However, adults' performance was worse, and their certainty was lower when they had to rely on attributions of Socratic ignorance (in the second-order condition), than when they could merely rely on simple knowledge tracking (in the first-order condition).

Figure Article 4.3

Results of Study 2 per Condition; Panel A: Average Certainty Ratings; Panel B: Percentage of Participants Successful in the Explicit Identification Test.



Note: The dotted lines represent the level of performance predicted by chance (i.e., an average rating of 50 in panel A and 50% in panel B). Error bars represent 95% CI. Panel A: Comparisons against chance by one-sample Wilcoxon signed-rank tests and comparisons between conditions by Wilcoxon signed-rank tests. Panel B: Comparisons against chance by binomial tests and comparison between studies by Fisher's exact test.

** $: p < .01$, *** $: p < .001$

The results of Study 2 suggest that adults may simplify the problem of interpreting information requests by using simple knowledge tracking rather than representing Socratic ignorance. This hypothesis predicts that when interpreting questions, adults exhibit a bias toward assuming that speakers can request information about things that they do not know, even when there are no reasons to assume that speakers are aware of their ignorance. We tested this prediction in Study 3 by conceptually replicating Study 2, while adding a third condition that flipped the logic of the second-order test. In this "heuristic condition," the speaker asked a question about the location of an object using a novel label. The label was ambiguous and could refer to one of the two objects. The speaker did not know about the location of one of the two potential referents of the novel label; yet, he could not see that this object had been displaced. Thus, he had illusory knowledge regarding the location of this object. The other potential referent of the label was visible to the speaker, who thus had real knowledge about the location of that object. In this heuristic condition, simple knowledge tracking should yield the selection of one referent for the novel label (the object whose location is unknown to the speaker). In contrast, in the heuristic condition, tracking Socratic ignorance should result in assuming that both unfamiliar objects are equally unlikely to be the label's referent (since the speaker knows about the location of one object and believes that he knows about the location of the other object).

5 Study 3

5.1 Methods

5.1.1 Participants

We switched language (from French to English) from Study 2 to Study 3 to access more participants on the online recruitment platform. We tested three groups of sixty-four adult native English speakers (first-order condition: $M_{age} = 23.7$ years; $SD = 4.47$; age range: 18–35 years; second-order condition: $M_{age} = 24.9$ years; $SD = 5.59$; age range: 18–35 years; heuristic condition: $M_{age} = 25.9$ years; $SD = 5.26$; age range: 18–35 years). The participants were recruited using the same online platform as in Study 2. The sample sizes, inclusion, and exclusion criteria were the same as in Study 2, except for the inclusion criteria of first language and nationality (we included only native English speakers from the United Kingdom in Study 3). We excluded three participants (one per condition), for failing on the attention check question at the end of the procedure.

5.1.2 Materials and Procedure

Study 3 followed the same procedure as Study 2, with the following exceptions: The actor was a male native English speaker in all the videos of Study 3; the verbal script he used in the video was adapted to English from the script used for the videos of Studies 1a-b and 2; when asking about the location of the novel object, the actor used the novel label “dollow” instead of “tralet.” Thus, after he returned through the curtains and pretended to search for an object, he put his hands on his hips, and asked, “*Where is the dollow? ... Where did the dollow go? ... Where could the dollow be?*”

Apart from these differences, the events of the familiarization video were the same in Studies 2 and 3 for the first-order and second-order conditions. In Study 3, we also tested a group of participants in a third condition, called the “heuristic” condition, in which we pitted knowledge against second-order ignorance.

The heuristic condition followed the same procedure as the first- and second-order conditions, except for the boxes used in the familiarization videos. In the heuristic condition, only one of the peripheral boxes had no backside, whereas the three other boxes had an opaque backside (the second peripheral box, and the two central boxes, see Figure 4.4 panel C1). Thus, from his perspective, the male actor was able to only see inside the box with no backside. After placing the two unfamiliar objects inside the central boxes, the male actor left the scene, and the objects were displaced, as in the first- and second-order conditions (Figure 4.4, panels C2 and C3). Thus, when the male actor returned after the displacement of the unfamiliar objects, he was able to see one of the unfamiliar objects, but not the other (see Figure S3 panel C in the Supplementary Materials). Moreover, from his viewpoint, he could not see that the object initially located in the central box with a backside had been displaced (Figure 4.4 panels C4, C5, and C6), thus making him unaware of his ignorance of this object's location. Examples of the familiarization videos of Study 3 are in the supplemental materials (Videos S3–S5 in the Supplementary Materials).

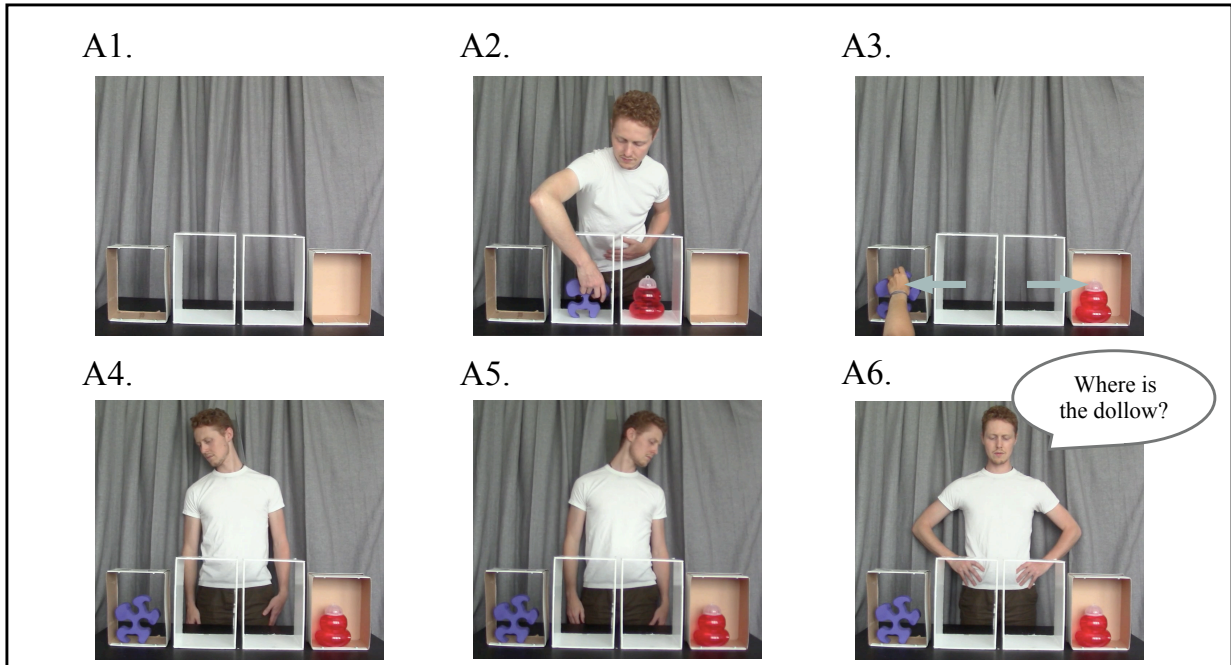
The same label (“dollow”) was always used to refer to the object that the male actor was searching for. During the familiarization and test phases, we counterbalanced the same factors as in Study 2.

After watching the familiarization videos, the participants were enrolled in the test phase that unfolded as in Study 2, except for the language used (English).

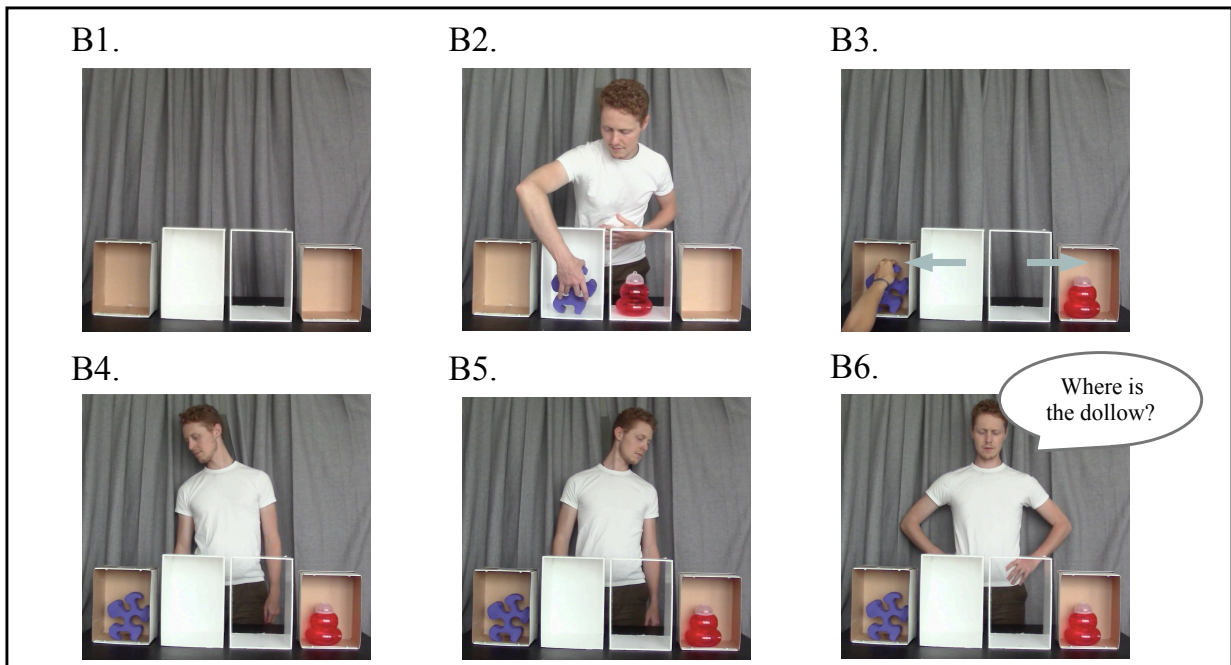
Figure Article 4.4

Critical Events of Study 3.

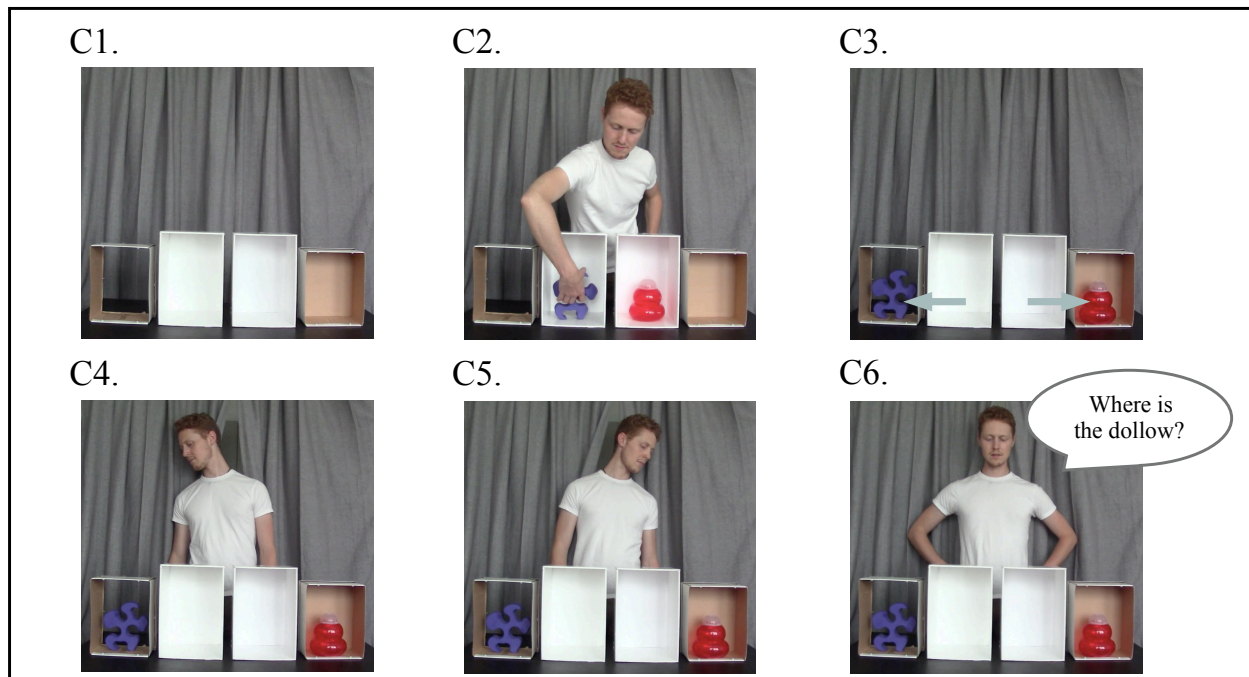
A. 1st Order condition



B. 2nd Order condition



C. Heuristic condition



Note: Panels A (A1–6): Photographs from the familiarization of the first-order test condition. Panels B (B1–6): Photographs from the familiarization of the second-order condition. Panel C (C1–6): Photographs from the familiarization of the heuristic condition.

5.1.3 Data Analysis

Unless specified, the statistical analysis procedures of Study 3 were the same as those in Study 2.

5.2 Results and Discussion

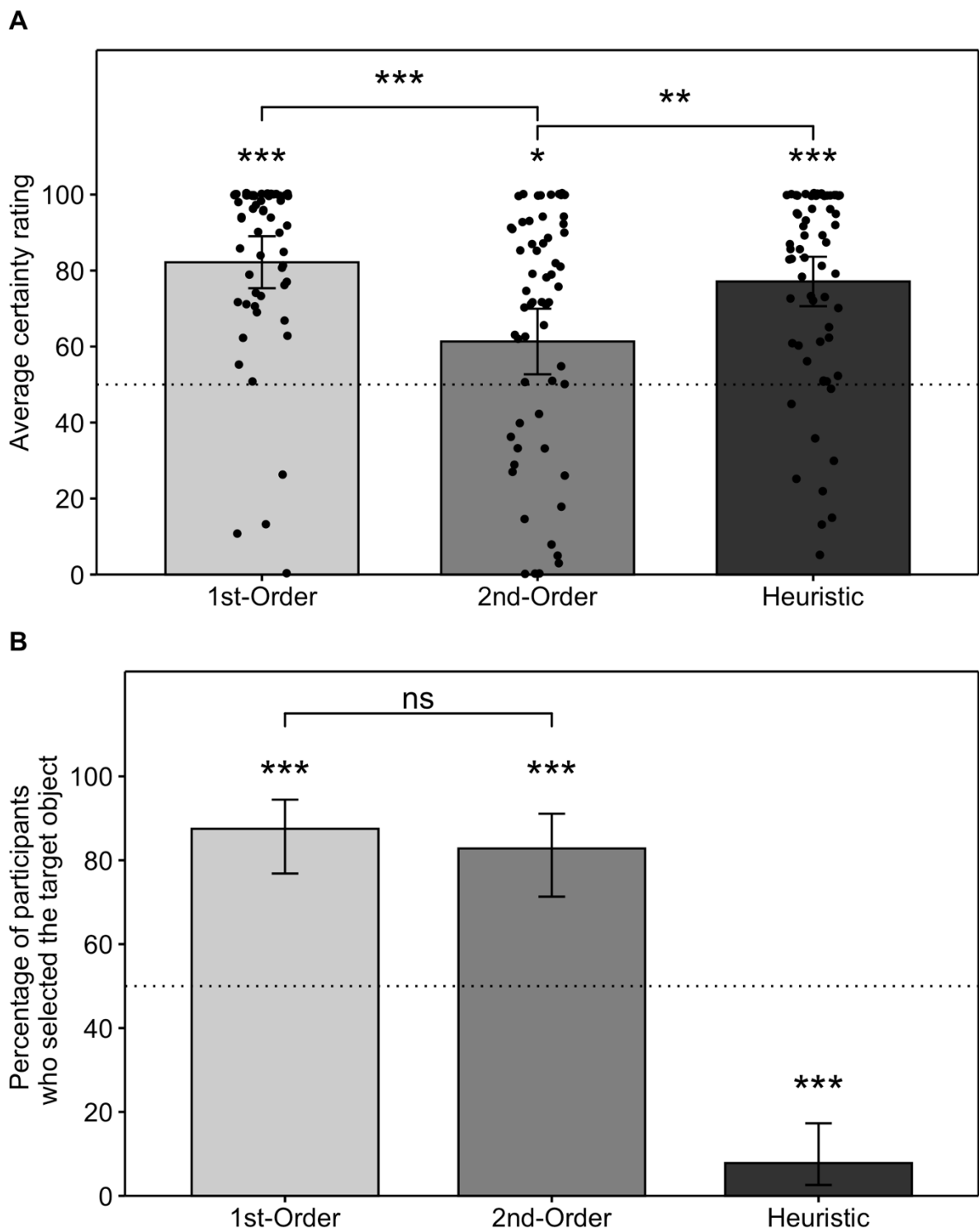
First, as shown in Figure 4.5 panel B, we analyzed the participants' performance in the first- and second-order conditions (a conceptual replication of Study 2). In the first-order condition, the participants were more likely to select the object that the male actor could not see when asking the question (56 choices out of 64, $p < .001$, $g = .37$, binomial test). In the

second-order condition, the participants were more likely to select the object whose past empty location was visible to the male actor when asking the question (53 successes out of 64, $p < .001$, $g = .33$, binomial test). Thus, Study 3 confirmed that adults could use both simple knowledge tracking and representations of Socratic ignorance to disambiguate questions. Unlike in Study 2, the participants were not significantly less likely to succeed in the identification test in the first-order condition than in the second-order condition test ($p = .62$, Fisher's exact test). We cannot explain this difference between the results of Studies 2 and 3 with certainty.

As Figure 4.5 panel A shows, participants' average certainty scores were significantly higher than predicted by chance in the first-order condition ($M = 82.2$, $SD = 27.4$, $Z = 1875.5$, $p < .001$, $r = .80$, Wilcoxon signed-rank test) and in the second-order condition ($M = 61.3$, $SD = 34.6$, $Z = 1344$, $p = .021$, $r = .33$, Wilcoxon signed-rank test). As in Study 2, the participants' certainty scores were significantly lower in the second-order than in the first-order condition ($U = 2883.5$, $p < .001$, $r = .41$, Mann-Whitney U-test).

Figure Article 4.5

Results of Study 3 per Condition; Panel A: Average Certainty Ratings; Panel B: Percentage of Participants Successful in the Explicit Identification Test.



Note: The dotted lines represent the level of performance predicted by chance (i.e., an average rating of 50 in panel A and 50% in panel B). Error bars represent 95% CI. Panel A: Comparisons against chance by one-sample Wilcoxon signed-rank tests and comparisons between conditions by Wilcoxon signed-rank tests. Panel B: Comparisons against chance by binomial tests and comparison between studies by Fisher's exact test.

Ns: not significant, *: $p < .05$, **: $p < .01$, ***: $p < .001$.

Following this, we performed analyses including data from the heuristic condition. In this condition, the participants identified the object displaced unbeknownst to the male actor as the referent of his question more often than predicted by chance (59 choices out of 64, $p < .001$, $g = .42$, binomial test). Thus, the adults assumed that the male actor requested information about the object whose location he was unaware of, even though he had not seen that this object had been displaced. This result is remarkable, given that in the second-order condition, adult participants demonstrated their capacity to take into account the male actor's ignorance of his ignorance of the object's location.

The participants' certainty scores were significantly higher than predicted by chance in the heuristic condition ($M = 77.1$, $SD = 26.0$, $Z = 1903$, $p < .001$, $r = .83$, Wilcoxon signed-rank test). Certainty scores did not differ significantly across the first-order and the heuristic condition ($U = 2364$, $p = .12$, $r = .15$, Mann-Whitney U-test; $BF_{01} = 2.89$, Bayesian Mann-Whitney U-test). Conversely, certainty scores were significantly higher in the heuristic condition than in the second-order condition ($U = 1469$, $p = .006$, $r = -.28$, Mann-Whitney U-test).

This pattern of results suggests that adults gave more weight to simple knowledge tracking than to representations of Socratic ignorance when interpreting the meaning of questions. Just like in Study 2, Study 3's participants selected the referent that was consistent

with tracking Socratic ignorance in the second-order condition, but with a much lower certainty than in the first-order and heuristic conditions.

Moreover, in the heuristic condition, simple knowledge tracking mechanisms should yield the inference that the male actor is asking about the location of one specific object (the one whose location he is ignorant of). By contrast, tracking Socratic ignorance should yield the inference that the speaker is equally likely to ask about the location of any of the two unfamiliar objects. The results of the heuristic condition show that the participants selected a referent that was consistent with simple knowledge tracking, with a level of certainty comparable to that observed in the first-order condition. Thus, representations of Socratic ignorance did not interfere with the participants' simple knowledge tracking in any detectable manner when they interpreted the experimenter's request for information.

The results of Study 3's heuristic condition strongly suggest that adult participants prioritize simple knowledge tracking over-representation of Socratic ignorance, with one caveat: when answering the test question, the participants were forced to choose between the two unfamiliar objects present in the videos. Perhaps they chose the object that was not visible to the experimenter because it was the best available option, even though they would have preferred to answer that the novel label did not refer to any of the two unfamiliar objects. We addressed this issue in Study 4.

6 Study 4

6.1 Methods

6.1.1 Participants

We tested sixty-four adult native English speakers ($M_{age} = 26.1$ years; $SD = 5.44$; age range: 18–35 years). The recruitment procedure, sample sizes, inclusion, and exclusion criteria

were the same as in Study 3. We excluded only one participant, for failing on the attention check question at the end of the procedure.

6.1.2 Materials and Procedure

Study 4 used the same materials and procedure as Study 3's heuristic condition, except for the options that the participants could choose from during the test phase when answering the identification question (“*Which object is the dollow?*”). In Study 4, the participants could answer either by selecting the picture of one of the two unfamiliar objects from the familiarization videos, or by answering, “*None of the above*”. Next, just as in Study 3, the participants were asked to drag a slider to indicate how certain they were about their answer (see Figure S5 panel B in Supplementary Materials).

6.1.3 Data Analysis

The statistical analysis procedures of Study 4 were the same as those in Studies 2-3.

6.2 Results and Discussion

In Study 4, the participants identified the object displaced unbeknownst to the male actor as the referent of his question more often than predicted by chance, i.e., 1/3 (57 choices out of 64, $p < .001$, $g = .56$, binomial test). In contrast, the participants answered by selecting the two other options less often than predicted by chance (object visible to the experimenter: 4 choices out of 64, $p < .001$, $g = -.27$, none of the objects: 3 choices out of 64, $p < .001$, $g = -.28$, binomials tests). Thus, just like in Study 3, the adults assumed that the male actor requested information about the object whose location he was ignorant about, even though he had not seen that this object had been displaced. Also, the participants' average certainty score was significantly higher than predicted by chance ($M = 70.7$, $SD = 32.3$, $Z = 1669$, $p < .001$, $r = .61$, Wilcoxon signed-rank test). In short, Study 4's results confirm those of Study 3's heuristic

condition, in a set-up in which the participants could answer that the speaker did not refer to any of the two unfamiliar objects.

7 General discussion

We investigated the mechanism supporting human beings' interpretation of requests for information, one of the most central functions of interrogative sentences, in six studies testing toddlers (Study S1), children (Studies 1a-b), and adults (Studies 2-4). Our results suggest that the interpretation of requests for information relies primarily on simple knowledge tracking, rather than on the representation of what people know that they do not know (Socratic ignorance attributions). First, we found no evidence that toddlers use representations of Socratic ignorance to interpret the meaning of requests for information (Study S1). Five- to seven-year-old children exhibited a similar pattern, even when considering only the performance of participants with high scores on second-order false belief tasks (Study 1b). In contrast, five- to seven-year-old children succeeded easily in identifying the referent of a speaker's question when disambiguation could be achieved through simple knowledge tracking (Study 1a). Adults were able to use both simple knowledge tracking and representations of Socratic ignorance to disambiguate the meaning of the questions. However, they were more confident in their identification of a speaker's referent when interpreting requests for information could be achieved by simple knowledge tracking than when representations of Socratic ignorance were needed (Studies 2-3). Moreover, adults showed a systematic bias toward assuming that speakers request information regarding what they do not know, even when speakers have no reason to be aware of their ignorance (Study 3, heuristic condition, Study 4). In short, our results suggest that the interpretation of requests for information is primarily guided by simple knowledge tracking rather than by representations of Socratic ignorance, throughout one's life.

To clarify, we do not claim that humans never appeal to the representations of Socratic ignorance to interpret requests for information. In fact, we demonstrated that adults can do so in the second-order condition of Studies 2-3. Similarly, we do not claim that simple knowledge tracking is always activated by default, whereas representations of Socratic ignorance are only activated in specific instances. Our results are compatible with the perspective that when interpreting speakers' meanings, adults integrate information coming from multiple cognitive systems in parallel (e.g., Degen & Tanenhaus, 2019), including information coming both from mechanisms representing Socratic ignorance, and from simple knowledge tracking systems. Importantly, our data suggest that, in many cases, the interpretation of requests for information relies more strongly on simple knowledge tracking than on representations of Socratic ignorance. Future research should investigate whether and how the prevalence of simple knowledge tracking over representations of Socratic ignorance is influenced by contextual factors, and builds on differences in activation frequency, speed, ease of processing, or in the weight given to the output of these two mechanisms.

It is noteworthy that simple knowledge tracking can also deal with fairly complex cases involving a speaker's complete ignorance, a specific form of ignorance of one's ignorance. In the experiments we conducted, we focused on how participants may distinguish illusory knowledge—when individuals mistakenly believe themselves to be knowledgeable about a piece of information—from Socratic ignorance. It is important to note that, agents can be ignorant of their ignorance because they have no beliefs about something. For example, someone who knows nothing about “TOI 700d” and does not even know that this planet exists (and thus, has no beliefs about it), is in a state of complete ignorance about TOI 700d. Understandably, someone who has no beliefs whatsoever about an entity or event is unlikely to refer to it and thus, to request information about it. Therefore, it is possible to exclude entities

that a speaker is completely unaware of, as possible targets of her requests for information by using simple knowledge tracking.

Four reasons may jointly contribute to the primacy of simple knowledge tracking in the interpretation of requests for information. First, simple knowledge tracking is less cognitively complex and less costly than representations of Socratic ignorance. Monitoring speakers' perspectives and knowledge is not cost-free, especially when they differ from one's own; in addition, it can be challenging to track what others know, or are ignorant of, even for adults (Barr, 2008; Cane et al., 2017; Epley et al., 2004; Hanna et al., 2003; Keysar et al., 2000; Nilsen & Graham, 2009; Samuel et al., 2019; Wu et al., 2013). Now, each representation of Socratic ignorance embeds a representation of first-order ignorance, thus making the former even more complex and cognitively costly than the latter (representing that "John knows that John does not know p" is more cognitively demanding than representing, "John does not know p").

Second, human adults, infants, and non-human primates spontaneously and efficiently discriminate what people know from what they are unaware of (e.g., for a review, see Phillips et al., 2020). It is not known whether the mechanisms supporting fast and efficient representations of knowledge can track recursive mental states embedded within mental states, such as Socratic ignorance. In fact, many authors have suggested that core abilities used to track others' knowledge need not involve complex representations of mental states decoupled from reality (Apperly & Butterfill, 2009; Burge, 2018; Flavell, 1988; Horschler et al., 2019; Low et al., 2016; Martin & Santos, 2016; Nagel, 2017; Perner, 1989; Phillips et al., 2020; Phillips & Norby, 2021; Wellman, 1992; Westra & Nagel, 2021). For example, some theories posit that simple forms of knowledge tracking might involve the representation of non-representational relations (e.g., registrations or sensing) between agents and actual objects, properties, or events (Apperly & Butterfill, 2009; Burge, 2018; Low et al., 2016). In these nonrepresentational theories, when an agent is ignorant about something, no relationship is

established between the agents and what they are ignorant of, and their ignorance might simply not be represented at all. Generally speaking, the exact nature and complexity (or lack thereof) of fast and efficient representations of knowledge are yet to be fully elucidated empirically. However, it is possible that some of the mechanisms that support fast and efficient tracking of others' knowledge may not be able to track Socratic ignorance.

Third, if someone is aware of not knowing a piece of information, one can be reasonably certain that she/he lacks that piece of information. The reverse, however, is not true: someone may very well be ignorant about a piece of information without being aware of her/his ignorance. Thus, learning that someone knows about her ignorance is reliable evidence of her ignorance. By contrast, learning that someone is ignorant about a piece of information is often insufficient to establish that she knows about her ignorance. As a result, for each given piece of information, more information can be gained about people's ignorance of that information than about their awareness of their ignorance of that information. In short, relying more strongly on simple knowledge tracking than on attributions of Socratic ignorance may be rational, since one should have more confidence in one's information about people's knowledge and ignorance, than in one's information about what people know that they do not know.

Fourth, assumptions of competence triggered by requests for information may also contribute to explaining why listeners may sometimes disregard information about what speakers are unaware of not knowing. One central function of requests for information is to communicate what kind of information might be cognitively useful to the people formulating such requests. Thus, requests for information convey a very special presumption of competence on behalf of the people formulating them. They imply that the people requesting information have sufficient knowledge to identify the kind of information that is cognitively useful for them. Part of this knowledge, of course, is knowledge of what they are ignorant of. Thus, requests for information convey a presumption of knowledge of one's ignorance attached to the person

formulating the request. Such a presumption of competence may override or mask pre-existing attributions of ignorance of one's ignorance.

The results of the current studies broaden the horizon of research directions. First, we identified a cognitive ability, the representation of Socratic ignorance, which is crucial in representing information search in others. Future studies should identify when and how representations of Socratic ignorance are triggered, how they operate, and their role in the representation of information search. Moreover, our studies reveal a developmental change from childhood to adulthood. Unlike toddlers and children, adults were able to use representations of Socratic ignorance to disambiguate the meaning of requests for information. This developmental change was unrelated to the emergence of the competence to form complex second-order representations of mental states (such as representations of Socratic ignorance). Indeed, in Study 1b, children who had a high score on second-order false belief task were able to answer complex questions about knowledge about knowledge, and beliefs about beliefs. Yet, they made little use of their capacity to represent second-order mental states when disambiguating requests for information. Thus, future studies should investigate when and how representations of Socratic ignorance start to be used to interpret information search, and questions.

Second, we found that the complex problem of interpreting requests for information is likely to be simplified by using heuristics, such as using simple knowledge tracking rather than relying on representations of Socratic ignorance. This result highlights that representing ignorance is a complex problem that may be addressed by using not just one, but many different kinds of cognitive mechanisms, including simple heuristic and complex representations of mental states. Future research should investigate the nature of the cognitive mechanisms supporting human representations of ignorance, and whether they are supported by a unique mechanism or by multiple distinct mechanisms.

Third, in our studies, we kept the speakers' characteristics fixed. Importantly, individuals are more likely to request information that they lack, in domains that they find interesting. Thus, future research should investigate whether and how the characteristics of informants (such as their competence, knowledge, honesty, or information about their interests) modulate the interpretation of their requests for information. Fourth, genuine requests for information convey a presumption about the desirability of a piece of information (Wilson, 2012). Our data suggest that a lack of information crucially contributes to its desirability. Yet, many other features may make a piece of information desirable. Thus, future work should investigate how the desirability of a piece of information is represented and how it guides the interpretation of requests for information.

Part III

General Discussion

Compendium, Perspectives and Contributions of this Thesis Project

“Things done with devotion and dedication lead to beautiful conclusion”

– Radha Shanti

1 Compendium

To sum up, information-seeking is one of the most general functions of cognition. Humans possess the special capacity to represent informativeness, which enables them to plan new behaviors, in order to maximize learning gains. This thesis investigated the early development of this capacity in humans, and its role in cognitive development in social and non-social contexts.

A first article studied the ontogeny of representations of informativeness in a context of individual learning. This research used experimental set-ups that were designed such that the exact same action could lead to different learning benefits depending on context. In a first Study, fourteen-month-old infants were faster to perform an action (opening a shutter) when it allowed them to see an object inside a box, than when it did not. This first result suggests that infants can adjust their information search behaviors to the future availability of visual data. It indicates that infants treat visual access as a source of information for themselves, and that they plan actions which have an epistemic goal (i.e., the goal of seeing an object). In a second Study, two-and-half-year-old toddlers were faster to flip a character when this action allowed them to reduce their uncertainty about the location of a target hidden among distractors. Similarly, in a third Study, two-and-half-year-olds were more likely to engage first in the action of flipping a

character than in the alternative action of squeezing, when the flipping action was more informative to discover the location of a target character.

These data show that toddlers do not engage in inflexible exploratory behaviors when they lack a piece of information (contra Kloo et al., 2017; and Perner, 2012). In the three studies of the first article, if the participants had merely used a general exploratory strategy, their information search behaviors should have been insensitive to the availability of information, and to the type of information that they lacked. Instead, infants and toddlers anticipated the availability of data and flexibly adjusted their planned actions consequently. Moreover, toddlers adaptively modified their information search strategy depending on the piece of information that they needed to reduce their uncertainty.

In short, in a context of individual information-seeking, toddlers anticipate the availability and cognitive utility of data, and adapt their behavior accordingly to optimize information gains. These results have direct consequences for the study of humans' capacity to represent alternative possibilities. They indicate that, by two years of age, toddlers can represent simultaneously, at least two distinct different hypotheses about what might be the case (contra Leahy & Carey, 2020). In our studies, if toddlers had simply represented a single hypothesis while treating it as if it were true, they should not have been faster to perform an action when it was likely to reduce their uncertainty over a set of hypotheses.

These results also have consequences for the study of children's representation of their own ignorance. It had been suggested that before the age of four, young children might be sensitive to their ignorance, without representing what they are ignorant about. These theories postulate that young children monitor behavioral or physiological correlates of their own ignorance (such as an elevated heartbeat, hesitating, and so on), but do not represent their ignorance as ignorance (Kloo et al., 2017; Leahy & Carey, 2020). While this hypothesis may seem a bit far-fetched, it can account for most of the previously published evidence for young

children's sensitivity to their own ignorance or uncertainty (e.g., Call & Carpenter, 2001; Goupil et al., 2016; Ruggeri, Swaboda, et al., 2019). Our data, however, refute this behavioral-reading account. They suggest that by two years of age, children have access to a representation of the specific piece of information that they lack (otherwise, how could they anticipate the learning consequences of their action, and flexibly select which kind of action they should perform depending on the piece of information that they lack?).

The first article reported in this PhD thesis indicated that toddlers can use representations of informativeness when learning individually. In a second article, we built on these results and examined how representations of informativeness may support learning in a social context. Several key theories imply that in order to interpret a communicated message, humans may rely on assumptions about the high cognitive benefits (and reduced costs) of what is communicated. Accordingly, a second article investigated whether and how toddlers prioritize interpretations of novel communicative cues whose benefits (i.e., informativeness) is high, and whose processing costs are low. In the set of studies reported in this article, an ambiguous novel communicated cue indicated a reward's location. In a first Study, the cue was placed on one of two opaque cups; thus, it could be interpreted as indicating either the location of the baited cup, or the location of the empty cup. Two-year-olds favored the interpretation that had the lowest processing costs, even though the cue was always placed on the empty cup. Thus, toddlers resisted assigning meanings that were hard to process to novel cues, when an alternative interpretation which was easier to process was available.

In a second Study, toddlers prioritized the most informative interpretation of a symbol, i.e., one which reduced more their uncertainty about the reward's location. Similarly, in a third Study, toddlers were more likely to discover the meaning of a cue when it was used in an informative manner. In short, these studies indicate that two-year-olds prioritize interpretations of novel cues that are easy to process and informative. Thus, from toddlerhood onward,

informativeness and processing costs guide the interpretation of communicated messages by tipping the odds in favor of interpretations with a high cost/benefit ratio. These results suggest that general expectations about the cognitive utility of communicated information support communicative development from a very early age. They also indicate that young children exert pressures on communicative systems that may contribute to their efficiency.

The second article of this thesis showed that toddlers prioritize interpretations of novel cues that are appropriately informative. A third article aimed at studying the early ontogeny of this capacity, during infancy. This research used a situation pitting two word learning strategies against each other: inferences based on expectations of informativeness, and tracking co-occurrence between words and their potential referents. In these studies, a speaker produced a novel label while pointing ambiguously toward a set of unfamiliar objects: one unique object belonging to a first category, and many identical copies of another category of object. In this situation, if participants assume that the speaker is sufficiently informative to allow her audience to identify the label's referent, they should infer that the novel label refers to the unique object. Alternatively, if participants track co-occurrences between labels and potential referents, they should expect that the novel label refers to the copied objects.

A first study, meant to validate our stimuli, showed that three- to five-year-old children seemed to rely more on expectation about the speaker's informativeness than on co-occurrence tracking, since they tended to assume that the novel label referred to the unique object. In contrast, in a second study, eighteen-month-olds interpreted the novel label as referring to the copied object. This result, which is quite counterintuitive, suggests that eighteen-month-olds prioritize a co-occurrence tracking strategy over inferences based on informativeness. Given the counterintuitive nature of this result, we are currently testing additional eighteen-month-olds to confirm it in a slightly different version of the same study, in which the experimenter is

not pointing anymore, and is rather simply looking ambiguously toward the potential referents of the label.

In short, the results from the third article revealed a developmental switch in children's word learning strategy, from co-occurrence tracking to inferences based on expectations of informativeness. In an additional condition, the actress who uttered the novel label could see only one exemplar of each object type (and could not see the other exemplar of the copied object, even though they were visible from the participants' viewpoint). In this case, eighteen-month-olds and preschoolers no longer showed any systematic expectation about the referent of the novel label. Thus, young children seemed to take into account the speaker's viewpoint when interpreting the actress's communicative action, rather than relying on their own viewpoint. In other words, children seem to take speakers' viewpoint at all ages when interpreting a new label. In contrast, children's reliance on expectation about the speaker's informativeness to identify the referent of labels seem to increase during toddlerhood.

Together, the second and third articles reported in this PhD thesis add to an increasingly large body of literature suggesting that, by two to three years of age, children interpret communicated information in a context-sensitive fashion. In line with several theoretical accounts, such as Grice's framework, Relevance theory, and RSA, they reveal that general expectations about the informativeness of communicative signals guide toddlers' and preschoolers' interpretation of novel cues.

The first three articles reported in this PhD thesis tested the role of representations of informativeness in supporting children's own learning, in non-social and in communicative contexts. Two additional articles tested young children's sensitivity to others' informational needs. One of these articles (see Article 5 - Non-verbal Rhetoric: 2- to 4-Year-Old Children Select Relevant Evidence When Trying to Influence Others), investigated toddlers' sensitivity to what kind of behaviors may be informative for others. This study suggests that by two years

of age, toddlers have the capacity to provide others with relevant data in order to influence them. In this experiment two-year-old children were invited to search for a toy placed in one box out of four. When asked about the location of the toy, the experimenter contradicted the participants and rejected their initial proposition. Consequently, toddlers were more likely to spontaneously engage in the action of rotating the box to show to the experimenter another side of the box when its content was visually accessible only from the participants' point of view, than when the box was fully transparent. Thus, toddlers turned the box when it could reveal relevant information to the experimenter. Such behavior can be translated as toddlers attempting to change the experimenter's belief about the toy location by affording a visual access of its position. Alternatively, young children might have rotated the box to justify their claim by providing the evidence of their source of knowledge. In short, both interpretations suggest that from two-year-old, toddlers are already sensitive to others' information need in function of the context and accordingly decide what kind of information can be used to convince others in case of a disagreement.

In a last article, we focused on the way other people's information search might be represented, when interpreting their questions. Individuals can only request a piece of information if they detect that they lack it. Thus, when interpreting a request of information, addressees could, in principle, rely on representations of Socratic ignorance (i.e., tracking what people know that they ignore). Such process would involve two levels of recursive representations of representations (otherwise known as second-order meta-representations). Alternatively, the interpretation of requests for information may involve simpler representations of knowledge (i.e., merely tracking what people know). We judged these hypotheses by testing toddlers, five- to seven-year-old children (who are at a transitional stage in the development of their capacity to manipulate second-order meta-representations, measured by second-order false belief task), and adults. In our experiments, a speaker asked a

question about an object's location using an ambiguous novel label, that could be disambiguated by tracking their state of knowledge. We manipulated what the speaker could see to modulate whether simple representation of knowledge, or representations of Socratic ignorance were needed to disambiguate the question. In a first study, toddlers showed no tendency to rely on representations of Socratic ignorance when disambiguating requests for information. In two subsequent studies, five- to seven-year-olds showed a similar pattern of results, even for those children who performed well in classic second-order false belief tasks. Moreover, children were much better at disambiguating the meaning of the question when simple knowledge tracking could be used to do so. Two additional experiments ran with adults showed that they were able to use both representations of Socratic ignorance and simple knowledge tracking to interpret questions. Yet, they were more confident about their interpretation when the speaker's meaning could be disambiguated using simple knowledge tracking. Moreover, adults tended to assume that a speaker would have knowledge of what they were ignorant about, even when the latter had no reason to know about his/her ignorance. In short, the interpretation of requests for information seems primarily guided by simple knowledge tracking –rather than by representation of Socratic ignorance–, a heuristic that reduces processing costs.

In short, humans are incredibly flexible learners, who can adjust their learning strategy by recursively representing the process of learning itself. This capacity enables us to design new behaviors in order to maximize information and learning gains. The present thesis investigated the early development of humans' capacity to model learning, focusing on early representations of informativeness, and on how they support individual and social learning. The results reveal that representations of informativeness play a key role in shaping cognitive development. In a context of individual information-seeking, toddlers anticipate the

availability and cognitive utility of data, and adapt their behavior to optimize information gains (Article 1). In a context of social learning via communication, two-year-olds interpret novel cues by processing them as if they were informative — as well as accurate and easy to process (Article 2). Moreover, children’s reliance on expectations of informativeness to interpret novel communicative cues increases during the first years of life, between eighteen months and three years (Article 3). Toddlers are also sensitive to what may be informative for others. When attempting to influence people, they provide them relevant information that they lack (Article 5). Interestingly, humans’ representation of information search also appears to evidence signature limits. When representing what kind of information people search for in order to interpret their questions, humans appear to prioritize representations of what people do not know over representations of Socratic ignorance (Article 4). The results of this thesis highlight how precocious competencies to represent informativeness shape humans’ learning.

2 Perspectives

This work opens up new research perspectives, such as evaluating capacities to represent informativeness during the first year of life, along with the study of novel areas of research.

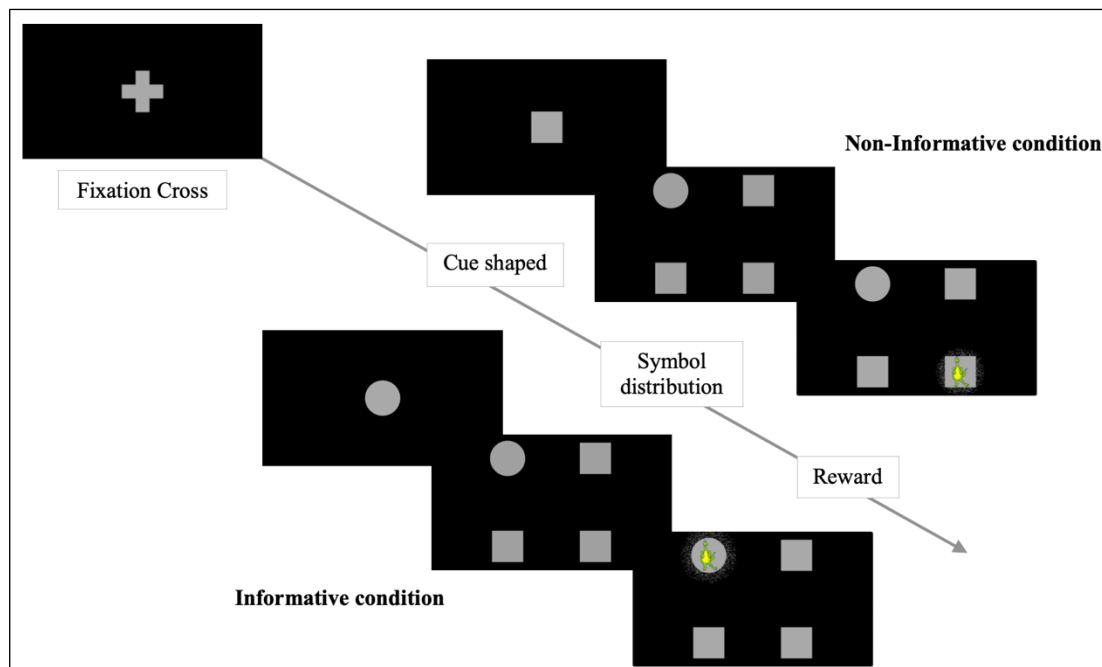
2.1 Individual Information Seeking

Several articles reported in this thesis imply that toddlers can represent and anticipate the availability and cognitive utility of data. Future studies should investigate the early development of this capacity, during infancy. To address this question, we designed a test adapted for preverbal infants, in order to assess whether they can represent and anticipate the cognitive utility of data. In this study, we will manipulate the informativeness of a visual stimulus by contextual factors, and we will measure two correlates of attention thought to be

sensitive to informativeness: pupil dilation (measured with an eye-tracker, Begus et al., 2016; Zénon, 2019), and theta-band oscillatory activity (measured with an electroencephalograph, EEG, Orekhova et al., 1999). At the beginning of each trial a cue will be presented on the screen (e.g., either a square or a circle). This cue will provide infants with information about the shape in which a reward will appear subsequently on the screen. For instance, when the cue will be a circle, then the reward will appear later in a circle, and when the cue will be a square, the reward will appear later in a square. Next, the cue will disappear, and four shapes will be presented on the screen for some time (e.g., three circles and one square, or three squares and a circle). Third, at the end of the trial, the visual reward (a dancing and smiling dinosaur) will appear in one of the shapes (see Figure 5). We will vary the distribution of the shapes in order to modulate whether the information given by the cue will be sufficient to predict where the reward will appear. Namely, the information conveyed by the cue will be sufficient to predict where the reward will appear only in the informative condition, but not in the uninformative one. If infants can represent and evaluate the cue's informativeness, they should react differently when seeing the cue at the beginning of the trial, depending on whether it is informative or uninformative. Reasonably, participants might allocate more attention to the cue when it will be more informative. This hypothesis would be confirmed if we were to observe a larger pupil dilation and stronger theta-band activity during the presentation of the cue, in informative trials compared to non-informative ones. Preliminary versions of this experiment tested on adults revealed promising results, however infant data is still under data collection. If successful this study might reveal that, representations of informativeness, observed during toddlerhood in our studies, emerge during early infancy.

Figure 5

Schematic Representation of Proposed Further Experiment Investigating the Cognitive Utility of Data



Note: At the beginning of each trial, there is a fixation cross, followed by a cue which can be either a circle, or a square. Then the screen present four shapes distributed in such a way that there are one unique exemplar of a shape type and three exemplars of the other type (i.e., circle or square shape). Finally, a dancing dinausor appears in one of the four shapes on condition that it is the same shape as the cue presented just before.

2.2 Expectation of informativeness in communication

The articles of this thesis investigated representation of informativeness in an individual learning context, and in a communicative context as well. The results indicate that toddlers are sensitive to the informativeness of stimuli when trying to fill gaps in their knowledge and when interpreting what others communicate. An important question for future research would be to test the extent to which all these capacities are supported by a single common cognitive mechanism, recruited to represent informativeness both when toddlers engage in individual

information-seeking, and when they try to understand a communicated novel signal. It seems possible that, for reasons of cognitive economy, a single mechanism supporting the representation of informativeness might be recruited in multiple domains, such as the ones we studied. In short, it would be interesting to test whether the mechanism that supports individual learning is recycled to guide the interpretation of communicated information (and vice versa). One way to conduct such an investigation might be to design studies contrasting different comparable domain involving a representation of informativeness and assessing whether shared neural signatures are observed in both domains.

Article 2 suggests that toddlers' interpretation of novel communicative cues is guided by cognitive costs and benefits, and prioritize interpretations whose cognitive cost/benefit ratio is high. Importantly, the studies reported in this thesis do not distinguish between a potential general cognitive tendency to prioritize processes whose cost/benefit ratios are high, from communication specific assumptions of cognitive utility triggered by the recognition of an intention to communicate. As a result, it would be interesting to investigate whether the expectations of ease of processing, informativeness and accuracy that we observed for communicative cues would be found for non-communicative cues as well. For instance, would the result of the studies of article 2 remain similar if the cues were not accompanied by signals indicating an intention to communicate?

It would also be interesting to explore the underpinning of humans' sensitivity to cognitive costs, and how they shape learning and cognition during early ontogeny. *Ceteris paribus*, efficient learners should prioritize the processing of stimuli and representations that are less costly. Indeed, even pieces of information that yield benefits may not be worth being processed when their processing is very costly. For instance, depending on your needs when looking for information about tomorrow's weather, you might want to look at the television announcement which provide simplified data, rather than at the sophisticated scientific data

available on a dedicated meteorology website. Thus, it would be interesting to test whether infants' learning is shaped by a general preference for simplicity and low costs, which may guide not only how they allocate their attention, but also how they generate hypotheses to account for data.

2.3 Interpretation of request of information

Last but not least, Article 4 studied how humans represent others' information-seeking, focusing on the interpretation of information requests. The integration of asker's Socratic ignorance in the interpretation of questions revealed original and unexpected results: The interpretation of request of information rests primarily on simple knowledge tracking than on attributions of Socratic ignorance. Notably, adults showed a tendency to rely on what the asker knows (rather than on what the asker knows that s/he ignores) to interpret their questions, even when the questioner had no reason to know about his/her ignorance. Yet, despite, their strong tendency to rely on simple knowledge tracking, adult participants also showed capacities to rely on representations of Socratic ignorance as well. Thus, it would be important to identify the situations in which representations of Socratic ignorance are triggered, how they operate more precisely, and how they develop.

3 Summary of contributions

In short, this PhD thesis investigated how the capacity to monitor the process of learning by forming representations of informativeness contributes to guide cognitive development in social and non-social contexts. This research yielded the following key discoveries:

Contribution 1. The capacity to anticipate the availability and cognitive utility of data, develops early, before children's third birthday. This capacity allows toddlers to flexibly plan efficient actions in order to fill gaps in their knowledge (Article 1).

Contribution 2. Toddlers' representation of their own uncertainty and of alternative possibilities cannot be accounted for by deflationary theories based on a mere monitoring of behavioral cues of uncertainty (Article 1).

Contribution 3. Toddlers prioritize informative interpretations of novel cues (Article 2), thus showing that general assumptions about the cognitive benefits of communicated information guide its interpretation from an early age.

Contribution 4. Cognitive costs play an important role in shaping young children's interpretation of a novel signal, with a prioritization of interpretations that are easy to process by two years of age already (Article 2). This thesis provides one of the first experimental investigation of the role of processing costs in shaping humans' interpretation of communicated information.

Contribution 5. There is a developmental switch in children's reliance on expectations of informativeness to interpret novel cues during the first years of life. Eighteen-month-olds are less likely than preschoolers to rely on expectations of informativeness to discover the referent of a novel label (Article 3).

Contribution 6. From toddlerhood onward, children can determine what kind of evidence may be sufficiently informative to influence others. Toddlers use this capacity to provide others with additional evidence in order to convince them, thereby highlighting the role of representations of informativeness in the onset of argumentative abilities (Article 5, reported in the annexes).

Contribution 7. When trying to determine what kind of information other search for, toddlers, children and adults prioritize representations of what other people know over more elaborate representations of what others know that they ignore (Article 4).

Contribution 8. Besides, the duration of the thesis was also an opportunity to conduct research on other domains of cognitive development. In an additional article, we investigated infants' early sensitivity to the source of social touch (see Article 6 Infants discriminate the source of social touch at stroking speeds eliciting maximal firing rates in CT-fibers).

Part IV

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Part V

Appendices

Supplementary Analysis of Article 1

In a complementary analysis, we reanalyzed our results for Study 2's Grasping Latency Ratios, after excluding data from the trials in which the participants grasped a card and directly placed it in the box without flipping it. These analyses confirmed our key results.

After excluding data from the trials in which the first grasping was not followed by flipping any of the cards, the robust mixed-model ANOVA using the Welch-James ADF procedure on mean GLR with condition (informative vs. non-informative) as between-subject factors and Trial (1-4) as a within-subject factor revealed a main effect of condition ($F(1, 9.75) = 7.52, p = .027$) thus confirming the effect of condition found with the entire dataset. The robust ANOVA did not reveal any other significant effect. The participants' average GLR was significantly lower than the value predicted by chance (1) in the informative condition ($M = 0.69, SD = 0.49, M_{dn} = 0.58, Z = 29, p = .023$, Wilcoxon signed-rank test), but not in the non-informative condition ($M = 1.17, SD = 0.54, M_{dn} = 1.07, Z = 97, p = .353$, Wilcoxon signed-rank test). Moreover, the participants average GLR were significantly lower in the informative condition than in the non-informative condition ($U = 86, p = .016$, Mann-Whitney U test).

Supplementary Materials of Article 2

1 Complementary analysis: Study 1

In Study 1 one of the cups was fully transparent. Thus, children choosing randomly one of the two opaque cups (while avoiding the transparent cup), should have selected the marked cup with a probability of 1/2. Subsequently, we performed additional analyses to compare children's likelihood of selecting the marker to 1/2. These analyses showed the same pattern of significant results as the ones reported in the main text.

In Study 1, the mean proportion of test trials in which the participants selected the marked cup as their first choice was significantly higher than 1/2 ($Z = 152, p = .004, r = .78$, Wilcoxon signed-rank test). The mean proportion of test trials in which Study 1's participants selected the marked cup as their second choice was significantly lower than 1/2 ($Z = 0, p < .001, r = -.1$, Wilcoxon signed-rank test).

2 Complementary analysis: Study 3's transparent condition

As in Study 1, in Study 3's transparent condition, children choosing randomly one of the two opaque cups (while avoiding the transparent cup), should have selected the marked cup with a probability of 1/2. Subsequently, we performed additional analyses on the data from Study 3's transparent condition, assuming that the level of performance predicted by chance in this condition was 1/2. These analyses showed the same pattern of significant results as the ones reported in the main text.

In Study 3's transparent condition, the mean proportion of test trials in which the participants selected the marked cup as their first choice did not differ significantly from 1/2

($Z = 53$, $p = .16$, $r = -.38$, Wilcoxon signed-rank test; $BF_{01} = 1.43$, Bayesian Wilcoxon signed-rank test). Yet, additional analysis of children's individual patterns of behaviors indicated that they did not behave randomly in Study 3's transparent condition. More participants selected the marked cup for at least 8 trials out of 9 than predicted by chance (4 participants out of 18, $p < .001$, $g = -0.28$, binomial test, with a proportion predicted by chance equal to .020, assuming a random choice of one of the two opaque cups in each trial). Similarly, more participants selected the unmarked opaque cup for at least 8 trials out of 9 than predicted by chance (7 participants out of 18, $p < .001$, $g = -0.11$, binomial test with a proportion predicted by chance equal to .020, assuming a random choice of one of the two opaque cups in each trial). Last, we assessed the proportion of participants neither systematically avoiding nor selecting the marked cup (i.e, selecting the marked cup at least two trials, and at most seven trials). This proportion was significantly lower than predicted by chance (7 participants out of 18, $p < .001$, $g = -0.11$, binomial test, a proportion predicted by chance equal to .96, assuming a random choice of one of the two opaque cups in each trial).

Furthermore, the mean proportion of test trials in which the participants enrolled in Study 3's transparent condition selected the marked cup as their second choice was significantly lower than 1/2 ($Z = 0$, $p < .001$, $r = -1$, Wilcoxon signed-rank test).

Supplementary Materials of Article 4

1 Study S1

1.1 Methods

1.1.1 Participants

We tested eighteen two-and-a-half-year-old children ($M_{age} = 27.83$ months; $SD = 3.88$; age range: 23–34 months). Five additional participants were excluded from the analysis for the following reasons: refusal to cooperate (3) and technical failure (2). The participants of Study 1 were recruited by sending letters to a randomly selected sample of toddlers born in the /MASKED FOR BLIND REVIEW/ area. Our sample sizes were set after referring to comparable studies (Nurmsoo & Bloom, 2008; Experiment 2, which reported an effect size $d = 1.219$ for the comparison of two-and-a-half-year-old children's performance against chance). A compromise power analysis performed with G*power (v. 3.1; Faul et al., 2007) indicated that our sample size yielded a power equal to .93 for comparison against chance by a two-tailed one-sample t-test ($d = .8$; $\alpha = .05$).

1.1.2 Materials and Procedure

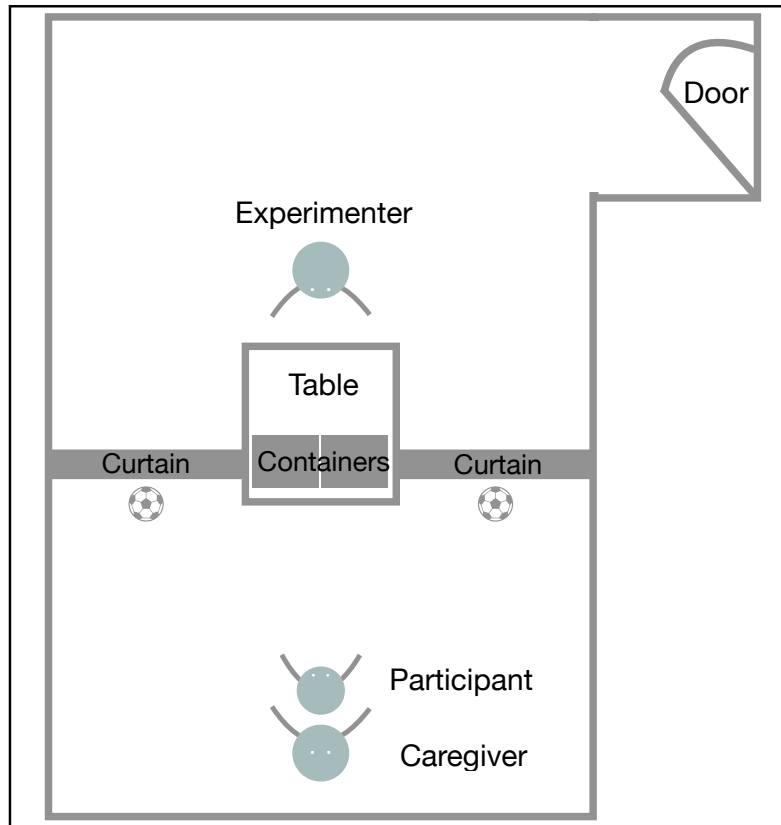
Experimental set-up. Toddlers were tested in a quiet room and were accompanied by a caregiver who was instructed not to influence the participants' choices at any time point of the test phase. The participants sat on their caregivers' laps on a chair positioned against the wall of the testing room (see Figure S1 for a schematic representation of the experimental set-up and photographs of critical events). A table (50x70 cm) was placed in the center of the room, in front of the participants, approximately 1.5 meters away from them. Two containers made of opaque cardboard (30x21x21 cm) were placed in a row on the table, approximately 20 cm apart

from each other, one on each side of the table. The containers had no front side, so that the participant could see inside them at all times. One of the boxes (henceforth, the hiding box) had an opaque backside while the other box (henceforth, the tube) had no backside. Thus, anyone located in front of the participant across the table could see inside the tube only, and could not see inside the hiding box. We counterbalanced the side of the table on which the hiding box was (right or left), across participants. The location of the tube varied accordingly. Moreover, two opaque curtains were hanging from the ceiling to the floor on each side of the table. Each of the curtains was positioned perpendicular to the rooms' lateral walls, and touched both the edge of the table and the wall. Thus, it was impossible for anyone located in front of the toddler across the table to see the areas located on the floor behind the curtains. These areas served as hiding locations for the balls used during the test phase. Three cameras (temporal resolution = 25 frames per second) recorded the participants' behaviors.

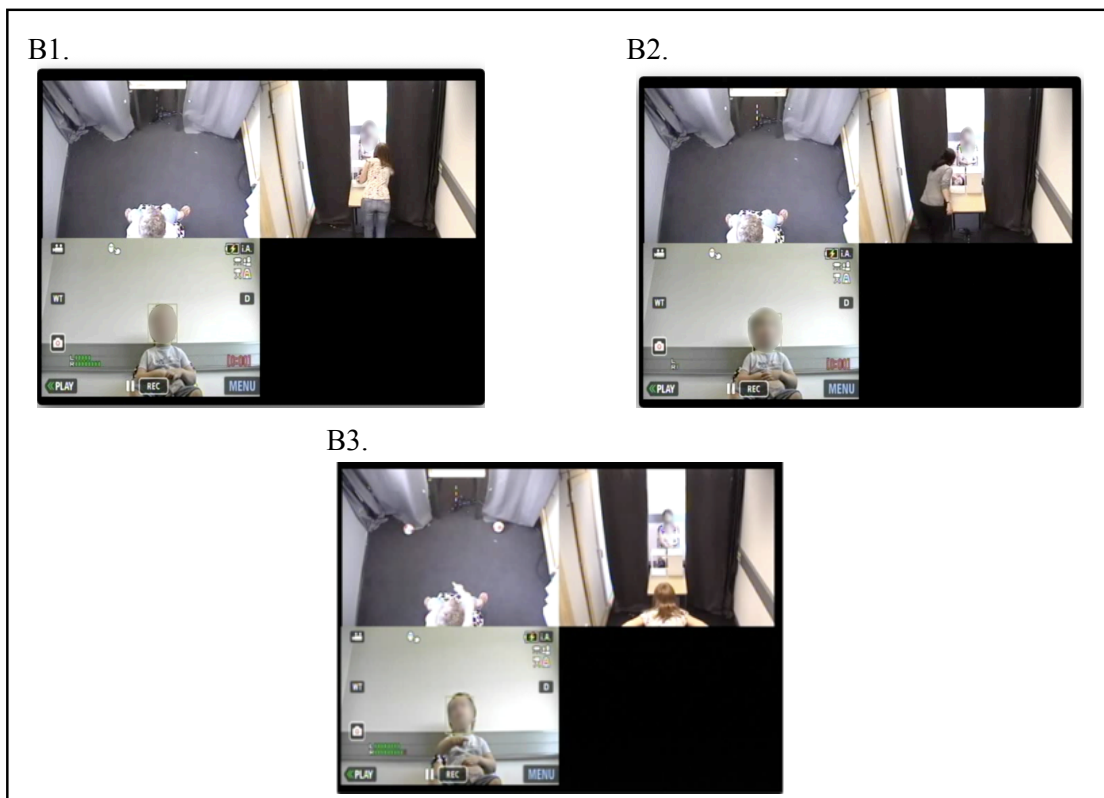
Figure S1

Schematic Representation and Critical Events of Study S1's.

A. Schematic representation of the test phase of Study S1.



B. Pictures of the real setup of Study S1.



Note: Panel A: Schematic representation of the spatial position and orientation of the participants during the test phase of Study S1. Two curtains prevented the experimenter from seeing the balls, which remained visible from the toddler's viewpoint. Panel B: pictures of the real set-up of Study S1. B1: The first experimenter places the balls in the containers. B2: A confederate displaces the balls behind the curtains while the first experimenter is absent from the room. B3: The experimenter looks toward the boxes, and asks about the location of one ball; the participant is shown answering by pointing toward one of the balls. For each sub-panel, the top left pictures show the participant from the ceiling point of view (this camera angle was used to code her pointing behaviors). The top right pictures show what could be seen from the experimenter's point of view. The bottom left pictures show a close-up of the participant (this camera angle was used to code her behaviors).

Warm-up phase. First, the experimenter crouched near the participant and showed a box containing four toys (a plush cat, a plastic duck, a plush fish, and a tiny shoe), while saying, *"I brought some toys with me... What's in this box?"* She then named each toy, before giving them to the participant, one by one. After the participants interacted for some time with each of the toys, the experimenter invited them to put them back inside the box by saying, *"Shall we put them back in the box? I have others..."* At the end of the warm-up phase, the experimenter stood up and moved across the table in front of the participants. Next, the ignorance induction phase was initiated.

Ignorance induction phase. After the warm-up phase, the experimenter showed the participant two identical colored plush balls while saying, *"Look, I brought two nice balls."* Next, she placed one ball in the hiding box and the other ball in the tube (starting with the container on the right side of the table see Figure S1 panel B1; positions are referenced from the experimenter's viewpoint). Meanwhile, the experimenter explained, *"I put this pretty ball here and I put this pretty ball here."* Next, the experimenter pretended to receive a phone call

and left the room while saying, “*Hey, my phone is ringing! I will answer and come back.*” Prior to the beginning of the experiment, the caregivers were asked to close their eyes from the moment when the first experimenter left the room until the end of the experiment. While the first experimenter was away, a second experimenter, unfamiliar to the participants, entered the room (without speaking or making eye contact with the participants). She approached the table and placed each of the balls in the hiding locations on the floor behind the curtains (see Figure S1 panel B2), moving the ball inside the container on the left, behind the left curtain and the ball inside the container on the right, behind the curtain on the right. Following this, the second experimenter left the room, and the test phase began.

Test phase. At the beginning of the test phase, the first experimenter returned to the room and walked toward the table. She stopped approximately 1.5 meters away from the table, in front of the participant (see the position of the experimenter in Figure S1 panel B3). She looked toward the table and empty containers with her hands on her hips. To ensure that her gaze was not directed toward any specific container, she fixated on a discreet mark located at the center of the table. To describe the scene with a mentalistic gloss, when the first experimenter returned after the balls were displaced by the second experimenter, the former was ignorant about the location of the two balls (since both of them were placed behind the curtains and were occluded from her; see Figure S1). However, she could see that the ball initially placed in the tube was no longer there, thus informing her of her ignorance of the location of this ball (we call this ball the “target” when reporting the analysis and results of Study S1). Conversely, the first experimenter could not see that the ball located initially in the hiding box was no longer there, thus rendering her unaware of her ignorance of the location of that ball (we call that ball the “distractor” when reporting the analysis and results of Study S1). Thus, in Study S1, if toddlers do not take into account the experimenter’s Socratic ignorance, and if they are primarily trying to inform her (by filling gaps in her knowledge, or by correcting

her false beliefs), they should be equally likely to point toward any of the balls. In contrast, if toddlers take into account the experimenter's Socratic ignorance, they should assume that she refers to the target ball, initially located in the tube.

The experimenter then looked at the participant, and asked the first prompt question: "*Well, where is the ball?*" Then, she looked around (first on her left side, next on her right side), as if searching for a ball, before looking at the participant while asking the second prompt question: "*Where did the ball go?*" Following this, she looked again toward the mark between the two boxes and asked a third prompt question ("*Where is that ball?*"). Finally, she looked at the participant, and she asked the fourth prompt question: "<Participant's name> *where is the ball?*" There was a delay of approximately 5 seconds between each prompt question. Each participant was enrolled in a single test trial (with four consecutive prompt questions).

1.1.3 Coding

The video recordings were coded offline frame-by-frame, for 20 consecutive seconds from the onset of the first prompt question. We coded two types of behaviors: points and looks. We measured: (i) which ball the infants first looked at after the onset of the first prompt question (i.e., the target or the distractor); (ii) the total duration of looking time toward the target and distractor; and, (iii) the proportion of target looks (number of looks toward the target/number of looks toward the target + distractor). We also collected exactly the same measures for the points. A point was defined as an extension of the infant's arm (either fully or slightly bent) and index finger or open hand, palm facing downward, in the general direction of the object (Liszkowski et al., 2006). One participant did not point toward any of the balls. For this participant, we coded the first point as missing data. The data were first coded by a primary coder. A second coder, who was unaware of the hypotheses of the study, coded 50% of the videos. The agreement between the coders was high for each measure: duration of an action (looking: Spearman's $\rho = 0.89$, $p < .001$; pointing: Spearman's $\rho = 0.90$, $p < .001$),

proportion of an action toward the target (looks: Spearman's $\rho = 0.96$, $p < .001$; points: Spearman's $\rho = 0.97$, $p < .001$), and first action (looks: Cohen's $k = .75$, 87.5% of agreement; points: Cohen's $k = 1$, 100% agreement). Subsequently, statistical analyses were performed on data from the primary coder.

1.1.4 Data Analysis

All statistical analyses reported in this study were two-tailed. Unless otherwise specified, the same general analysis procedures were used in Study 1 and in subsequent studies. The frequentist statistical analyses were performed using R software (v. 4.0.3; R Core Team, 2020). We used nonparametric tests when the data did not fulfill the assumptions of normality. When reported, the Wilcoxon signed-rank effect size refers to the matched rank biserial correlation of the *rcompanion* package (v. 2.3.27; Mangiafico, 2021). When we found null results, we conducted Bayesian tests with Jasp (v. 0.14.1; JASP Team, 2020), with a Cauchy Prior Distribution set to the default value (.707). When conducting the Bayesian Wilcoxon signed-rank test, we used a data algorithm with five chains of 1000 iterations. We report the Bayes factors expressing support for the null hypothesis over the alternative hypothesis (BF_{01}). Any value of BF_{01} larger than 3 is typically interpreted as meaningful evidence for the null hypothesis.

1.2 Results

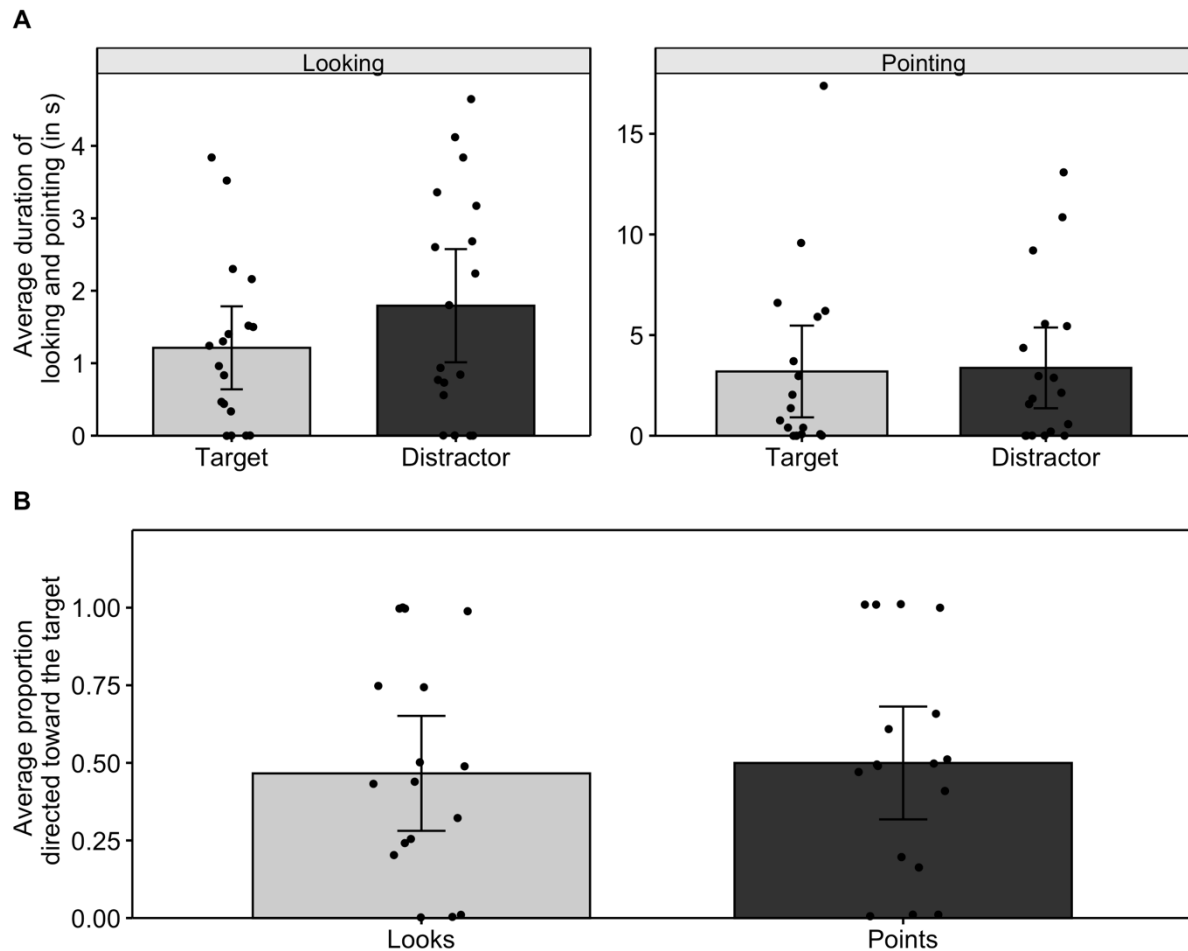
Looks. The participants' first looks were not more likely to be directed toward the target than predicted by chance (7 successes out of 18 – 38.9%; 95% $CI = [17.3, 64.3]$ $p = .48$, $g = -.11$, binomial test; $BF_{01} = 2.31$, Bayesian binomial test). As Figure S2 panel A shows, the participants did not look longer toward the target ($M = 1.21$ s, $SD = 1.15$) than toward the distractor ($M = 1.79$ s, $SD = 1.57$, $Z = 57$, $p = .23$, $r = -.33$, Wilcoxon signed-rank test; $BF_{01} = 2.10$, Bayesian Wilcoxon signed-rank test). As Figure S2 panel B shows, the proportion of

target looks did not differ from the theoretical value of .5, as predicted by chance ($M = .47$, $SD = .37$, $Z = 61$; $p = .73$, $r = -.10$, Wilcoxon signed-rank test; $BF_{01} = 3.817$, Bayesian Wilcoxon signed-rank test).

Points. During the test phase, the participants were not more likely to point first toward the target than predicted by chance (seven successes out of 17 – 41.2%; 95% $CI = [18.4, 67.1]$, $p = .63$, $g = -.09$, binomial test; $BF_{01} = 1.7$, Bayesian binomial test). The participants did not point for longer durations toward the target ($M = 3.19$ s, $SD = 4.58$, $M_{dn} = 1.06$ s) than toward the distractor ($M = 3.37$ s, $SD = 4.03$, $M_{dn} = 1.99$ s, $Z = 75$, $p = .96$, $r = -.02$, Wilcoxon signed-rank test; $BF_{01} = 4.076$, Bayesian Wilcoxon signed-rank test). Moreover, the proportion of target pointing did not differ from the theoretical value of .5, as predicted by chance ($M = .50$, $SD = .35$, $Z = 46.5$; $p = .97$, $r = -.10$, Wilcoxon signed-rank test; $BF_{01} = 3.793$, Bayesian Wilcoxon signed-rank test).

Figure S2

Results of Study S1; Panel A: Average Duration of Looking and Pointing in Seconds per Ball Type (target and distractor); Panel B: Average Proportion of Looks and Points Toward the Target ball.



Note: Error bars represent 95% CI.

1.3 Discussion

In Study S1, toddlers showed no sensitivity to the experimenter's Socratic ignorance when interpreting her questions. In fact, there was moderate evidence for the null hypothesis for the two most fine-grained measures: the proportion of target looks and the proportion of target points. Thus, Study S1 provided no support for the view that early developing representations of Socratic ignorance guide the interpretation of questions (Hypothesis 1). In Studies 1a and 1b, we assessed whether the use of Socratic ignorance to interpret questions

emerges along with changes in the capacity to attribute second-order mental states. Thus, we tested older children (five- to seven-year-olds) because the capacity to attribute second-order mental states, measured by second-order false belief tasks, typically increases between five and seven years of age (Miller, 2009).

Furthermore, in Study S1, we did not compare the participants' capacity to use simple knowledge tracking with their capacity to rely on representations of Socratic ignorance. We addressed this issue in Study 1a by testing a first group of participants (five- to seven-year-old children) on a first-order question test in which they could determine the meaning of a request for information by using simple knowledge tracking.

2 Detailed Scripts for the Second-Order False Belief Tasks

In the second-order false belief tasks, the participants heard stories and they were asked different types of questions: (1) control questions, (2) second-order knowledge questions, and follow-up justification questions and (3) second-order false-belief questions, and follow-up justification questions. When the participants answered incorrectly on one of the control questions, they were corrected, and the experimenter asked the question again, till the participants provided the correct answer.

The participants received no feedback on their answers on the test questions (second-order knowledge questions, false belief questions, and follow-up justifications).

Each participant was tested on the birthday puppy and chocolate bar stories (order of presentation counterbalanced across participants).

2.1.1 *Chocolate bar story*

Pierre et Emilie are brother and sister. They are in the living room.

Their mother bought a chocolate bar and gives it to Pierre. Emilie doesn't get any chocolate, because she has been naughty.

Pierre eats some of his chocolate and puts the remainder into the drawer. He doesn't give any chocolate to Emilie. Emilie is upset that she does not get any chocolate.

After that, Pierre goes to help his mother in the kitchen. Emilie is alone in the room. Because she is upset, she takes the chocolate from the drawer and puts it into the toy box. While she is putting the chocolate into the toy box, Pierre is passing by the window. He sees that Emilie takes the chocolate out of the drawer and puts it into the toy box. Emilie does not see Pierre.

- Control question 1: Where is the chocolate now ? (correct answer: in the toy box)

- Control question 2: Does Pierre know that Emilie put the chocolate into the toy box ?
(correct answer: yes)
- Control question 3: Does Emilie know that Pierre saw her put the chocolate into the toy box ? (correct answer: no)

Now, Pierre comes back to the living room. Kevin wants to eat some of his chocolate. He says, “Hum, I would like to some chocolate”.

- Second-order knowledge question: Does Emilie know that Pierre knows where the chocolate is ? (correct answer: no)
- Second-order knowledge justification follow-up question: Why ?
Remember, Emilie does not know that Pierre saw her moving the chocolate.
- Second-order false belief question: Where does Emilie think that Pierre will look for the chocolate ? (correct answer: in the drawer)
- Second-order false belief justification follow-up question: Why does she think that ?

2.1.2 Birthday puppy story

Tonight, it's Louis's birthday and his mum wants to surprise him with a puppy. She has hidden the puppy in the basement.

Louis says, “Mum, I really hope you got me a puppy for my birthday”.

Because Louis's mother wants to surprise him with a puppy, instead of telling Louis she got him a puppy, she says, “Sorry Louis, I didn't get you a puppy for your birthday. I got you a really nice ball instead.”

- Control question 1: Did the mother really get a ball for Louis's birthday ? (correct answer: no)
- Control question 2: What does Louis think that his mom bought for him? (correct answer: a ball)

- Control question 3: Why does Louis's mum say she will get him a ball for his birthday?
(correct answer: to surprise him)

Now, Louis, says to his mother: "I am going outside to play." On his way outside, Louis goes down to the basement to fetch his skates. In the basement, Louis finds his birthday puppy. Louis says to himself: "Wow, mum didn't get me a ball; she really got me a puppy for my birthday." His mother does not see that Louis goes down to the basement and finds the birthday puppy.

- Control question 4: Does Louis know that his mother got him a puppy for his birthday?
(correct answer: yes)
- Control question 5: Does Louis's mum know that he saw the puppy in the basement?
(correct answer: no)

Now, the telephone rings, ding-a-ling! Louis's grandmother calls to find out what time the birthday party is. The mother tells grandma on the phone that she got Louis a puppy for his birthday, but that Louis doesn't know this. Then grandma asks mum on the phone, "Does Louis know what you will really get him for this birthday?"

- Second-order knowledge question: What does the mother say to grandma? (correct answer: no)
- Second-order knowledge follow-up justification question: Why does mum say that? Remember the mother does not know that Louis saw what she got him for his birthday.

Then, grandma asks mum on the phone, "What does Louis think you got him for his birthday?"

- Second-order false belief question: What does the mother say to grandma? (correct answer: a ball)
- Second-order false belief follow-up justification question: Why does mum say that?

2.1.3 Coding

The participants received a score of 1 for each correct answer on a test question (second-order knowledge and second-order belief questions), and for each correct answer on the corresponding follow-up justification question, thus resulting in a score ranging from 0 to 4 both for second-order knowledge questions, and for second-order false belief questions. The answers to the justification questions were coded following Sullivan and colleagues' (1994) criteria: for each question, the participants received a score of 1 for an appropriate justification (explicit second-order reasoning, implicit second-order reasoning, communicated information or location information) and they received a score of 0 for an inappropriate justification (first-order reasoning, story facts, nonsense or no response).

3 Tables

Table S1

Results of the Linear Models Testing the Effect of the Age (in months, mean centered), Second-Order Knowledge Score, Second-Order False Belief Score and Study on the Eye-tracking Test of Studies 1a and 1b.

Eye-tracking test		Predictors	Estimate	SE	t-value	p-value	CI 2.5%	CI 97.5%
Study 1a	Age model	Intercept	1.02	0.092	11.00			
		Age	0.005	0.008	0.63	.54	-0.012	0.022
	Second-order knowledge model	Intercept	0.81	0.20	3.98			
		Second-order knowledge score	0.074	0.063	1.17	.26	-0.062	0.21
	Second-order false belief model	Intercept	0.90	0.15	6.12			
		Second-order false belief scores	0.057	0.056	1.01	.33	-0.064	0.18
Study 1b	Age model	Intercept	0.78	0.036	21.64			
		Age	-0.004	0.003	-1.53	.13	-0.010	0.001
	Second-order knowledge model	Intercept	0.70	0.079	8.88			
		Second-order knowledge score	0.029	0.027	1.09	.29	-0.024	0.083
	Second-order false belief model	Intercept	0.84	0.065	12.92			
		Second-order false belief scores	-0.029	0.025	-1.71	.25	-0.078	0.021

Table S2

Results of the Generalized Linear Mixed Models to Test the Effect of the Age (in months, mean centered), Second-order Knowledge Score, Second-Order False Belief Score and Study on the Explicit Identification Test of Studies 1a and 1b.

Explicit identification test		Predictors	Estimate	SE	z-value	p-value	CI 2.5%	CI 97.5%
Study 1a	Age model	Intercept	2.91	1.24	2.35			
		Age	-0.052	0.10	-0.512	.61	-0.36	0.13
	Second-order knowledge model ^a	Intercept	2.67	2.17	3.26			
		Second-order knowledge score	-0.20	0.64	0.11	.74	-3.17	0.83
	Second-order false belief model	Intercept	2.66	1.66	1.60			
		Second-order false belief scores	0.027	0.65	0.04	.97	-1.51	1.60
Study 1b	Age model	Intercept	0.21	0.27	0.79			
		Age	-0.023	0.021	-1.08	.29	-0.065	0.018
	Second-order knowledge model	Intercept	-0.054	0.58	-0.093			
		Second-order knowledge score	0.10	0.20	0.52	.60	-0.29	0.50
	Second-order false belief model	Intercept	0.68	0.50	1.35			
		Second-order false belief scores	-0.21	0.19	-1.11	.27	-0.59	0.15

Note: ^a due to quasi-complete separation of data we used Firth's bias reduction method; we report *Wald's Chi-squared*-values instead of *z*-values for this analysis.

Table S3

Sample Size Estimation for Study 1b for Comparisons Against Chance Performed with Wilcoxon Signed-rank Tests (eye-tracking experiment), and with Binomial Tests (explicit identification test).

	Children (5- to 7-years-olds)	
Estimate of effect size based upon Study 2a	Proportion of looks	$d = 0.67$
	Explicit identification	$g = .44$
Estimate of sample size (n required to achieve a power $> .9$)	Proportion of looks	27
	Explicit identification	12
Power achieved with $n = 28$	Proportion of looks	.91
	Explicit identification	$>.99$

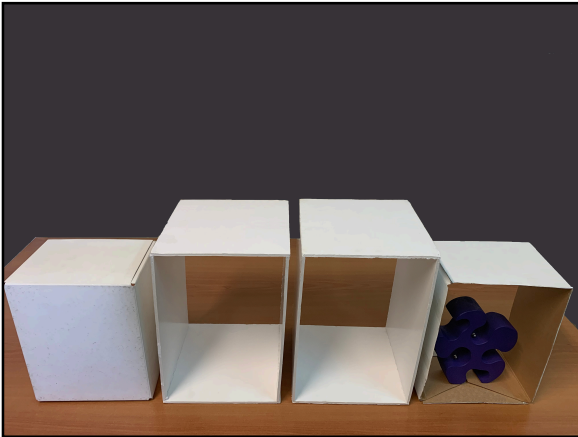
Note: The first row reports estimates of effect sizes based upon Study 1a's results. The second row reports estimates of the minimal sample sizes required to achieve a power higher than .90 ($\alpha = .05$), assuming effect sizes identical to those computed for Study 1a. Based on these estimates we planned to test 28 participants to achieve sufficient power in all our groups. The third row reports the power achieved by running 28 participants, assuming effect sizes identical to those computed for Study 1a.

4 Figures

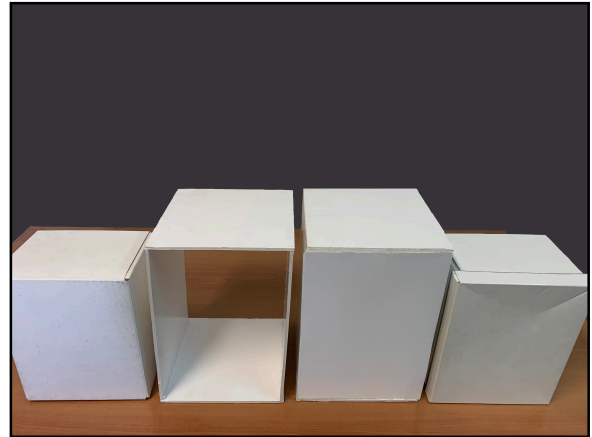
Figure S3

Pictures of What Was Visible From the Actors' Viewpoint in Studies 1a-4, per Condition.

A. 1st Order condition



B. 2nd Order condition



C. Heuristic condition

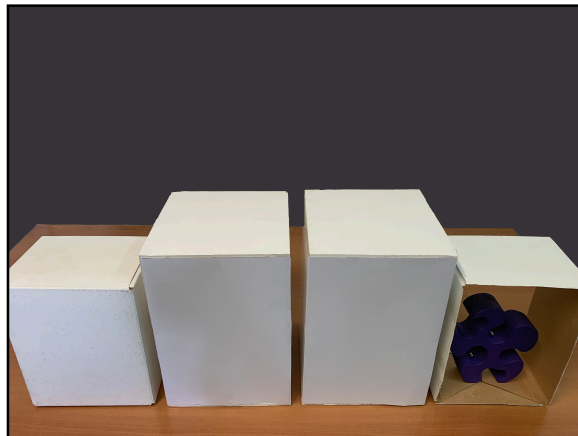
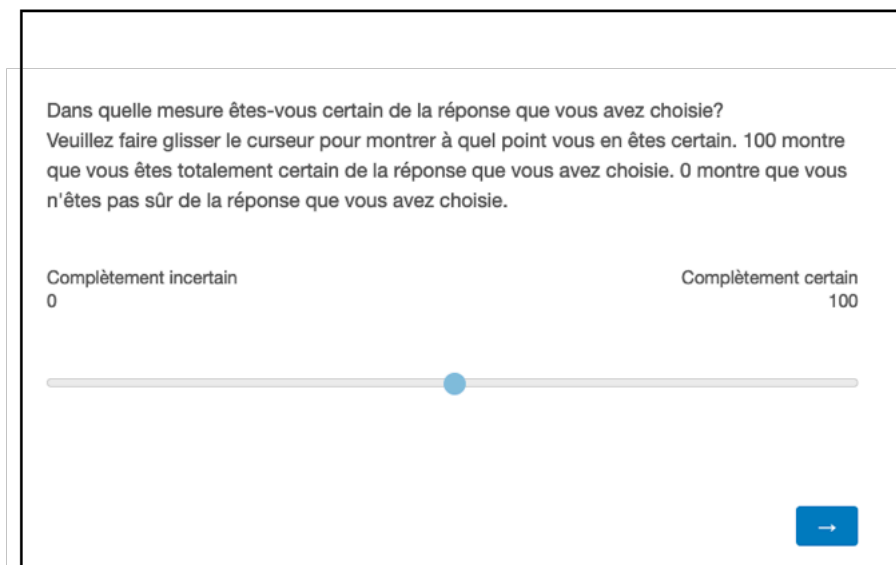


Figure S4

Screenshots from the test phase of Study 2.



A. Explicit identification test



B. Certainty scale

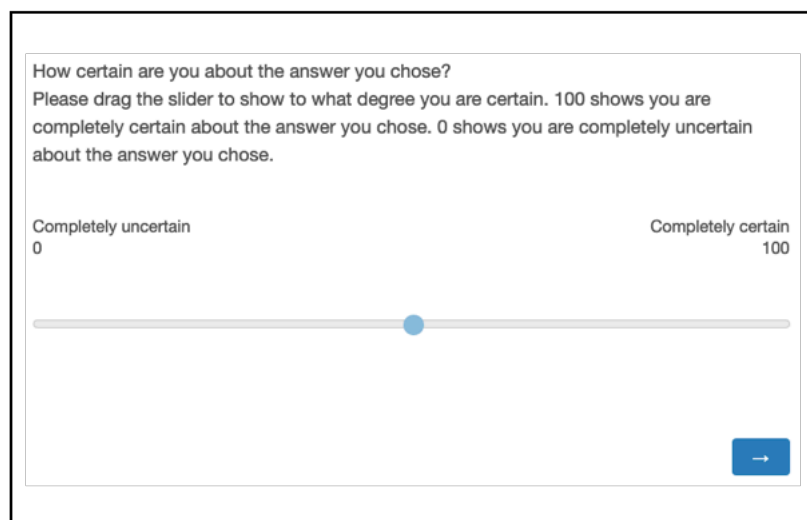
Note: Panel A illustrates the identification question test. Panel B illustrates the rating of certainty. An English translation of the text in the screenshot can be found in Figure S5.

Figure S5

Screenshots from the test phase of Study 3.



A. Explicit identification test



B. Certainty scale

Note: Panel A illustrates the identification question test. Panel B illustrates the rating of certainty.

5 Procedural Details of the Attention Check Question

After the experiment, the participants were tested on an attention check question. The screen displayed the following instruction “*Please write in the next question box the color of the object below*”, above a picture of the purple wooden unfamiliar object seen in the experiment. Next, the picture disappeared, and a novel instruction appeared “*Based on the previous instructions, write your answer in the box below:*” with a text entry box below in which the participants could type in their answer. The answers “purple” and/or “blue” were coded as correct. The participants who did not succeed on the attention check question were excluded from analysis.

6 Cluster Mass Test Analysis

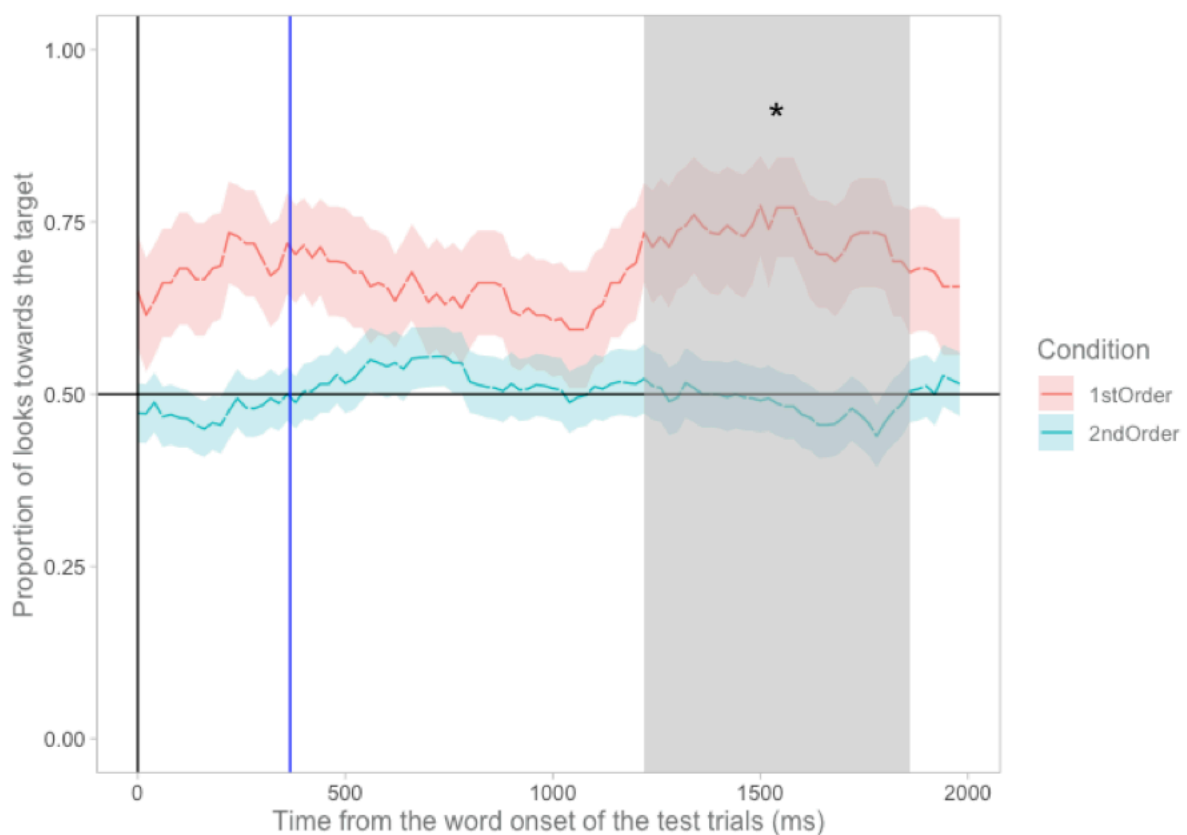
We ran a cluster-based permutation analysis on the proportion of looks toward the target to look for time windows revealing a significant difference between Studies 1a and 1b (for examples of comparable analyses see, Dautriche et al., 2015; de Carvalho et al., 2019; Havron et al., 2019; for a formal presentation of the analysis itself, see Maris & Oostenveld, 2007). This analysis was performed on the whole sample of participants ($N = 72$), since we observed no effect of Age on performance in the eye-tracking experiment. For each 20 ms time sample, we ran a two-tailed independent t-test on the arcsin-transformed proportion of looks toward the target to test for the effect of Study (Study 1a – first-order ignorance vs. Study 1b – second-order ignorance). Adjacent time samples were grouped in a cluster when their t-value was greater than a threshold corresponding to a statistically significant difference ($t = 2.06$). The size of each cluster was measured by computing the sum of all t-values within that cluster. In order to evaluate the probability that a cluster existed by chance, we ran 1000 simulations where condition (Study 1a – first-order ignorance vs. Study 1b – second-order ignorance) was randomly assigned for each test sequence. For each simulation, we computed the size of the largest cluster, just like for the real data (sum of all the t-values within a cluster of significant t-values). Clusters found in the real data were considered meaningful if the probability of observing a cluster of the same size or bigger in the simulations was smaller than 5%, i.e., a threshold equivalent to a p-value of 0.05. This analysis was conducted in R (v. 4.0.3; R Core Team, 2020) using the package `eyetrackingR` (v. 0.1.8; Dink & Ferguson, 2015).

The cluster-based permutation analysis confirmed that there was a significant effect of Study (1a vs. 1b) on performance in the eye-tracking experiment. As Figure. S4 shows, this effect was distributed in the pre-defined time window, with one time windows where the proportion of looks toward the target object type tended to be different across Studies (1a vs. 1b) (1220-1860 ms: $p = .015$). Note that in this experiment, there were repeated consecutive

prompt sentences encouraging the participant to look at the target object, both during the familiarization and test phase, thus explaining why, on average, the participants already looked at the target object at word onset in Study 1a (first-order condition).

Figure S6

Proportion of Looks Toward the Target from the Onset of the Novel Label in Studies 1a and 1b.



Note: The time-windows goes from 367 ms after the onset of the novel label (blue vertical line) to 2000 ms. Colored shading represents ± 1 SEM. The cluster-based permutation test revealed tendencies for statistical differences (dark grey windows) between the Study 1a (red curve) and Study 1b (blue curve).

*: $p < 0.5$

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Article 5

Non-verbal Rhetoric: 2- to 4-Year-Old Children Select Relevant Evidence When Trying to Influence Others

This article investigates the early emergence of reason-giving. Toddlers are sensitive to disagreements, and they can track several kinds of informational access, such as visual perception. We investigated whether young children use these skills (a) when assessing whether providing reasons is needed and (b) when selecting appropriate behaviors to support their claims. An experimenter disagreed with 2- to 4-year-old children ($N = 71$) about the location of a toy placed in 1 of 4 boxes. In the fully transparent condition, the boxes were transparent, and the toy was visible to the experimenter and to the participant. In the window condition, the boxes were partially opaque, and the toy was initially hidden from the experimenter but visible to the participant through a transparent window. In this condition, toddlers could make the toy visible to the experimenter by rotating the baited box. Participants in the window condition were more likely to rotate the baited box than those in the transparent condition. Thus, children were more likely to rotate the box when this action was an efficient way of supporting their claims by revealing new and relevant information to the experimenter. These results demonstrate the presence of precursors of crucial skills required for reason-giving and reveal that from 2 years of age, children do not use fixed persuasion strategies. Instead, they select

relevant evidence when attempting to influence others.



Nonverbal Rhetoric: 2- to 4-Year-Old Children Select Relevant Evidence When Trying to Influence Others

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This article investigates the early emergence of reason-giving. Toddlers are sensitive to disagreements, and they can track several kinds of informational access, such as visual perception. We investigated whether young children use these skills (a) when assessing whether providing reasons is needed and (b) when selecting appropriate behaviors to support their claims. An experimenter disagreed with 2- to 4-year-old children ($N = 71$) about the location of a toy placed in 1 of 4 boxes. In the fully transparent condition, the boxes were transparent, and the toy was visible to the experimenter and to the participant. In the window condition, the boxes were partially opaque, and the toy was initially hidden from the experimenter but visible to the participant through a transparent window. In this condition, toddlers could make the toy visible to the experimenter by rotating the baited box. Participants in the window condition were more likely to rotate the baited box than those in the transparent condition. Thus, children were more likely to rotate the box when this action was an efficient way of supporting their claims by revealing new and relevant information to the experimenter. These results demonstrate the presence of precursors of crucial skills required for reason-giving and reveal that from 2 years of age, children do not use fixed persuasion strategies. Instead, they select relevant evidence when attempting to influence others.

Keywords: argumentation, disagreement, reasoning, naïve epistemology, justification

Supplemental materials: <http://dx.doi.org/10.1037/dev0000779.supp>

Psychologists have long noted how early some reason-giving and reason-evaluating capacities develop and the crucial cognitive role that these abilities play in development. Piaget claimed that “logical reasoning is an argument which we have with ourselves, and which reproduces internally the features of a real argument” (Piaget, 1928, p. 204; see also Doise & Mugny, 1984; Perret-Clermont, 1980; Vygotsky, 1978). More recent theories have

stressed the evolutionary importance of argumentative and, more generally, reason-giving and reason-evaluating skills, suggesting that these skills should develop early (Mercier & Sperber, 2011, 2017; Tomasello, 2014). Yet, to this date, we do not know how early reason-giving develops. To address this developmental issue, we test the existence and nature of reason-giving during toddlerhood, using a nonverbal paradigm.

Recent experiments suggest that preschoolers’ reason-giving already shows two signatures of argumentative skills: (1) a capacity to recognize when producing reasons is needed and (2) some ability to select appropriate reasons. In one experiment, separate pairs of 3- and 5-year-old children played a game together (Köymen, Rosenbaum, & Tomasello, 2014). In this game, some moves were more conventional than others. Both age groups were more likely to provide reasons when making unconventional than conventional moves. This finding shows that preschoolers are already attuned to whether a situation warrants providing reasons. Another experiment suggested that preschoolers possess some capacity to select reasons that are effective and convince others. In Köymen, Mammen, and Tomasello (2016), 3- and 5-year-old children were able to adjust their reason-giving to the state of knowledge of their interlocutor. Children were provided with a good reason to perform an unconventional action, either as pairs or individually, and they were then asked to perform the unconventional action, always as pairs. When the children were paired with another child who had heard the reason at the same time as them, they were less likely to use this reason in their interaction, compared with when they

This article was published Online First July 8, 2019.

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The authors declare no conflicts of interest.

We thank Pauline Le Floch, Aurélie Giraud, and all the members of the Institute for Cognitive Science Marc Jeannerod for their help. We are especially grateful to the daycare centers that hosted the project (Crèche Hénon, La Maison des Chatons, People and Baby, Les crèches les Petits Chaperons Rouges) and to all the families and toddlers that participated in this study. This research was supported by grants from the Agence Nationale pour la Recherche (PragTICAL ANR-14-ACHN-0020; VICCOM ANR-16-TERC-0001-01; EUR FrontCog ANR-17-EURE-0017) to Olivier Mascaró and Hugo Mercier.

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were paired with another child who had not heard the reason at the same time as them. Preschoolers could thus use common knowledge between themselves and their interlocutor, or lack thereof, to adjust their reason-giving strategies (see also Mammen, Köymen, & Tomasello, 2018).

In sum, preschoolers are sensitive to whether reasons are needed, and they provide their interlocutors with relevant reasons when attempting to influence them. The goal of this article is to investigate whether younger children's nonverbal communicative behaviors already show these two signatures of reason-giving skills. As we argue presently, many of the basic skills required to produce reasons are likely to develop early during infancy and toddlerhood.

Recognizing When Reasons Are Needed

Reason-giving is most appropriate when we believe our audience has ignored, doubted, or disagreed with what we have communicated—or when we deem our audience likely to do so. Two-year-old children already have some sensitivity to such disagreements. For instance, they contradict adults who name objects incorrectly, often by using negation (Choi, 1988; Hummer, Wimmer, & Antes, 1993; Kim, 1985; Koenig & Echols, 2003; Pea, 1982; Rakoczy & Tomasello, 2009). Toddlers and preschoolers also react to third-party assessments of propositions. They prefer to learn what an informant communicates if other people assent rather than dissent to this testimony (Fusaro & Harris, 2008, 2013). Moreover, toddlers and children recognize that someone might explicitly deny the truth of a proposition. This ability is most evident in their capacity to process truth-functional negations (Austin, Theakston, Lieven, & Tomasello, 2014; Feiman, Mody, Sanborn, & Carey, 2017; Hill, Collier-Baker, & Suddendorf, 2012; Mascaro & Morin, 2015; Mascaro & Sperber, 2009). In short, a sensitivity to explicit disagreements about the truth of a proposition is already present during toddlerhood. As a result, explicit markers of disagreement such as denials are likely to help children identify when they need reasons to influence others, at least from toddlerhood onward.

Selecting Efficient Means of Influencing Others

To influence others, one needs more than recognize when they disagree (or might disagree) with one's claims. One also needs to select behaviors that can efficiently influence others, an ability that is likely to improve with the development of representations of mental states (also known as mentalizing or theory of mind, Premack & Woodruff, 1978). Indeed, children's use of others' mental states when making influence attempts improves throughout childhood when practicing deception (Lee, 2013; Mascaro & Morin, 2014; Mascaro, Morin, & Sperber, 2017) and honest persuasion (Bartsch & London, 2000; Bartsch, Wade, & Estes, 2011). Furthermore, the amount and quality of children's attempts in persuasion tasks correlates positively with their capacity to predict explicitly agents' behavior on the basis of their beliefs (Bartsch, London, & Campbell, 2007, Study 2; Kołodziejczyk & Bosacki, 2015; Lonigro, Baiocco, Baumgartner, & Laghi, 2017; Peterson, Slaughter, & Wellman, 2018; Slaughter, Peterson, & Moore, 2013). In short, available evidence suggests that the development of mentalizing abilities constrains the set of persuasion strategies

that are available to children. This hypothesis makes a straightforward developmental prediction: the first reason-giving behaviors to emerge are likely to be those that involve precociously developing mentalizing abilities.

One of the most primary forms of mentalizing abilities is the capacity to recognize informational access (e.g., Martin & Santos, 2016; Wellman, 1992). Infants and toddlers have some sensitivity to the factors that influence what others know. They recognize that communicative actions can inform others (Liszkowski, Carpenter, Striano, & Tomasello, 2006; Martin, Onishi, & Vouloumanos, 2012; Song, Onishi, Baillargeon, & Fisher, 2008; Vouloumanos, Martin, & Onishi, 2014; Vouloumanos, Onishi, & Pogue, 2012; for a review see Harris & Lane, 2014). Furthermore, infants and toddlers recognize that visual perception provides people with information about their surroundings (Luo & Baillargeon, 2007; Luo & Johnson, 2009; Moll & Tomasello, 2006; Sodian, Thormer, & Metz, 2007; Southgate, Senju, & Csibra, 2007). For example, in Moll and Tomasello (2006), toddlers interacted with an adult searching for an object. One candidate object was hidden from the adult but was visible to the participant. The other candidate object was visible to both the participant and the adult. When asked to help the adult find the object that she was looking for, 24-month-old toddlers gave the adult the object that was hidden from her. These results suggest that toddlers have some sensitivity to what other people can see. Thus, infants and toddlers recognize some of the conditions enabling informational access in others. This capacity is likely to support the development of the first reason-giving behaviors geared toward influencing others.

In sum, two basic capacities required to produce reasons efficiently are present well before children can recruit them in a verbal context: a sensitivity to disagreements and expectations about the kind of experiences (such as seeing) that can inform others. Here, we investigate whether these two abilities support the early development of reason-giving in toddlers. No experimental study has specifically tested reason-giving at such an early age, in part because previous studies relied on measures of verbal production. To be suitable for very young children, our study relies on nonverbal behaviors, a possible precursor of verbal reason-giving.

Operationalization Principle

In our study, we tested whether toddlers adjust their nonverbal behaviors to the context when trying to provide support for their claims. We manipulated whether the exact same action (rotating a box) was relevant by varying the presence of explicit disagreement. An experimenter asked toddlers to indicate the location of a box containing a toy. Participants could provide their answer by pointing at the correct box or by grasping it. They could also manipulate the position of the boxes by rotating them. In the window condition, a box containing a toy was opaque except for a transparent window that faced the participants but was hidden from the experimenter. Thus, participants could provide additional evidence about the toy's location by rotating the box and making the toy visible to the experimenter through the transparent window. The fully transparent condition used the same procedure as the window condition except that the box containing the toy (as well as the other boxes) was entirely transparent, making the toy visible to the experimenter at all times. Thus, in this condition, partici-

pants could not provide additional evidence about the location of the toy by rotating the box.

During the baseline phase, there was no reason for participants to assume that the experimenter disagreed with them. In contrast, during the test phase, the experimenter contradicted participants after they indicated where the toy was located. We hypothesized that during the test, the participants would rotate the box more often when this action was relevant to provide evidence for their claims (i.e., in the window condition). We chose to test 2- to 4-year-old participants because we wanted to (a) assess reasoning at the earliest age possible and (b) evaluate possible developmental effects. Because we used denials in our experimental setup, we did not test 1-year-old children because, at that age, the understanding of truth-functional negation is not well consolidated (Austin et al., 2014; Feiman et al., 2017).

Method

Participants

Two groups of 2- to 4-year-old children participated in this study (window condition: $n = 35$, $M_{\text{age}} = 35.51$ months, range = 23–48 months, 14 girls; fully transparent condition: $n = 36$, $M_{\text{age}} = 35.67$ months, range = 23–48 months, 13 girls). Eleven additional participants were excluded ($M_{\text{age}} = 31.27$ months, range = 24–41 months, six girls) because they did not understand the task, that is, they did not answer correctly by pointing toward or reaching for the location of the dog in at least three out of the four baseline trials (five participants), because of technical failure (one participant), or because participants stopped interacting with the experimenter after being contradicted (five participants). Our rejection rate (11 participants out of 82, 13%) is similar to what has been observed in comparable studies (e.g., Moll & Meltzoff, 2011; Moll & Tomasello, 2006). However, it should be noted that our sample is representative only of the children kept in the analysis, and who were thus able to understand the task and willing to engage with the experimenter. The mean age of the excluded participants tended to be lower than the mean age of the participants in the window condition, $t(44) = 1.78$, $p = .082$, $d = .69$, and in the fully transparent condition, $t(45) = 1.78$, $p = .071$, $d = .72$, presumably because the youngest of our participants were more likely to fail to understand the task.

The research reported in this article followed the guidelines of the Declaration of Helsinki and it was approved by the local board of daycare centers involved in the project. The written informed consent of participants' caregivers was obtained prior to the study. Institutional Review Board approval from ethics committees for bio-medical research was not sought because this project involves purely behavioral measures, and it falls out of the scope of bio-medical research (Title: "Nonverbal Rhetoric"; Institution: Institute for Cognitive Sciences Marc Jeannerod). The participants were recruited from urban daycare centers and preschools in a large French city. They came from mixed socioeconomic backgrounds and were native French speakers. They were randomly assigned to one of the two conditions (window vs. fully transparent).

We aimed at achieving the largest possible sample size, given our recruitment opportunities. Therefore, we tested all the available participants within our target age range in the schools that we

contacted. To assess the resulting power to detect a difference between participants' number of rotations of the box across conditions (window vs. fully transparent) with a Fisher's exact test, we ran a compromise power analysis with G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007). This analysis postulated a low probability to rotate the box during the trials of the fully transparent condition ($p_r = .1$) and a large effect size ($\alpha = .05$, $\beta = .05$, odds ratio [OR] = 6.71, Chen, Cohen, & Chen, 2010). It revealed that our sample size yielded an implied power equal to .90.

Materials and Procedure

Participants were tested in a quiet room at their daycare center. The main experimenter was aware of the study's hypotheses (as in many comparable experiments, e.g., Moll & Tomasello, 2006; Warneken & Tomasello, 2006). A daycare employee familiar to the participants, and unaware of the hypotheses of the study, acted as a confederate and was present in the room during the entire experiment. Both the experimenter and the confederate were instructed not to influence participants' choices during the warm-up and test phases. One camera (temporal resolution = 25 frames/second) recorded participants' behaviors. Toddlers sat in front of the experimenter, across a child-size table. The experimenter said: "Look, I brought little boxes to play with." She placed four plastic boxes (8 cm × 6 cm × 5 cm) on a rectangular cardboard tray (60 cm × 27 cm) positioned in the center of the table, approximately 30 cm from the participants. Three of the boxes were empty; a small plastic dog was glued inside the fourth box. Boxes were closed with lids, and they were locked so that participants could not open them easily.

Window condition. In the window condition, each box was entirely covered with opaque white paint except for a transparent window (4.5 cm × 4.5 cm) located on its front side. The experimenter placed the boxes so that their opaque sides faced her, while the transparent windows faced the toddlers. Participants could thus see the boxes' contents—including where the dog was—at all times. In contrast, it was not possible to see the boxes' content from the experimenter's point of view.

The experimenter explained as follows: "Let's play a game. You have to find the little dog." Then, during each baseline trial, the experimenter asked the prompt question, "Where is the dog?" We evaluated the participants' answer to the prompt question in the same way in the baseline, pretest, and test trials. In all cases, participants could answer by pointing at or reaching for one of the boxes. For each trial, we considered that the participants selected accurately the box containing the toy when they pointed at it, reached for it, or rotated it. When a child's answer to the prompt question was ambiguous or directed toward more than one box, the experimenter repeated the prompt question until the participant selected only one box. When participants pointed at or reached for an empty box in response to the prompt question, we assumed that they failed to select the correct box. During the baseline trials, when the participant failed to indicate the correct box, the experimenter pointed at the baited box and said, "Here is the dog."

In the baseline, pretest and test trials, we also recorded whether participants answered the prompt question by rotating the box containing the dog so that its front part (i.e., the transparent window in the window condition) faced the experimenter. To do

so, participants had to rotate the box clockwise or counterclockwise around its vertical axis more than 90 degrees from its position at the beginning of the experiment (thus making it possible for the experimenter to see the dog from her viewpoint in the window condition). In a given trial, a participant was allowed to both point at and rotate the same box (no participant pointed at one box and rotated another one).

Once the child had pointed at or reached for the box containing the plastic dog, the experimenter proceeded to the next baseline trial. At the end of each baseline trial, the experimenter swapped the location of the box containing the dog with the location of one of the empty boxes. There were four baseline trials. For each trial, the experimenter placed the box containing the dog in a different position, using the following fixed order: right end of the row (Trial 1), third position from the right end of the row (Trial 2), left end of the row (Trial 3), and second position from the right end of the row (Trial 4). The left and right sides referenced here are from the participants' viewpoint. The experimenter displaced the box containing the dog prior to each of the baseline trials.

After the fourth baseline trial, the experimenter placed the box containing the dog in the second position from the right end of the row of boxes. She reached for her cellphone in her pocket while saying, "Oh, I have a phone call, I'll be right back" before leaving the room. While she was away, the confederate took the box containing the dog and placed it at the left end of the row. After staying outside the room for approximately 15 s, the experimenter came back in the testing room. She sat across the table in front of the participant and said, "Let's continue the game!", and the pretest trial began. The experimenter asked, "Where is the dog?" Once participants had pointed at, reached for, or rotated one of the boxes, the experiment proceeded to the test phase. The first test trial started by the experimenter contradicting participants by saying, "No . . . the dog is not there . . ." before asking the prompt question again: "Where is the dog?" Once the participant had pointed at, reached for, or rotated one of the boxes, the experimenter proceeded to the next test trial. Unlike in the baseline trials, during the pretest and test trials, the experimenter did not indicate the real location of the dog to the participants when they failed to select the correct box. Each test trial started by the experimenter using a specific sentence to contradict the participants. During the second trial she contradicted participants by saying, "Is the dog there? No, I don't think so," and during the third trial, she contradicted participants by saying, "Well, it's not there!" During the test trials, the boxes were not manipulated by the experimenter or by the confederate. The experimenter simply contradicted the participant three times (once per test trial), each time after the child answered the question about the location of the dog ("Where is the dog?"). We used only three test trials because we were worried that our participants might stop responding after being contradicted too many times. The fact that the boxes could be rotated was never demonstrated to the participants.

Fully transparent condition. The fully transparent condition followed the same procedure as the window condition, except that the plastic boxes used in the game were entirely transparent. Thus, both the participant and the experimenter could see the location of the plastic dog at all times.

Coding and Analysis

For each baseline and test trial, we coded whether participants accurately indicated the location of the dog, by pointing at or by reaching for the baited box. For each participant, we computed the proportion of trials in which they correctly indicated the location of the dog, resulting in three accuracy ratios ranging from 0 to 1, one for the baseline trials, one for the pretest trial, and one for the test trials. We also assessed whether participants rotated the box containing the dog during each baseline trial, during the pretest trial, and during each test trial. Each participant scored 1 for each trial in which they rotated the box, for a total number of potential rotations per participant ranging from 0 to 4 during baseline trials and from 0 to 3 during test trials.

Data were coded offline. A primary coder aware of the study's hypotheses coded the entire dataset, and a secondary coder unaware of the study's hypotheses double-coded a subset of the data ($n = 26$). The interrater agreement was high for all our measures (average $\rho = .93$, range = .87–.99; agreement on whether the participants rotated the box or not during the test trials: $\kappa = 1$). We analyzed the data from the primary coder. All the statistical analyses reported in this are two-tailed. We performed Mann–Whitney U tests by compiling the null distribution of the rank-sum statistic using exact permutations (Bergmann, Ludbrook, & Spooren, 2000). Statistics were computed using R 3.4.3 (R Core Team, 2018), with the following packages: *lme4* (v1.1–19; Bates, Mächler, Bolker, & Walker, 2015), *exactRankTests* (v0.8–29; Hothorn & Hornik, 2015), and *coin* (v1.2–2; Hothorn, Hornik, Van de Wiel, & Zeileis, 2008).

Results

Preliminary Analyzes

Preliminary analyzes revealed that condition (window vs. fully transparent) had no effect on participants' accuracy ratios during baseline trials ($M = .96$, $Mdn = 1$, $SD = .09$ vs. $M = .96$, $Mdn = 1$, $SD = .09$, $U = 1275$, $Z = .27$, $r = .03$, $p = 1$, Mann–Whitney U test), pretest trials ($M = 1$, $Mdn = 1$, $SD = 0$ vs. $M = 1$, $Mdn = 1$, $SD = 0$) or during test trials ($M = .89$, $Mdn = 1$, $SD = .18$ vs. $M = .88$, $Mdn = 1$, $SD = .17$, $U = 1283$, $Z = .33$, $r = .04$, $p = .76$, Mann–Whitney U test). In short, there was no detectable difference in participants' ability to locate the dog across conditions. The participants' accuracy ratios were significantly lower during the test trials than during the baseline trials in both conditions (window condition: $W_+ = 105$, $W_- = 15$, $Z = -2.56$, $r = .31$, $p = .01$; fully transparent condition: $W_+ = 118$, $W_- = 18$, $Z = -2.59$, $r = .31$, $p = .01$, Wilcoxon's tests for matched pairs). Similarly, the participants' accuracy ratios were significantly lower during the test trials than during the pretest trial in both conditions (window condition: $W_+ = 0$, $W_- = 55$, $Z = -2.80$, $r = .33$, $p = .005$; fully transparent condition: $W_+ = 0$, $W_- = 78$, $Z = -3.06$, $r = .36$, $p = .002$, Wilcoxon's tests for matched pairs). These results reveal that the participants reacted to being contradicted by the experimenter, and that they were sensitive to the negative evaluation of their answer by the experimenter.

Furthermore, condition (window vs. fully transparent) had no effect on participants' tendencies to rotate the boxes during the baseline trials (four participants out of 35 rotated the box at least

once in the window condition, 1 participant out of 36 did so in the fully transparent condition, $OR = 4.52, p = .199$, Fisher's exact test) or during the pretest trial (three participants out of 35 rotated the box at least once in the window condition, and three participants out of 36 did so in the fully transparent condition, $OR = .69, p = 1$, Fisher's exact test). Thus, when participants were not contradicted by the experimenter, their tendency to rotate the boxes was comparable—and very low—across conditions. Detailed descriptive statistics for the number of rotations per condition during the baseline, pretest and test phase are reported in Table 1.

Main Analyzes

Next, we analyzed whether participants rotated the box containing the dog during each trial of the test phase as a binary outcome, using generalized linear mixed models with a binomial distribution (logit link). To explicitly take into account repeated measures, all mixed models included participant identity as a random intercept. We fit two different kinds of models: (1) the null models, featuring participant identity as the only predictor and (2) the hypothesis-driven models, which included condition as an additional factor. We used likelihood ratio tests (LRTs) to compare the overall fit of each of these models. For the estimates of the model parameters, the 95% confidence intervals (CIs) were assessed by computing a likelihood profile and finding the appropriate cutoffs based on the LRT.

We built the hypothesis-driven model by including participant identity as a random intercept, and the fixed effect of condition (window vs. fully transparent). The hypothesis-driven model provided a better fit than the null model (LRT: $\chi^2[1] = 8.93, p = .003$), thus revealing that during the test, the participants rotated the target box more often in the window condition than in the fully transparent condition ($\beta = 1.24, SE = .44, 95\% CI [.46, 2.30], Z = 2.80$). Nonparametric analyses confirmed this result (the number of participants that rotated the box at least once was 16 out of 35 in the window condition vs. five out of 36 in the fully transparent condition, $OR = 5.22, p = .004$, Fisher's exact test, see Figure 1).

To assess whether our main result held for the youngest participants in our sample, we analyzed separately the performance of 2-year-old children (window condition: $n = 19, M_{age} = 29.42$ months, range = 23–36 months; fully transparent condition: $n =$

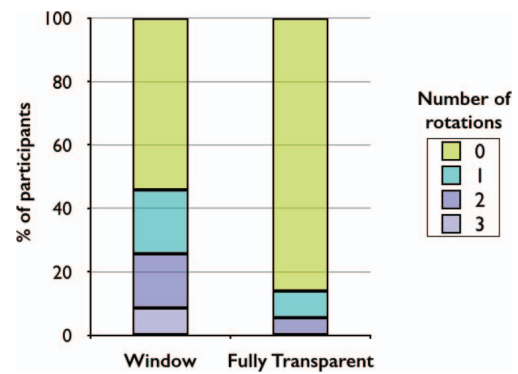


Figure 1. Number of rotations of the box containing the dog during the test phase per percentage of participants and per condition (window vs. fully transparent). See the online article for the color version of this figure.

17, $M_{age} = 28.76$ months, range = 23–35 months) and of 3-year-old children (window condition: $n = 16, M_{age} = 42.75$ months, range = 37–48 months; fully transparent condition: $n = 19, M_{age} = 41.84$ months, range = 37–48 months). For each of these age groups, we built a null model including only participant identity as a random intercept and a hypothesis driven model, which included condition (window vs. fully transparent) as an additional factor. The hypothesis-driven model provided a better fit than the null model by a LRT both for 2-year-old children ($\chi^2[1] = 7.49, p = .006$) and for 3-year-old children ($\chi^2(1) = 4.14, p = .042$), thus confirming that the participants of each age group rotated the box more in the window condition than in the fully transparent condition (2-year-old children: $\beta = 1.31, SE = .60, 95\% CI [.36, 2.81], Z = 2.19$; 3-year-old children: $\beta = 1.47, SE = .75, 95\% CI [.10, 3.42], Z = 1.96$). Nonparametric analyses tended to confirm these results, although they reached only marginal significance for 3-year-old children (for 2-year-old children, the number of participants that rotated the box at least once was eight out of 19 in the window condition vs. 1 out of 17 in the fully transparent condition, $OR = 11.64, p = .019$; for 3-year-old children, the number of participants that rotated the box at least once was eight out of 16 in the window condition vs. four out of 19 in the fully transparent condition, $OR = 3.75, p = .09$, Fisher's exact tests).

We also performed additional analyses to assess the effect of a set of exploratory variables on the participants' tendency to rotate the box during the test phase, focusing on the effects of gender, number of rotations during the baseline phase, number of rotations during the pretest phase, age, and interaction between age and condition (see the online supplemental material). These analyses revealed only an effect of the number of rotations during the baseline phase, indicating that the participants that rotated the target box more during the baseline phase also rotated it more during the test phase. These analyses also confirmed that the effect of condition (window vs. fully transparent) remained significant, even after accounting for the effect of all the exploratory variables.

Discussion

Between the ages of 2 and 3—or even earlier—toddlers have been shown to pay attention to disagreements (Hummer et al.,

Table 1
Descriptive Statistics for the Number of Rotations During the Baseline, Pretest, and Test Trials per Condition (Window vs. Fully Transparent)

Statistic	Window condition			Fully transparent condition		
	Baseline	Pretest	Test	Baseline	Pretest	Test
	Number of rotations					
<i>M</i>	.14	.09	.8	.03	.08	.19
<i>Mdn</i>	0	0	0	0	0	0
<i>SD</i>	.43	.28	1.02	.17	.28	.52
<i>SE</i>	.07	.05	.17	.03	.05	.09
Minimum	0	0	0	0	0	0
Maximum	2	1	3	1	1	2
Skew	2.95	2.83	.87	5.51	2.89	2.52

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1993; Koenig & Echols, 2003), and they are sensitive to the kind of input—such as visual perception—that can provide others with information (Moll & Tomasello, 2006; Nurmsoo & Bloom, 2008). The present experiment assessed whether young children could select relevant evidence when attempting to influence others.

Two- to 4-year-old children were presented with an experimenter who asked them about the location of a toy placed in one of four boxes, and the experimenter disagreed with the information initially provided by the participant. In the fully transparent condition, all boxes were transparent, so the children did not have any obvious means of providing further support for their claims to the experimenter. In contrast, in the window condition only the children, and not the experimenter, could see in which box the toy had been placed. Thus, the children had the opportunity to turn the box toward the experimenter as an additional means of supporting her claim about the toy's location.

Children rarely turned the baited box when the boxes were fully transparent. In contrast, children were more likely to turn the box in the proper context: when the experimenter was disagreeing with them and when turning the box could reveal new and relevant information to the experimenter (i.e., in the window condition). These results are compatible with two—nonmutually exclusive—interpretations of what children attempted to achieve by rotating the baited box in the window condition. A first possibility is that the participants aimed to change the experimenter's belief about the location of the target toy by showing it to her. Second, it is possible that by rotating the baited box the children attempted to justify their answer by demonstrating to the experimenter that they had visual access to the location of the toy. Both of these interpretations suggest the presence of precursors of skills crucial for reason-giving: deciding when to use reason-giving and choosing reasons appropriately as a function of the context.

Overall, our participants rotated the box at a low baseline rate. This pattern can be explained by the fact that (a) in the fully transparent condition, rotating the box was irrelevant, and (b) the participants had to discover on their own that the boxes could be rotated. Remarkably, approximately half of the participants rotated the box at least once (16 participants out of 35, 46%) in the windows condition, in which this action was relevant to support their claims about the toy's location. Thus, a substantial subset of the participants established on their own the relevance of rotating the box as a way of supporting their claims.

Our study was not designed to assess capacities for reason-giving at the individual level. Therefore, it is difficult to make strong claims about the participants that did not rotate the box in the windows condition. They might have (a) not realized that they could rotate the box, (b) not dared to do it, or (c) not realized that rotating the box was an appropriate way of providing support for their claims. Our data do not allow us to disentangle these possibilities. Crucially, the fact that the participants' tendency to rotate the box was significantly higher in the window condition than in the fully transparent condition indicates that by 2 years of age, at least a large subset of children is capable of selecting relevant evidence when providing support for a conclusion.

Three important features may explain why young children succeeded in engaging in reason-giving in our study. First, our par-

ticipants had to provide support for something true. By contrast, the capacity to persuade someone of something false appears to develop later, during the preschool years (e.g., Lee, 2013; Mascaro et al., 2017; Russell, Mauthner, Sharpe, & Tidswell, 1991). Thus, the fact that in our experiment, children were asked to give reasons in a benevolent and truthful manner might have contributed to their success.

Second, in our study nonverbal reason-giving consisted in making an object visible to support claims about its location. The informative value of direct visual perception is recognized early by infants and toddlers (e.g., Luo & Johnson, 2009; Moll & Tomasello, 2006; Nurmsoo & Bloom, 2008). By the age of 2, children also have sufficient perspective taking abilities to place an object behind a screen in order to hide it from someone (Flavell, Shipstead, & Croft, 1978; McGuigan & Doherty, 2002; Mascaro et al., 2017). Importantly, previous studies of perspective taking have not assessed children's ability to recruit the evidential weight of perception to provide support for a claim. Our study reveals that 2- and 3-year-old children can use their perspective taking abilities to manipulate an object to make it visible for an adult and that they do so when it is relevant to support claims about the object's location.

A third reason why many children succeeded in our task is that we made the disagreement between the experimenter and the participant explicit, building upon young children's capacity to contradict an adult who is mistaken (Hummer et al., 1993; Koenig & Echols, 2003). Crucially, when contradicting someone, a child may simply deny this individual's claims without trying to select the most relevant evidence that may change the individual's mind. By contrast, in our study, the difference between children's behavior in the window and in the transparent conditions shows that children modulate their response to convey relevant information in order to provide support for their claims.

Previous studies suggest that children can evaluate others' reasons from 2 years of age (Castelain, Bernard, & Mercier, 2018; Castelain, Bernard, Van der Henst, & Mercier, 2016; Corriveau & Kurkul, 2014; Koenig, 2012; Mercier, Bernard, & Clément, 2014; Mercier, Sudo, Castelain, Bernard, & Matsui, 2018). Yet, to evaluate reasons and to produce them to influence others are quite different tasks. Indeed, to evaluate a reason, one needs to assess the epistemic weight of a piece of information that is already presented to us as a reason. By contrast, to produce reasons efficiently, one needs to find a decent reason in a vast space of possible reasons (Mercier, 2012). Moreover, finding a good reason means assessing the persuasive value of a piece of evidence from someone else's viewpoint. This process requires accounting for some of the audience's mental states (knowledge, beliefs) that may differ from one's own. Our study indicates that children adjust their reason-giving attempts to the informational access of their audience from 2 years of age onward.

Observational data suggest that children start providing what appears to be reasons nearly as soon as they can produce sentences, between the ages of 18 and 24 months (Kuczynski & Kochanska, 1990; Kuczynski, Kochanska, Radke-Yarrow, & Girnus-Brown, 1987; Perlman & Ross, 2005). By the age of 3, children have been said to “generate and think about positive and negative reasons for pursuing different courses of action or for holding specific sets of beliefs” (Stein & Bernas, 1999, p. 97; see also Dunn & Munn,

1987). Our data shed light on the cognitive underpinnings of these early reason-giving behaviors.

One route to discover what kind of behavior is likely to influence others is simply to rely on previous successes. Across repeated instances of social interactions, very young children may discover that by engaging in certain behaviors (e.g., smiling, crying, shouting, insisting, negating a contradictor's viewpoint), they are more likely to get others to comply with their requests or to agree with them (e.g., Bartsch, Wright, & Estes, 2010; Weiss & Sachs, 1991). This kind of fixed strategy is efficient up to a point. A more powerful way of influencing others is to rely on abstract principles that guide the selection of reasons, which one may call *naïve rhetoric*. A naïve rhetoric is likely to include some sensitivity to the role of evidence in persuading others. We find that the roots of naïve rhetoric are already present during toddlerhood. In our study, participants did not rely on a fixed, preestablished strategy. If they had, they would have rotated the boxes equally across conditions (window vs. fully transparent). Instead, toddlers were sensitive to the type of evidence that their interlocutor already had access to. When trying to provide support for their claims, toddlers were more likely to provide the experimenter with a piece of information when it was novel rather than when it was already known.

Observing flexible reason-giving in toddlers introduces a host of novel questions about the development of argumentative skills, and naïve rhetoric. Do toddlers assume that some sources of evidence (e.g., direct perception) are stronger than others (e.g., testimony)? Do they make assumptions about the way evidence from different sources are combined? Do they evaluate the well-formedness of their own reasons? Our results indicate that addressing these questions and therefore testing the preverbal roots of human reason-giving during infancy and toddlerhood is feasible.

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Received April 17, 2018

Revision received May 24, 2019

Accepted May 30, 2019 ■

Call for Nominations

The Publications and Communications (P&C) Board of the American Psychological Association has opened nominations for the editorships of *American Psychologist*, *History of Psychology*, *Journal of Family Psychology*, *Journal of Personality and Social Psychology: Personal Processes and Individual Differences*, *Psychological Assessment*, and *Psychological Review*. Anne E. Kazak, PhD, ABPP, Nadine M. Weidman, PhD, Barbara Fiese, PhD, M. Lynne Cooper, PhD, Yossef S. Ben-Porath, PhD, and Keith J. Holyoak, PhD are the incumbent editors.

Candidates should be members of APA and should be available to start receiving manuscripts in early 2021 to prepare for issues published in 2022. Please note that the P&C Board encourages participation by members of underrepresented groups in the publication process and would particularly welcome such nominees. Self-nominations are also encouraged.

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Deadline for accepting nominations is Monday, January 6, 2020, after which phase one vetting will begin.

Article 6

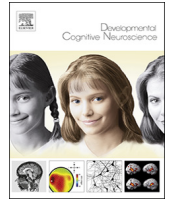
Infants discriminate the source of social touch at stroking speeds eliciting maximal firing rates in CT-fibers

The evaluation of interpersonal touch is heavily influenced by its source. For example, a gentle stroke from a loved one is generally more pleasant than the same tactile stimulation from a complete stranger. Our study tested the early ontogenetic roots of humans' sensitivity to the source of interpersonal touch. We measured the heart rate of three groups of nine-month-olds while their legs were stroked with a brush. The participants were stroked at a different speed in each group (0.3 cm/s, 3 cm/s, 30 cm/s). Depending on the Identity condition (stranger vs. parent), the person who acted as if she was stroking the infant's leg was either an unfamiliar experimenter or the participant's caregiver. In fact, the stimulation was always delivered by a second experimenter blind to the Identity condition. Infants' heart rate decreased more in reaction to strokes when their caregiver rather than a stranger acted as the source of the touch. This effect was found only for tactile stimulations whose velocity (3 cm/s) is known to elicit maximal mean firing rates in a class of afferents named C-tactile fibers (CTs). Thus, the infants' reaction to touch is modulated not just by its mechanical properties but also by its social source.



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Infants discriminate the source of social touch at stroking speeds eliciting maximal firing rates in CT-fibers

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ARTICLE INFO

Keywords:

Infancy research
Touch
Social cognition
Social grooming
CT fibers
Caregiving

ABSTRACT

The evaluation of interpersonal touch is heavily influenced by its source. For example, a gentle stroke from a loved one is generally more pleasant than the same tactile stimulation from a complete stranger. Our study tested the early ontogenetic roots of humans' sensitivity to the source of interpersonal touch. We measured the heart rate of three groups of nine-month-olds while their legs were stroked with a brush. The participants were stroked at a different speed in each group (0.3 cm/s, 3 cm/s, 30 cm/s). Depending on the Identity condition (stranger vs. parent), the person who acted as if she was stroking the infant's leg was either an unfamiliar experimenter or the participant's caregiver. In fact, the stimulation was always delivered by a second experimenter blind to the Identity condition. Infants' heart rate decreased more in reaction to strokes when their caregiver rather than a stranger acted as the source of the touch. This effect was found only for tactile stimulations whose velocity (3 cm/s) is known to elicit maximal mean firing rates in a class of afferents named C-tactile fibers (CTs). Thus, the infants' reaction to touch is modulated not just by its mechanical properties but also by its social source.

1. Introduction

Tactile contact plays an obvious role in many social interactions such as greetings, sex, comfort and physical aggression. A light interpersonal touch can also elicit positive feelings, generosity, and compliance (Crusco and Wetzel, 1984; Fisher et al., 1976; Guéguen, 2002; Guéguen and Fischer-Lokou, 2002, 2003; Hornik, 1992; Willis and Hamm, 1980). Because of the role of tactile stimulation in regulating social interactions and social relationships, interpersonal touch is often processed in very different ways depending on its source. In human adults, the total bodily area where touch is considered acceptable or pleasant is larger for closer relationships (Heslin et al., 1983; Jourard, 1966; Suvilehto et al., 2015). Similarly, heterosexual men rate the same tactile stimulation as more pleasant when they think that the person touching them is an attractive woman rather than another man (Gazzola et al., 2012; Scheele et al., 2014). In short, human adults do not treat interpersonal touch just as a mechanical event, but also as a social one, whose socio-cognitive evaluation depends on the source of the touch. Here, we probe the underpinnings of the sensitivity to the source of interpersonal touch during infancy, focusing on positive affective touch processing, via the preferential activation of C Tactile fibers (henceforth, CTs).

Interpersonal touch regulates social relationships from infancy

onward. Tactile stimulation is a part of the typical repertoire of mammalian caregiving behaviors (Feldman, 2011), and touching and being touched is crucial for bodily and neuro-cognitive development in humans and in non-human primates (Brauer et al., 2016; Bremner and Spence, 2017; Cascio et al., 2019; Feldman et al., 2014; Field, 2010, 2014; Harlow and Zimmermann, 1958; Reece et al., 2016; Seidl et al., 2015; Simpson et al., 2017; Suomi, 1995). Interpersonal touch reduces infants' response to stress (Feldman et al., 2010; Stack and Muir, 1990, 1992) and enhances social learning (Della Longa et al., 2017). Furthermore, the quality of tactile interactions between caregivers and infants has important long-term social consequences, influencing the formation of bonds and attachment behaviors throughout the lifespan (Feldman, 2011; Field, 2014; Hertenstein, 2002; Hofer, 1987, 1995). Thus, interpersonal touch is a crucial medium for mammalian infants to react adaptively to their environment. Therefore, there is evolutionary leverage for the emergence of cognitive processes dedicated to processing the social role of touch from infancy onward. Such processes need to be able (i) to react adaptively to the source of touch, (ii) specifically for tactile stimulations that carry affiliative content. The first step to achieve these two functions is to detect relevant kinds of social touch.

At the neural level, the identification of affiliative touch is likely to involve CTs, a class of unmyelinated afferents present in the hairy skin

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<https://doi.org/10.1016/j.dcn.2019.100639>

Received 26 July 2018; Received in revised form 14 March 2019; Accepted 15 March 2019

Available online 19 March 2019

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(McGlone et al., 2014; Morrison et al., 2010). In human adults, the mean firing rate of CTs in response to touch is maximal for tactile stimulations that have the thermo-mechanical properties of caresses: a temperature of 32 °C, matching the external temperature of human skin (Ackerley et al., 2014b), and an intermediate velocity between 1–10 cm/s (Ackerley et al., 2014b; Löken). CTs also respond to very low indentation forces in the range 0.3–2.5 mN (Cole et al., 2006; Vallbo et al., 1999) which also correspond to a gentle caress.

CTs project to a network of cerebral regions that play an active role in social cognition, including the posterior insula, posterior superior temporal cortex, medial prefrontal cortex, and dorsal anterior cingulate cortex (Björnsdotter et al., 2014; Gordon et al., 2013; Olausson et al., 2002, 2008; Van de Winckel et al., 2013; Voos et al., 2012). Strokes of intermediate velocity, which elicit the highest mean firing rates in CTs, are also rated as more pleasant than slower or faster strokes by children, adolescents, and adults (Ackerley et al., 2014a; Croy et al., 2017; Essick et al., 2010; Löken et al., 2009; Sehlstedt et al., 2016). Thus, CTs may act as an entry point for an early developing system dedicated to processing affiliative touch. In line with this proposal, Fairhurst et al. (2014) found that strokes of intermediate velocity (3 cm/s) elicit a larger decrease in heart rate and longer individual gazes towards the stroking stimulus than slower or faster strokes in nine-month-old human infants. Furthermore, from two months of age, strokes of intermediate velocity (3 cm/s) elicit more activity in the temporal and in the insular cortex than faster strokes (20 cm/s) (Jönsson et al., 2018). In short, cerebral, physiological and behavioral measures suggest that strokes of intermediate velocity have a special status for infants, and that they trigger activity in brain areas linked to socio-affective processing.

We built upon these previous results to test whether infants' response to interpersonal touch is (i) modulated by the source of tactile stimulation, (ii) specifically for tactile stimulations that are known to elicit maximal mean firing rates in CTs. We measured the heart rate of three groups of nine-month-olds while their legs were stroked with a brush. The participants were stroked at a different speed in each group (0.3 cm/s, 3 cm/s, 30 cm/s). Depending on condition, the person who acted as the source of touch was either the participants' caregiver ("parent condition") or an unfamiliar experimenter ("stranger condition"). In fact, another experimenter blind to the Identity condition always delivered the strokes, thus ensuring that the mechanical properties of the tactile stimulation were kept constant across treatments. A cardiac deceleration during touch is usually interpreted as indicative of relaxation (Aureli et al., 1999; Drescher et al., 1985; Tricoli et al., 2017; Weiss, 1992). Here, to test whether infants are sensitive to the source of touch, we compared their heart rate deceleration in the parent and in the stranger condition. Furthermore, to assess the role of CTs in infants' sensitivity to the source of touch, we evaluated whether the effect of Identity (parent vs. stranger) is stronger when strokes are given at an intermediate (i.e., CT-optimal) velocity rather than at a slow or fast velocity.

2. Material and methods

2.1. Participants

We tested 9-month-old participants. By this age, infants' aversive reaction to strangers is well established (Sroufe, 1977). Furthermore, the cerebral response to affective touch of infants younger than 8 months of age might still be immature (Kida and Shinohara, 2013; Miguel et al., 2017; Pirazzoli et al., 2019). Sample sizes were modeled after those in comparable studies (Fairhurst et al., 2014). Given the age of the participants and our experiment's duration (approximately 10 min), it was not possible to collect within-subject data across all three velocity conditions (see e.g., Sailer and Ackerley, 2019; Von Mohr et al., 2017 for other studies comparing the effect of social touch between subjects). As a result, each participant was only tested once, in a

single velocity condition. Sixteen nine-month-old infants for each group were retained in the analysis (slow condition: 7 girls, 9 boys; $M_{age} = 275$ days; $SD = 18$ days; age range: 242–305 days; CT-optimal condition: 9 girls, 7 boys; $M_{age} = 280$ days; $SD = 17$ days; age range: 244–305 days; fast condition: 9 girls, 7 boys; $M_{age} = 275$ days; $SD = 22$ days; age range: 242–305 days). Twenty-five additional participants were excluded from the analysis because the participant became too distressed to make it possible to complete data collection (9), leg movements or positions that prevented the experimenter from delivering the tactile stimulation (8), snatched electrodes (4) or technical failure (4). The research reported in this manuscript followed the guidelines of the declaration of Helsinki and was approved by an independent ethical committee for bio-medical research (CPP Sud-Est II, IRB: 00009118). The parents of all participants gave their written informed consent prior to their inclusion in the study.

2.2. Materials

We used two identical synthetic fiber brushes (Raphael Kaërell 8254, width: 5 cm). The first was used by the experimenter hidden behind the curtain and served to deliver the tactile stimulation. The second brush was held by an adult (either the participant's parent or an unfamiliar experimenter) who acted as the possible visible source of touch. Heart rate responses were recorded using a 3-lead electrocardiogram (Biopac MP36, electrodes Biopac EL104). Two electrodes were placed under each clavicle, and the last one was placed on the left floating rib. The experiment was recorded by 4 different cameras (at 25 frames/s). Two ceiling cameras recorded the global scene and allowed us to confirm offline that the caregivers followed the instructions appropriately. Two additional cameras—one focused on the infant's upper body and the other on the infant's legs—allowed us to identify excessive movement artifacts offline. Participants were placed in an infant chair (Childwood, Seat Evolu 2, 56 × 56 × 92 cm). A large tray of plastic and pieces of opaque fabric affixed to the chair prevented participants from seeing who was touching their leg. Throughout the experiment, the experimenter that stroked the participant was hidden behind an opaque curtain located on the infant chair's right side (sides are given from the participant's viewpoint). A hole in the curtain enabled the hidden experimenter to brush the infants' right shin. A video of the exact duration of one experimental block, i.e. 130 s (extracted from Baby Mozart, Baby Einstein) was played on a tablet placed approximately 40 cm away from the participant (9,7", 24.1 × 18.5 × 0.8 cm). The same video was repeated for each block.

2.3. Procedure

Prior to the experiment, a first experimenter (E1) trained caregivers to follow the experimental procedure and prepared the settings. Once the setup was ready, E1 left, and the experiment began. A second experimenter (E2, the "stranger") entered the room. E2 did not interact with the participants prior to the experiment. The experiment began with a waiting period of 60 s, during which the parent and E2 stood on the left side of the participant. The remainder of the experiment was divided into 4 blocks. Each block began with 10 s of positioning, during which the parent and E2 moved to their respective sitting positions. One adult sat in front of the participant, and the other adult sat on the participant's left side, each at about 60 cm from the infant chair (see Fig. 1).

The adult sitting in front of the infant placed the paintbrush next to the participants' right leg, without touching the leg (brush-down position). When the adult was in this position, the plastic tray affixed to the infant chair prevented the participant from seeing the forearms or hands of the adult or the brush that she held. Since the infants' leg was accessible to the adult sitting in front of the participant, it was theoretically possible for this adult to stroke the participant's leg with the brush. Furthermore, the arms and hands of the person sitting on the left

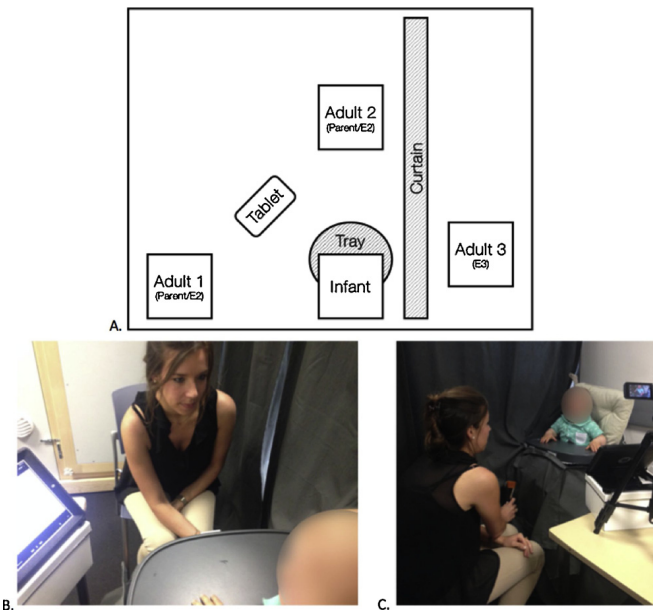


Fig. 1. Panel A: Schematic representation of the spatial position and orientation of the participants. Each box represents a participant: either the subject (infant), the unfamiliar experimenter (E2) or the parent, and the experimenter stroking the infant's leg (E3). A tablet displayed videos during the experiment, a plastic tray prevented infants from seeing who stroked their legs and a curtain separated the room in two parts, and allowed E3 to remain hidden from the infant's viewpoint. Panels B and C: Pictures of the real set up. The adult is positioning the paintbrush next to the participants' right leg, without touching the leg (brush-down position).

side were fully visible to the participant throughout the block, thus demonstrating that she could not stroke the infants' leg. A piece of fabric affixed to the chair prevented the parent and E2 from seeing how the participant's leg was stroked. The positioning was followed by three consecutive trials, each divided into four segments: resting (10 s), presentation of the brush (5 s), stimulation (10 s) and resting (20 s).

During the resting periods, the person sitting in front of the participant held the paintbrush in the brush-down position next to the participants' leg, but no tactile stimulation was given. During the presentation of the brush (5 s), the person sitting in front of the infant showed her the paintbrush by raising it to the participant's eye level for approximately 2 s, before placing the brush back in the brush-down position next to the participant's legs. The presentation of the brush served to show infants that the person sitting in front of them had a brush in hand. The presentation of the brush was followed by the stimulation period (10 s), which followed the same procedure as the resting period, with one exception: during the stimulation period, a third experimenter hidden behind the curtain (E3) stroked the participant's leg at a velocity of 0.3 cm/s (slow condition), 3 cm/s (CT-optimal condition) or 30 cm/s (fast condition). Strokes were applied on the right side of the shin region of the right leg, along an axis parallel to the tibia (following Tuulari et al., 2017). The length of the stimulated area was 3 cm. This length was chosen to allow us to run the brush over the entire stimulated area during the 10 s of stimulation for all velocities, including in the slow condition (0.3 cm/s). Given the size of CTs receptive fields in humans (mean field size 7 mm², Wessberg et al., 2003), a length of 3 cm is sufficient to run across the receptive fields of numerous individual CTs. The stimulated area was marked out with a surgical pen prior to the experiment. Strokes were delivered back and forth, thus resulting in a single repetition of the brushing in the slow condition, 10 repetitions in the CT-optimal condition and 100 repetitions in the fast condition. The paintbrush was handheld by E3 who was trained to deliver the stimuli in all three velocities. E3 also used videos displaying the paintbrush moving at the appropriate speed as a guide,

and she controlled visually that the bending of the hairs of the brush was constant across conditions (for validations of this type of procedure, see Fairhurst et al., 2014; Tricoli et al., 2013). The curtain and the additional pieces of fabric affixed to the chair prevented E3 from seeing who was sitting in front of the participant. After each stimulation, there was a 20-s resting period that served to prevent fiber fatigue.

We measured the heart rate of the infants during the stimulation phase for each trial. To have an estimate of infants' baseline cardiac rhythm, we also measured the heart rate during the 10 s of the resting period that preceded the presentation of the brush and during the 10 s of the resting period that followed the tactile stimulation offset. For each trial, the infants' baseline cardiac rhythm was calculated by averaging the heart rates computed over these pre- and post-stimulation resting periods. During the positioning phase at the beginning of the second, third and fourth block, the stranger and the parent exchanged roles. They swapped sitting positions, and the adult who sat in front of the infant during the preceding block gave the brush to the other adult. As a result, the stranger and the parent each sat in front of the infant for 2 blocks. Whether the stranger or the parent sat in front of the infant during the first block was counterbalanced across participants in the CT-optimal condition and in the fast condition. Due to an experimental error, in the slow condition, the caregiver sat in front of the infant during the first block for 7 participants, while the stranger sat in front of the infant during the first block for 9 participants. Two different discrete sounds indicated when adults had to show the infant the paintbrush (during the presentation of the brush phase) and when they had to swap sitting positions (during the positioning phase).

Following an anonymous reviewer's suggestion, we also collected data on the caregiver's attitudes towards interpersonal touch *a posteriori* (a few months after the study was run). To this end, we contacted the caregivers who participated to the experiment with the infants to ask them to fill in the Social Touch Questionnaire, which measures the respondents' anxiety towards situations involving interpersonal touch (SQT: Wilhelm et al., 2001, twenty items, a higher score indicating a higher anxiety towards interpersonal touch), and the stroking subscale of the Parent-Infant Caregiving Touch Scale, which measures self-reports of how often the caregiver stroked her baby's back, head, tummy, arms, and legs (S-PICTS: Koukounari et al., 2015, four items, a higher score indicating a higher frequency of stroking behaviors directed towards the infant). The caregivers were asked to fill in the S-PICTS to report their behaviors when the infants were 9-month-old (i.e., when they participated to our study). Data was collected online, by sending a direct link to the questionnaires to the participants by e-mail. Out of 48 participants, 41 replied to our request and filled in the questionnaires (slow condition: $n = 15$, CT-optimal condition: $n = 12$, fast condition: $n = 14$).

2.4. Data analysis

After a visual inspection of the video recordings and cardiac data, we removed segments with (i) excessive movements from the participant and (ii) noisy cardiac data (the percentages of removed segments were respectively 13.37% for the slow condition, 17.36% for the CT-optimal condition, and 11.46% for the fast condition). For the remaining segments, we extracted the heart rate in heartbeats per minute (BPM) from the raw cardiac ECG data (using AcqKnowledge 4.4.2). Next, we computed the mean heart rate during stimulation and baseline for each condition (parent vs. stranger): we separately averaged heart rates during stimulation (0–10 s from stroking onset) and during baseline (10 s before the presentation of the brush and 10 s following the stimulation period). These values were then averaged across trials for each Identity condition (parent vs. stranger). The ratio of the signal change in heart rate (Hr) was calculated for each participant by computing the difference between the stimulation and baseline mean heart rates divided by the baseline mean heart rate (Loggia et al., 2011).

$$Hr = \frac{\text{AverageHeartRate}_{\text{Stimulation}} - \text{AverageHeartRate}_{\text{Baseline}}}{\text{AverageHeartRate}_{\text{Baseline}}}$$

By performing our main analyses on Hr, a baseline-corrected measure, we reduce the influence of inter-individual differences heart rate on our results. All statistical analyses reported in this paper are two-tailed. Unless specified otherwise, the data fulfilled the criteria for standard parametric analyses. Assumptions of normality were assessed with Lilliefors tests, which revealed that the data from the STQ and the S-PICTS departed from normality. Subsequently the correlations with the STQ and S-PICTS scores were analyzed using Spearman's rho. The scores on the STQ and on the S-PICTS were not correlated ($\rho = -0.06$, $p = .692$), thus justifying to analyze them separately. The internal consistency was good for both questionnaires (Cronbach's $\alpha = .88$ for the SQT, and $\alpha = .72$ for the S-PICTS). All the statistical analyses reported in the main manuscript were performed using Statistica (version 12), with two exceptions. When data violated assumptions of homoscedasticity as assessed by Levene's test, we used the Welch-James approximate degrees of freedom (ADF) test instead of a traditional ANOVA (Keselman et al., 2003; Lix and Keselman, 1995; Welch, 1951). These analyses were conducted in R using the package 'welchADF' (<https://cran.r-project.org/web/packages/welchADF/index.html>). Partial correlation analyses were performed in R using the ppcor package (v.1.1.1, Kim, 2015).

3. Results

A mixed-model ANOVA using the Welch-James ADF procedure on mean signal change in heart rate from baseline to test (Hr) with Identity (parent vs. stranger) as a within-subject factor and Velocity (slow, CT-optimal, fast) as a between-subject factor revealed an interaction between Identity and Velocity ($F(2, 27.91) = 3.59$, $p = .041$). The ANOVA on mean Hr revealed no other significant effect. We conducted two additional ANOVAs in order to compare participants' cardiac responses in the CT-optimal condition, with their responses in each of the other velocity conditions. In the comparison of the results from the CT-optimal condition to those from the slow condition, a mixed-model ANOVA using the Welch-James ADF procedure on mean Hr with Identity (parent vs. stranger) as a within-subject factor and Velocity (CT-optimal vs. slow condition) as a between-subject factor revealed a main effect of Identity ($F(1, 23.64) = 4.735$, $p = 0.040$) and an interaction between Identity and Velocity ($F(1, 23.64) = 6.139$, $p = 0.021$). Additionally, in the comparison of the results from the CT-optimal condition and those from the fast condition, a mixed-model ANOVA on mean Hr with Identity (parent vs. stranger) as a within-subject factor and Velocity (CT-optimal vs. fast condition) as a between-subject factor also revealed an interaction between Identity and Velocity ($F(1, 30) = 5.933$, $p = 0.021$, $\eta_p^2 = 0.165$). Thus, the effect of Identity on mean heart rate and on mean Hr varied depending on the velocity of the tactile stimulation, and it was significantly different for strokes of intermediate, i.e., CT-optimal velocity rather than for slow or fast velocity.

As Fig. 2 shows, in the CT-optimal velocity condition, Hr was significantly lower in the parent condition ($M_{Hr} = -0.020$, $SD = 0.035$) than in the stranger condition ($M_{Hr} = 0.001$, $SD = 0.029$, $t(15) = 2.67$, $p = .017$, $d = 0.67$, paired Student t-test). In contrast, Identity (parent vs. stranger) had no significant effect on Hr in neither the slow condition ($M_{Hr} = -0.005$, $SD = 0.015$ vs. $M_{Hr} = -0.006$, $SD = 0.017$, $t(15) = -0.31$, $p = 0.76$, $d = -0.077$, paired Student t-test) nor the fast condition ($M_{Hr} = -0.007$, $SD = 0.029$ vs. $M_{Hr} = -0.012$, $SD = 0.029$, $t(15) = -0.69$, $p = 0.50$, $d = -0.17$, paired Student t-test).

Planned post hoc analyses revealed that the mean Hr was significantly below 0, thus indicating a heart rate deceleration from baseline to stimulation only in the parent condition of the CT-optimal velocity condition ($t(15) = -2.29$, $p = 0.037$, $d = -0.57$, univariate Student t-test). In contrast, the mean value of Hr did not differ

significantly from 0 in the stranger condition of the CT-optimal velocity condition ($t(15) = 0.20$, $p = 0.85$, $d = 0.049$, univariate Student t-test). Furthermore, the mean value of Hr did not differ significantly from 0 in any of the Identity conditions in the slow condition (parent condition: $t(15) = -1.29$, $p = 0.22$, $d = -0.32$; stranger condition: $t(15) = -1.48$, $p = 0.16$, $d = -0.37$, univariate Student t-tests) or in the fast condition (parent condition: $t(15) = -0.89$, $p = 0.39$, $d = -0.22$; stranger condition: $t(15) = -1.58$, $p = 0.13$, $d = -0.40$, univariate Student t-tests).

Complementary analyses also confirmed that our main results remained significant after controlling for measures of infants' looking behaviors towards their parent and towards the stranger, and after controlling for the caregivers' scores on the STQ, and on the S-PICTS (see Supporting Information Complementary Results and Analyses).

Fairhurst et al. (2014), reported a significant positive correlation between the caregiver's STQ score and the infant's cardiac response to strokes of intermediate, i.e., CT-optimal, velocity ($r = .56$, $p = .02$), but not for strokes of slow- ($r = .20$, $p = .42$) or fast-velocity ($r = .14$, $p = .58$). In a complementary analysis, we sought to replicate this result conceptually by assessing the correlations between the infant's cardiac response (mean Hr) and the caregiver's score for each of the questionnaires, and for each Velocity condition (slow, CT-optimal and fast). Pre-planned analyses revealed a significant positive correlation between infants' Hr mean response and caregivers' STQ score in the CT-optimal condition ($\rho = .77$, $p = .004$) but not in the slow or in the fast velocity conditions (respectively $\rho = .35$, $p = .201$ and $\rho = .14$, $p = .625$). These results dovetail with those reported by Fairhurst et al. (2014), and they suggest that the greater the caregiver's anxiety towards social touch, the lower the infant's heart rate deceleration in response to CT-optimal, intermediate velocity, touch. Furthermore, there was a marginally significant negative correlation between the infant's mean Hr and the caregiver's S-PICTS score in the CT-optimal condition ($\rho = -0.55$, $p = 0.067$) but not in the slow or in the fast velocity conditions (respectively $\rho = .068$, $p = 0.811$ and $\rho = .309$, $p = 0.283$). These results suggest that the more interactions and tactile stimulation between caregiver and infants there are, the greater the infant's heart rate deceleration in response to CT-optimal, intermediate velocity, touch. Last, the partial correlation between the caregiver's SQT scores and the infants' mean Hr remained significant while controlling for the self-reported stroking behaviors directed towards the infant measured by the S-PICTS ($\rho = .48$, $p = 0.020$).

In addition, we ran a series of exploratory analyses in order to examine a possible connection between the caregiver's self-reported tactile behaviors and attitude towards interpersonal touch, and the infant's differential response to touch depending on the person acting as the source of the touch (parent vs. stranger). This exploratory analysis revealed no significant results (see Supporting Information Complementary Results and Analyses).

4. Discussion

In the CT-optimal condition of our experiment, infants' response to strokes of intermediate velocity did not just depend on their mechanical properties. It varied depending on the possible source of the touch, thus dovetailing with data from adults (Gazzola et al., 2012; Scheele et al., 2014). In short, our results reveal that human infants do not treat interpersonal touch as a purely mechanical event, and that they react to its social source. This type of contextual modulation plays a crucial social function, by allowing touch to regulate social interactions and relationships between individuals. This function can be fulfilled by at least two different kinds of—mutually non-exclusive—cognitive mechanisms. First, top-down processes can influence the evaluation of touch (e.g., McCabe et al., 2008). For example, infants could evaluate more positively a tactile stimulation because they identify its source as their caregiver (for evidence for representations of caregiving relationships in infants, see Johnson et al., 2010; Johnson, Dweck, &

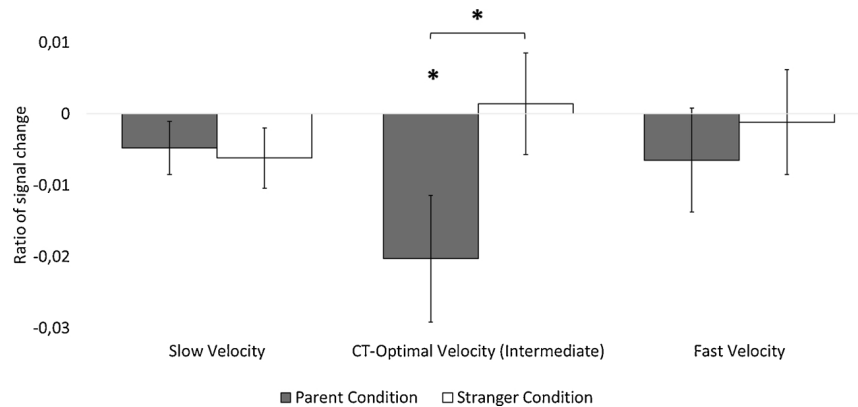


Fig. 2. Mean ratio of signal change in heart rate from baseline to test (SEM) for all stroking velocity condition (slow, CT-optimal and fast). *: $p < 0.05$.

Chen, 2007). Second, affective priming can modulate participants' response to touch. In our case, infants could evaluate the hedonic value of intermediate velocity touch more positively when it is paired with a pleasant or familiar visual stimulus — the face of their caregiver (for comparable effects in adults, see Ellingsen et al., 2014, 2016; Croy et al., 2014; for effect of familiarity on the processing of caregivers' faces in infants, see Kahana-Kalman and Walker-Andrews, 2001). Regardless of the exact cause of the different reactions of the infants in the caregiver and stranger condition, these differences reveal that the sensory and affective component of touch interacts with a sensitivity to the identity of the source of touch from infancy onward.

The integration of tactile information with other perceptual inputs plays a key role in the formation of a representation of one's own body from birth onward and throughout infancy (Bremner et al., 2008; Filippetti et al., 2013, 2014; Filippetti et al., 2015; Freier et al., 2016; Rigato et al., 2014; Zmyj et al., 2011). Our results reveal that a multi-sensory interaction is also central to infants' response to interpersonal touch. The participants' visual, auditory and olfactory environment was identical during the baseline and during the phase of tactile stimulation across velocity conditions. Therefore, the effect of Identity that we observed specifically for strokes of intermediate velocity was likely driven by the interaction between tactile and visual information.

We found that the modulation of infants' response to the identity of the source of touch was stronger for strokes of CT-optimal velocity than for faster or slower strokes. This result suggests that CTs, and the network of brain area upon which they project, may play a central role in infants' sensitivity to the source of interpersonal touch. More specifically, in adults the mean firing rate of individual C-Tactile afferents is known to be higher for stimulations of intermediate, rather than slow or fast velocity, and it correlates with explicit ratings of the pleasantness of caresses (Ackerley et al., 2014a; Löken et al., 2009). Therefore, the mean firing rate of CTs (as opposed to the number of spikes elicited in CTs) is a plausible candidate neural code for the identification of pleasant touch by infants in our experiment.

In Fairhurst et al. (2014), infants' heart rate decelerated from baseline in response to a tactile stimulation delivered at intermediate speed by an experimenter. In contrast, we did not observe a similar deceleration in our study. One possible explanation for this difference could be that in our case, the experimenter who acted as the "stranger" did not interact at all with the participants before the experiment. Moreover, in Fairhurst et al.'s study the experimenter was located behind the participants and infants actually had to turn their heads and bodies to view the experimenter holding the brush used for stroking. This may have reduced the 'salience' of the source of touch. In addition, infants in Fairhurst et al.'s study were sitting in a seat on their parents' laps. While the seat prevented the parent from directly touching her infant, it may still have created a sense of caregiver presence in infants. Thus, the difference between our results and those of Fairhurst et al. (2014) may be explained by the fact that in our stranger condition the

person acting as the source of touch (i) was salient and (ii) was a complete stranger.

Infants' heart rate deceleration in reaction to CT-optimal velocity strokes tended to correlate with caregivers' attitudes towards interpersonal touch measured by the SQT (as in Fairhurst et al., 2014), and with self-reports of caregiving stroking behaviors (measured by the S-PICTS). These correlations have to be interpreted with caution, since we merely collected self-reports from parental questionnaires. Yet, they suggest that (i) infants' cardiac reaction to strokes of CT-optimal velocity varies and that (ii) it is stronger in infants whose caregivers have low social anxiety towards touch, and engage frequently in caregiving stroking behavior directed towards the infant. Furthermore, the correlation between infants' heart rate deceleration in response to CT-optimal velocity strokes and caregivers SQT scores remained significant after controlling for caregivers S-PICTS scores. This additional result suggests tentatively that part of the relationships between the caregivers' attitude towards interpersonal touch and the infants' cardiac reaction to CT-optimal velocity strokes might be independent from the infants' experience with parental stroking behaviors.

Touch has been argued to play a key role in building a representation of the bodily self (Bremner and Spence, 2017; Filippetti et al., 2013; Meltzoff et al., 2018; Saby et al., 2015), which in turn is crucial to distinguish oneself from others, engage in social interaction, and predict and interpret the behaviors of others (De Vignemont, 2014; Meltzoff, 2007; Müller et al., 2017). How the modulation of infants' responses to the source of interpersonal touch that we observed in our study builds upon a representation of the interacting bodily and social selves is an important question for future research. More generally, more work on touch is needed to understand the early ontogeny of social cognition. Currently, the overwhelming majority of studies on early social cognition focus on the role of visual (and to some minor extent auditory) inputs. Yet, touch serves social and communicative functions from the first year of life and it is a privileged route for early social interactions between caregivers and infants. Moreover, interpersonal touch is central to the social life of humans and non-human primates and is processed by specific channels that are likely to contribute to social cognition (such as CTs and the brain areas upon which they project). Finally, as our data suggest, human infants do not treat interpersonal touch as a purely mechanical event, and they react to its social source.

Author note

The authors declare no conflict of interest.

Acknowledgements

We are grateful to all members of the Institute for Cognitive Science Marc Jeannerod for their help at all stages of this research, to Merle

Fairhurst and Line Löken for providing helpful information on how to evaluate infants' sensitivity to pleasant touch; to Andrew Bremner, Teodora Gliga, Laura Pirazoli, and anonymous reviewers for insightful comments on the interpretation of our data; to Alicja Brzozowska for bringing the possibility of using the PICTS to our attention; to Aurélie Giraud for helping us with complementary coding of data; and to Anne Cheyraud for helping us with the data analysis. We also express our gratitude towards all of the families that participated in this project. This research was supported by a grant from the French "Agence Nationale de la Recherche" (PragTICAL, ANR-14-ACHN-0020) to OM.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.dcn.2019.100639>.

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