In the Driver's Seat of Development: An Investigation of Infants' Curiosity-driven Exploration

Elena Constanze Altmann, B.Sc., M.Sc.

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

May 2024

Department of Psychology

In the Driver's Seat of Development: An Investigation of Infants' Curiosity-driven Exploration

Elena C. Altmann

Thesis Abstract

Curiosity is considered the intrinsic drive to explore the world and discover new things we want to learn about. It has also been linked to enhanced memory formation and beneficial developmental outcomes in adults. It has been conceptualised mainly from one of two perspectives: as a state triggered by features of the environment (e.g. novelty, uncertainty, surprise) or as a personality trait impacting how we perceive and approach such information. Even though curiosity is evidently a crucial developmental construct, neither perspective nor the interaction between state and trait curiosity in infancy is well understood and research is long overdue.

This thesis comprises four empirical studies offering methodological innovations in the conceptualisation and measurement of infants state and trait curiosity. Study 1 introduces a novel, gaze-contingent eye-tracking paradigm that captures infants' dynamically evolving state curiosity through their information sampling choices. Study 2 demonstrates the development and validation of the Infant and Toddler Curiosity Questionnaire (ITCQ), which measures trait curiosity in infants aged 5 to 24 months via caregiver reports. Study 3 examines the correspondence between these manifestations of state and trait curiosity, and Study 4 validates the ITCQ's predictive strength by applying the new measure to early language development - one of the most prevalent areas of developmental research.

The results suggest that infants dynamically structure their exploration based on their preceding engagement with the encountered information, with some of the observed variance within such active exploration explained by individual differences in trait curiosity. Furthermore, exploration tendencies as a manifestation of infants' trait curiosity differentially predict vocabulary size one year later, demonstrating its benefits but also revealing potential risks. Overall, this set of empirical findings evidences that infants are curious learners and that the correspondence between their state and trait curiosity is already measurable and informative early in development. Importantly, this work opens up new avenues for future research and advances our understanding of infant curiosity holistically.

The table of contents

List of Figures

List of Tables

Acknowledgements

I would like to start by thanking Prof Gert Westermann and Dr Marina Bazhydai, who are simply the best supervisors I could have ever wished for, not only because they were supportive and nurturing, but also because our work together was incredibly organic. A pivotal moment for me on this journey, I remember, was the very beginning, when I first contacted you, Gert, about applying for the PhD position, and you replied within minutes that you'd be happy to discuss my study ideas, but that you were on your way home and would get back to me - which you did not long after. I'm not saying that this was a sign that you had too much time on your hands (never!), but it immediately made me feel like "I think I really want to do my PhD with him". And I have not thought otherwise since. Thank you also for the many walks we took, especially during the lockdowns, which was also how we first met in person about 3 or 4 months into my PhD. Not only did I thoroughly enjoy the discussions of our theories and whatnot, but it also made me probably the fittest I have been in the last decade. Marina, thanks to you, I could always count on timely feedback, so that I could already marinate new thoughts and ideas while waiting for Gert to catch up (almost never for long, of course). You also helped me realise opportunities to develop additional skills and gain work experiences through various projects. Thank you both for being with me on this journey, guiding me, and cheering for me. I’m looking forward to our high-impact collaborations in the future!

To my friends and colleagues who were in the same boat as me, struggling through the isolation of the lockdowns, the depression-inducing marking periods, and the enduring PhD experience as a whole: thank you for pulling through with me. Thank you, Laura, for being my first friend here after we both arrived in the middle of the pandemic. Our friendship is, and always will be, so dear to me. Didar, thank you for being the closest person and colleague I've had here - not only did we share our testing time in Lancaster's fantastic Babylab, but I couldn't have made it through this as cheerfully without our gym and swimming sessions. And Julie, I’m incredibly grateful to have met you during our Master’s Programme in Amsterdam; sharing my passion for singing, karaoke, and K-dramas but also for hosting me during a lovely and even productive visit to Oslo this year. Thanks also to Kat, Szilvi, James, Yanxi, Nushur, and Sam for our lovely walks, afternoon teas, game nights, and delicious dinners!

Als letztes möchte ich noch meiner Familie danken. Nun, nach fast 10 Jahren seit Beginn meiner Studentenzeit, steh ich hier mit meiner Doktorarbeit, und es gab keinen Tag, an dem ihr an diesem Erfolg gezweifelt hättet. Ihr habt mich immer ermutigt, meinen Träumen und Zielen nachzustreben und habt mir stets eure Unterstützung zugesagt – natürlich nur „solange es meiner Weiterbildung galt“. Ich weiß es wirklich sehr zu schätzen! En Thomas, we hebben het gehaald! Bedankt dat je me altijd hebt gesteund! Met jou aan mijn zijde weet ik dat ik alles kan bereiken - of ik nu wil of niet. Ik kan niet wachten op ons leven samen begint.

Declaration

I declare that the work presented in this thesis has not been submitted, in whole or in part, for the award of a higher degree at this or any other university. I further declare that this thesis is a product of my own work which was conducted and completed under the supervision of Professor Gert Westermann and Dr. Marina Bazhydai. Lastly, I declare that artwork for the chapter images was created by myself using artificial intelligence, namely Copilot/Designer.

Signature: Elena C. Altmann **Date: 14.05.2024**

COVID-19 Impact Statement

[Removed as per Lancaster University's guidelines]

Permission to Submit in Alternative Format

[Removed as per Lancaster University's guidelines]

Thesis Structure

This thesis is structured as follows:

The first chapter is an introductory chapter that summarises and critically reviews previous theoretical conceptualisations of and research on curiosity as a state and as a trait.

The second chapter includes the first experimental study that constitutes this thesis. This chapter focused on the role of 10-12-month-old infants dynamic information sampling conceptualising their state curiosity across active exploration. This chapter was submitted to Cognition, received a “revise and resubmit” decision and is currently under the second round of the review process. This chapter is presented in the form it was last submitted to the journal.

The third chapter includes the second experimental study that constitutes this thesis. This chapter focused on the development of a new caregiver report measure of trait curiosity in infants and toddlers aged 5 to 24 months. This chapter was submitted to Infancy and is currently under the first round of the review process. This chapter is presented in the form it was submitted to the journal.

The fourth chapter includes the third experimental study that constitutes this thesis. This chapter examined the relation between trait curiosity and active exploration patterns in 10-12-month-old infants. This paper is currently being prepared for submission to Cognition. This chapter is presented in its current form.

The fifth chapter includes the fourth experimental study that constitutes this thesis. This chapter focused on the role of trait curiosity in infants’ language development trajectories. This paper is currently being prepared for submission to First Language. This chapter is presented in its current form.

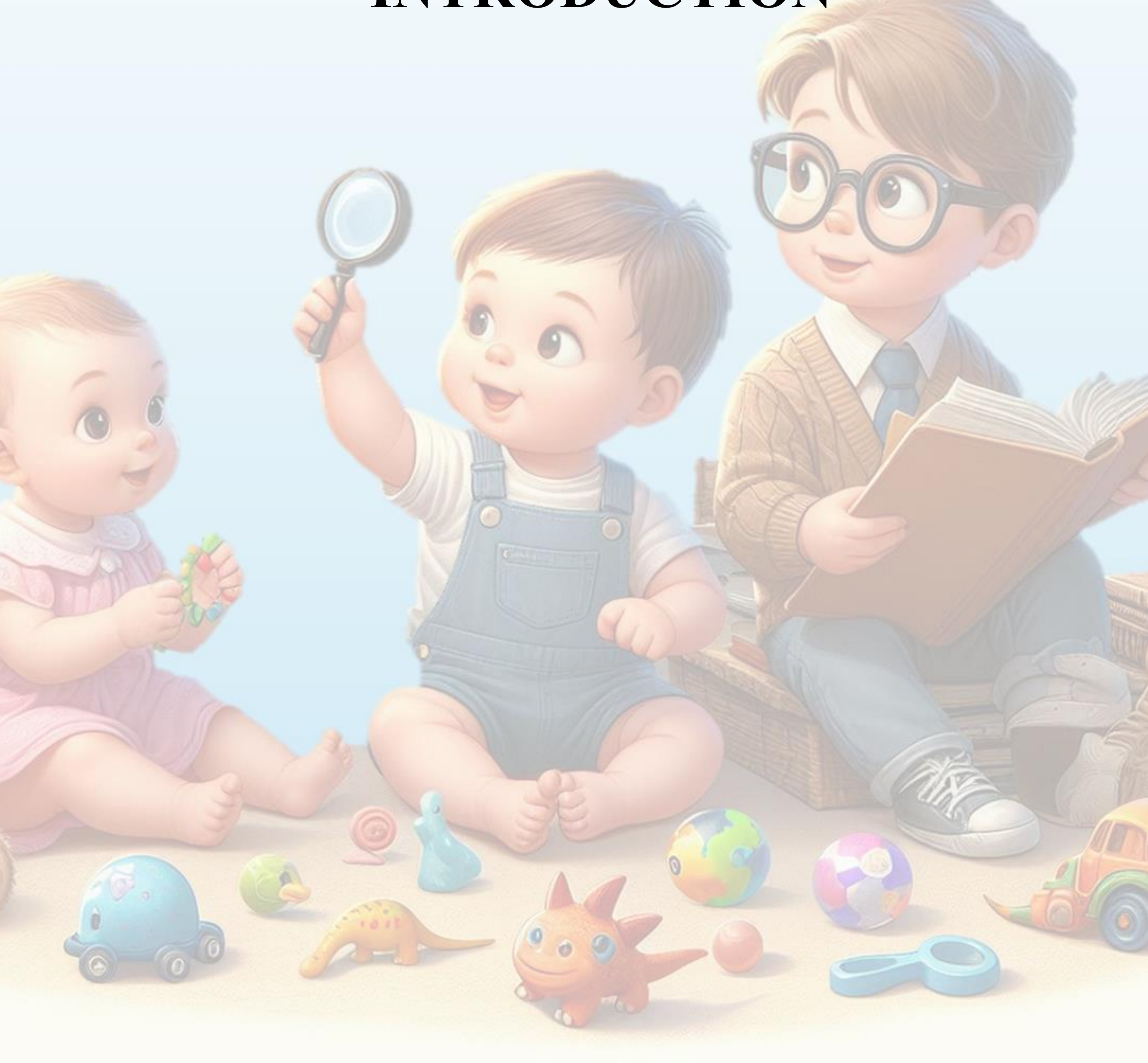
The final chapter is the general discussion section that brings together the findings of all experimental studies presented in this thesis and proposes theoretical explanations and methodological considerations spanning across all presented empirical work.

References for Chapter 1 and Chapter 6 are presented at the end of the thesis in the form of a consolidated bibliography. References as well as supplementary information for Chapters 2, 3 4, and 5 are presented at the end of each chapter.

To acknowledge the collective theoretical and methodological intellectual contributions in Chapters 2 through 5, I report the studies using the first-person plural voice. In Chapters 1 and Chapter 6, I report the literature and findings in the first person singular voice. Where appropriate, I cross-referenced the experimental chapters by providing both, the current Psyarxiv reference as well as the corresponding chapter in this thesis.

The experimental studies comprising this thesis are in preparation for publication or under review in academic journals and have been presented at scientific conferences.

1 GENERAL INTRODUCTION



1.1 Opening Discussion

One of the most positively connotated human characteristics is that of being and staying curious. This quality has been viewed as the driver for learning and personal growth, linked to academic and occupational success as well as to mental health later in life. Generally speaking, the height of curiosity is associated with childhood, as children come up with unconventional experiments and can relentlessly generate new and creative questions about the world, which adults may struggle to answer. Nevertheless, in considering curiosity as a mechanism for exploring the world, learning new things, and growing throughout development, scientific investigations regarding this important construct have neglected one particular age group for too long: infants.

Infants still have the whole world to explore and need to construct their knowledge from the ground up (Piaget, 1976). During this period, they develop a range of skills that enable them to engage in new forms of exploration and learning. For the longest time, however, research has predominantly viewed them as passive information processors, highlighting their sensitivity towards probabilistic information in the environment (e.g., Saffran & Kirkham, 2018). For example, they can extract patterns of statistical structures within stimulus sequences via associative learning, such as word segmentation based on co-occurring syllables (e.g., Saffran et al., 1996), transitional probabilities of elements within a sequence (e.g., van Heugten & Shi, 2010), probabilities of observing certain events (e.g., Altvater-Mackensen et al., 2017) as well as conditional learning of cause and effect (e.g., Meltzoff et al., 2012; Waismeyer & Meltzoff, 2017). They are able to abstract rules from such regularities (for a meta-analysis, see Rabagliati et al., 2019) and form predictive models (e.g., Köster et al., 2020) which allow them to anticipate stimuli (e.g., Emberson et al., 2015), track and update their representations of said regularities (e.g., Gerken et al., 2011, 2015; Kayhan et al., 2019; Kidd et al., 2012; Poli et al., 2020; Tummeltshammer & Kirkham, 2013), and thereby learn to navigate through our complex and ever-changing world (e.g., von Hofsten, 2004; Wang et al., 2016).

Yet, infants also hold a very active role in selecting the information they wish to engage with, which is neglected in these perspectives. While information processing itself may aim to minimise uncertainty and prediction errors (e.g., Clark, 2013), infants actively explore their environment discovering and engaging with novel and uncertain stimuli (Bazhydai et al., 2021 for review). Such active exploration seems to be guided by attentional biases towards informative stimuli based on their potential to relate to and update the infants' internal representations, enabling them to make sense of the overwhelming amount of information available in the environment (e.g., Smith et al., 2018). It is likely that active and passive learning interact with each other, as basic learning mechanisms let infants form predictive models of regularities in the encountered information, which in turn give rise to active exploration and curiosity-based information sampling to continue generating and improving such models. Reversely, this curiosity-based mechanism likely affects how long infants engage with passively presented information, for instance, until a robust association has been formed or the prediction error has been minimised (e.g., Poli et al., 2020; Rose et al., 1982).

Active, curiosity-based learning considers what the individual wants to engage with and learn about at that moment (Twomey & Westermann, 2018) and is linked to a positive learning experience. Furthermore, compared to older children and adults who can focus on information because they are required to (e.g., in the classroom or at work), infants' sustained attention arguably relies primarily on their curiosity. In contrast, attempts to prolong their engagement with stimuli they are not curious about typically leads to fussiness and emotional displays of wanting to disengage. Due to such emotional dynamics and correspondingly positive and negative reinforcement of engaging with similar learning opportunities in the future, curiosity's importance in early development and the need for psychological research cannot be underestimated. Yet, studies on infant curiosity have only recently begun to emerge, and there is still no consensus about its definition, conceptualisation, or measurement.

Over the past 70 years, curiosity research has emerged as a prominent field of study. During this period, numerous theoretical frameworks have been developed, and a multitude of studies have demonstrated the importance and benefits of both state and trait curiosity. While state curiosity pertains to aspects of the environment and information that elicit curiosity, trait curiosity is concerned with more stable tendencies. This body of literature, however, primarily focuses on the adult experience, employing metacognitive self-report measures to assess levels of curiosity. Nevertheless, while some of the aforementioned approaches have been extended into the domain of childhood, these conceptualisations arguably cannot be applied in the context of infancy. Consequently, some have gone as far as stating that there is no such thing as infant curiosity because these metacognitive abilities first need to develop (Inan, 2013). I argue that the disregard of infants within this research field is due to a lack of theoretical and methodological conceptualisations that can measure and explain curious engagement across development.

The objective of this thesis, therefore, is to make contributions to both dimensions in order to further the measurement and our understanding of infant curiosity and its developmental importance.

This inaugural chapter will serve to provide a general overview of existing curiosity research and identify knowledge gaps in the literature. I will first describe what is meant by the psychological construct of curiosity, differentiating between state and trait curiosity and discussing their theoretical conceptualisations. Subsequently, I will emphasise the significance of investigating curiosity in infancy, based on prior findings from adult and child samples. I will then review the various methods of measuring either form of curiosity, discussing the applicability and informativeness of these options for infant studies. Finally, I will provide an overview of the aims of each subsequent chapter.

1.2 What is curiosity?

Our understanding of curiosity encompasses the dynamic and multifaceted nature of an intrinsic drive to explore, inquire, and engage with novel stimuli, experiences, and information unrelated to external rewards. It is a construct for which probably every person has an intuitive idea (e.g., when someone is described as very curious). However, psychological research has persistently struggled to establish consensus over the definition, dimensionality, and cognitive underpinnings of curiosity, as well as its developmental trajectory from infancy onward (Begus & Southgate, 2018; Kidd & Hayden, 2015). Furthermore, most frameworks focus on aspects of the information in our environment, conceptualising and testing under which circumstances we are most curious with varying assumptions of cognitive richness. This focus relates to state curiosity, whereby certain aspects of the information elicit states of curiosity which trigger exploration and approach behaviours as a function of novelty, surprise, a knowledge gap, or potential learning progress. Conversely, there is a vast amount of adult research focusing on curiosity as a personality trait in the form of stable, self-reported tendencies to perceive, create and approach new learning opportunities. The following sections will present and critically evaluate the literature on both perspectives, with a particular focus on their application in infant research.

1.2.1 What is state curiosity?

A multitude of theoretical frameworks have postulated that curiosity is a transient response to various elements of the environment, with increasing procedural sophistication and assumed cognitive richness. Originally, curiosity was defined as a mere attentional bias towards novel, complex and ambiguous stimuli, with its conceptualisation embedded in a behaviourist approach (Hall & Smith, 1903). Subsequently, approaches adopted a more procedural perspective, conceptualising curiosity as a positive mechanism to maintain an optimal level of arousal, or as a drive to resolve an aversive state.

1.2.1.1 Curiosity as a positive state. An example of an optimal arousal theory, Berlyne (1960) distinguished between diversive and specific exploration with differential underlying mechanisms by which an individual could achieve an optimal level of arousal. He defined diversive exploration as seeking any stimulation in order to increase a sub-optimal level of arousal and avoid boredom, whereas specific exploration was posited to be a response to over-stimulation, leading to an arousal reduction through continued exposure to the same stimulus. Although Berlyne proposed these two types of exploration, he acknowledged that exploratory behaviour and behaviour by which knowledge is acquired are likely to often coincide.

Similarly, Spielberger & Starr (1994) posed an optimal stimulation model, where the organism's exploration behaviour is driven by two competing processes as a function of uncertainty encountered in the environment: a positive state of curiosity and an unpleasant state of anxiety. In this context, minimal uncertainty prompts exploration to seek out novel stimuli, thereby resulting in the experience of a pleasant state of curiosity. In contrast, an excess of uncertainty instigates a state of anxiety, for instance, regarding potential dangers in the environment, and consequently diminishes further exploration. This approach, however, would predict the individual to constantly seek out novel information and stimulation. Thus, it cannot explain why an individual would ever engage with a single stimulus for an extended period of time, nor why one would ever desire to hear the answer to a question, as doing so effectively resolves the uncertainty and reduces the positive state of curiosity.

1.2.1.2 Curiosity as a negative state. In contrast, drive approaches view curiosity as a drive to resolve a negative state of uncertainty. For instance, Berlyne (1954, 1955, 1960) proposed that uncertainty-inducing information (e.g., a novel or unfamiliar object) triggers curiosity, which drives exploration and engagement with the object until enough information has been gathered to resolve said uncertainty. Furthermore, it was suggested that the degree of uncertainty and the resulting state curiosity predicted proportional benefits for memory formation. This was supported by findings indicating that adult participants formed more robust memories of information that confused them (Berlyne, 1954). Jepma et al. (2012) further elucidated this association by demonstrating that blurred images facilitated incidental information encoding, with similar findings recently observed in infants (X. Chen et al., 2022). This was interpreted to show that uncertainty triggers a general state of curiosity, which enhances the individual's capacity to process the momentarily encountered information.

Other approaches conceptualised the drive to reduce uncertainty to be based on incongruencies between our experiences and what we believe to be true about the world. These approaches defined curiosity as the drive to update our internal representations in the pursuit of constructing new knowledge (Piaget, 1976), which is further enhanced in the presence of uncertainty (Berlyne, 1954). This approach considered an individual's level of prior knowledge and was tested in infants using 'violation of expectation' paradigms. Infants in a study by Stahl and Feigenson (2015), for instance, tended to visually explore and encode more information in the context of scenes that violated their expectations (e.g., a ball moving through a wall rather than being stopped by it). This behaviour was interpreted as initiating exploration in order to seek out explanations for the experienced incongruency. It is, however, important to exercise caution when considering this assumption as it presumes infants to have robust representations of the world and its physical laws. Consequently, it is arguably rather rich and could not yet be replicated in a robust manner.

1.2.1.3 The knowledge gap theory. The final approach, which views curiosity as a drive to resolve an aversive state of uncertainty, and to this day one of the most popular frameworks, is the information gap theory (Loewenstein, 1994; but recently reconsidered in the context of interest formation by Murayama et al., 2019). Here, curiosity is defined as the drive to close specific knowledge gaps, thereby reducing an aversive state of "not knowing". This framework, comparatively, assumes the highest level of cognitive development from the individual, as the process of identifying such gaps requires meta-cognitive awareness of one's own knowledge. It was proposed that the perceived size of these gaps is linked to "feeling-of-knowing" (FOK) judgments. Stronger FOKs correspond to smaller perceived knowledge gaps, creating a sense of being closer to uncovering the desired information ("tip of the tongue feeling"), and consequently intensifies the experienced curiosity. However, there have been inconsistent findings concerning the specific relationship between FOK and curiosity ratings (Litman et al., 2005; van Lieshout et al., 2018; Wade & Kidd, 2019) possibly because they reflect curiosity about one's own knowledge rather than the piece of information itself.

Furthermore, this framework cannot precisely differentiate whether knowledge gaps motivate information seeking to reduce an aversive state of curiosity, or because they induce a positive state of curiosity driving the pursuit of knowledge (see Litman et al., 2005). In fact, a drive to reduce an aversive state alone could not explain why humans would approach new situations, create new knowledge gaps themselves (e.g., by coming up with creative questions or trying to solve impossible riddles), and report enjoying those experiences. Neurophysiological studies (Gruber et al., 2014; Jepma et al., 2012; Kang et al., 2009) provide support for this criticism by demonstrating increased activity in the dopaminergic reward areas following unresolved states of curiosity (e.g., unanswered trivia questions). This indicates that curiosity is a positively experienced state in anticipation of information, rather than being a rewarding experience solely in the context of resolving it.

Furthermore, it is important to note that the knowledge gap theory establishes certain limitations on what one can be curious about. For example, the recognition of a knowledge gap necessitates having some degree of prior knowledge. Furthermore, the level of meta-cognition required to identify such states is arguably not yet developed in infants, and thus cannot explain curious exploration early in development. While some philosophers have gone as far as to state that infants therefore, by definition, cannot be curious (e.g., Inan, 2013), any observation of an infant would challenge this position. Instead, these definitions should be viewed as a rich conceptualisation of curiosity originating from a focus on the adult mind. It is consequently necessary for the research field to adapt them in order to expand their applicability into younger populations like, for instance, Schulz and Bonawitz (2007) accomplished.

Specifically, they were able to design a study testing the knowledge gap theory in children aged between 4 and 7.5 years by conceptualising the drive to close a knowledge gap via observable exploration behaviours. Their findings indicated that children preferred to explore a familiar functional toy over a novel one if a preceding demonstration did not sufficiently explain its working mechanism. Conversely, children demonstrated a preference for exploring a novel toy if the mechanism had previously been demonstrated fully, thus eliminating the need to close a knowledge gap. This adaptation suggests the potential for integrating theoretical and methodological conceptualisations of curiosity to align existing approaches with the developing mind (see also De Eccher et al., 2024). However, this still leaves open the questions regarding spontaneous exploration in the absence of an identified knowledge gap, as well as its application in infancy.

1.2.1.4 The interest/deprivation theory. The interest/deprivation theory (Litman & Jimerson, 2004), building upon and combining the two perspectives, proposes that curiosity can be understood as a positive and a negative state. The positive state of interest is characterised by novelty-seeking, whereas the negative state of deprivation is associated with a specific and deliberate search for information to resolve a specific knowledge gap. The two states are described as qualitatively distinct from one another and as being closely linked to the motivational systems of *wanting* and *liking* (referring to Berridge, 1999; Berridge & Robinson, 1998).

Specifically, interest is defined as a positive state that motivates individuals to seek out and enjoy learning new things. It thereby overlaps with the positive definitions of curiosity and is stated to be linked to the motivational system of *liking*. The extend to which a stimulus is liked, or how interested an individual is in it, is then said to be determined by how well the information can be processed (Reber et al., 2002). Conversely, deprivation is defined as an unpleasant state that motivates individuals to seek out specific information to resolve an aversive state of uncertainty. It thereby overlaps with negative definitions of curiosity and is said to be linked to the system of *wanting* or the 'need-to-know'. However, it is also possible to view these systems as a unified entity, with differentiation occurring according to the temporal horizon for receiving and processing information. To elaborate, interest/liking, as mentioned above, is considered to be triggered by readily available information that is easy to process. From this perspective, deprivation/wanting can be viewed as a response to the need for not directly accessible information based on the same drive to process it.

In summary, the reviewed approaches consider mature cognition, including metacognitive awareness, and typically adopt a bi-state approach. Nevertheless, they can be deconstructed to converge on the idea that curiosity is a drive to gather information that can update our knowledge. The experienced state of curiosity is then linked to the relation between one's prior knowledge and the accessibility and processibility of said information.

1.2.1.4 Learning progress maximisation. A recent framework emerging from the field of developmental robotics offers a precise computational account in line with the above rationale. This is the framework of *learning progress maximisation* (see review in

Gottlieb et al., 2013). Learning progress, here, refers to the update of an individual's internal representation of the world, for instance in the form of a decrease in prediction error (Kaplan & Oudeyer, 2007; Poli et al., 2020, 2022; Ten et al., 2021; and thus not in conflict with predictive processing frameworks, e.g., Clark, 2013; Friston, 2010; Lieder & Griffiths, 2020). Importantly, this framework does not imply a cognitively rich motivation to succeed in a specific learning task. Instead, it conceptualises curious information sampling and exploration on a continuous spectrum and predicts that an individual will be most curious about stimuli that are neither too similar nor too different compared to their internal representations. This is because such stimuli offer the largest update opportunity relative to the individual's current knowledge.

This reiterates the drive perspectives, where the individual aims to reduce uncertainty, and integrates the optimal arousal perspective, where neither too much nor too little uncertainty is pleasurable. In this way, it can explain continued exploration, learning, and growth from infancy onward. For example, learning progress maximisation can be used to explain observations regarding infants' shifting from a familiarity towards a novelty preference as a function of information encoding (e.g., Hunter & Ames, 1988; Kosie et al., 2023; Oakes et al., 1991; Rose et al., 1982). Furthermore, it aligns with Berlyne's (1960) proposed inverted U-shaped, optimal learning curve and observations of the Goldilocks effect in infants. That is, Kidd et al. (2012, 2014) found that infants looked the longest towards stimulus sequences of intermediate predictability. Poli et al. (2020) subsequently demonstrated computationally, that a stimulus sequence's learning progress could predict infants' looking and looking away above and beyond predictability or surprise alone. Similarly, Twomey and Westermann (2018) showed in a computational model that learning progress maximisation could best explain infants' categorisation successes previously observed through sequences that maximised or minimised stimulus differences (Mather & Plunkett, 2011). They also emphasised the importance of considering the individual's in-the-moment readiness to learn, as what maximises learning changes with every new experience.

In accordance with the general proposition that curiosity is a drive to achieve a pleasant or intrinsically rewarding state, this mechanism specifies that making and anticipating learning progress is associated with an intrinsic reward. As previously stated, this assumption has been corroborated by adult studies in which dopaminergic reward areas demonstrated heightened activity during self-reported states of curiosity (Gruber et al., 2014; Jepma et al., 2012; Kang et al., 2009; Lau et al., 2020; Ligneul et al., 2018).

Indeed, the implementation of an algorithm that rewarded and thus positively reinforced behaviours that maximised learning progress led a robot to explore in a manner similar to that of infants: it did not waste resources on what was too easy or too difficult to learn, and successfully self-discovered various effects it could have on its environment, leading to further exploration and learning (Baranes & Oudeyer, 2013; Forestier & Oudeyer, 2016; Kaplan & Oudeyer, 2007; Oudeyer et al., 2007). However, the underlying mechanisms of such dynamically evolving states of curiosity within infants' active, moment-to-moment information sampling remain poorly understood. This question will be investigated in Chapter 2.

1.2.1.5 Interim summary. In this section, I reviewed the most prominent theoretical approaches to conceptualising state curiosity. These approaches define curiosity through characteristics of the information in our environment which elicit an intrinsic drive to explore and gather information to update our representational models of the world. The only approach that can explain such exploration from infancy onward is learning progress maximisation, as it does not assume metacognitive awareness and harmonises both spontaneous explorative behaviours and more sustained engagement with information. It is important to note that none of these perspectives explicitly included an effect of trait curiosity on modulating these behaviours. The only mention of trait curiosity was made by Spielberger & Starr (1994) and Litman & Jimerson (2004) in the form of a stronger tendency to experience the proposed states. Nevertheless, this does not account for a mechanism of trait curiosity, nor can it specifically predict individual differences in information sampling strategies. Consequently, such trait curiosity has not been the focus of the experimental studies testing these theories. Given the indisputable existence of individual differences in the manner in which information is processed, evaluated, and sampled, it is evident that the exclusion of trait curiosity within theoretical conceptualisations of curiosity represents a substantial gap in the literature.

1.2.2 What is trait curiosity?

As alluded to above, a comprehensive understanding of curiosity necessitates its consideration as a trait. A trait perspective requires the measurement of more stable behavioural tendencies in which the construct is manifested (for further details on such measurement, please refer to section 1.4). In contrast to adult research, where such manifestations are predominantly captured in self-reflections on feelings of curiosity and interest (for reviews, see Grossnickle, 2016; Jirout & Klahr, 2012; Wagstaff et al., 2021), in infants and pre-verbal children, its manifestation typically refers to self-guided exploration and interactions with their environment (for a review, see Bazhydai et al., 2021). Indeed, infants are known to be active learners whose exploration skills – gross-motor, fine-motor, and communicative – undergo a significant evolution throughout the first two years of life (Lockman, 2000; Piaget, 1976). These skills are then used to gain new information (e.g., Aguirre et al., 2022) by interacting with their physical (Adolph & Hoch, 2019; Bourgeois et al., 2005; Fontenelle et al., 2007; Hoch et al., 2019) and social (Bazhydai et al., 2020; Karasik et al., 2014; Liszkowski et al., 2007) environment.

A number of studies have documented variability in specific exploration behaviours throughout the first two years of life and across various experimental paradigms (e.g., Bornstein et al., 2013; Colombo et al., 1991; Fortner-wood & Henderson, 1997; Franchak et al., 2016; Mandler et al., 1987; Muentener et al., 2018; Piccardi et al., 2020; Slone et al., 2019; Smith & Yu, 2013; Wass & Smith, 2014), likely reflecting differences in infants' trait curiosity. To specify individual tendencies across active exploration, conceptualisations such as the breadth and depth of exploration (Caruso, 1993) as well as specific and diverse exploration (Berlyne, 1960) could be employed. For example, an infant with a tendency for broad and diverse exploration may display interest and interactions with a multitude of objects in their environment. In contrast, an infant inclined towards more in-depth and specific exploration may prioritise focusing on the functions of a single object and requesting further information about it from knowledgeable others. The differentiation between wider and more specific exploration also maps onto the framework of exploration and exploitation, which I will shortly introduce here as it is a central framework to this thesis.

This framework originally described the dilemma of when to optimally disengage from exploiting a rewarding yet depleting resource and, instead, explore the uncertain environment to discover new sources worth exploiting (Charnov, 1976). Considering the optimal moment of disengagement can, furthermore, be attributed to state curiosity. With regard to the mechanism of learning progress maximisation, for instance, it conceptualises the moment when disengagement is optimal in order to avoid wasting resources on what is too familiar or too unfamiliar. However, it can also be used to identify more global tendencies across multiple observations of sequential information sampling choices. In this way, the balance between exploration and exploitation may be indicative of an individual's trait curiosity.

In order to achieve the greatest possible reward and thus optimally construct one's knowledge, it is necessary to engage in both exploration *and* exploitation (e.g., Meder et al., 2021; Pelz et al., 2015; Ruggeri et al., 2016). In the context of infants' knowledge construction, for example, it is necessary to engage in exploration of the wider environment in order to discover numerous objects and generate diverse experiences, thereby reducing the uncertainty of the environment as a whole (Blanco & Sloutsky, 2020, 2021; Lapidow & Bonawitz, 2023; Liquin & Gopnik, 2022; E. Schulz et al., 2019; Şen et al., 2024; Sumner et al., 2019). Nevertheless, it is equally crucial to direct subsequent exploration towards specific objects to extract and robustly encode the information they can provide (exploitation). Infants may then differ in the extent to which they prioritise exploration over exploitation, although no evaluation of either tendency is imposed at this stage.

While previous research has explored individual differences in infants' active exploration behaviours (e.g., Caruso, 1993), this work has not been employed to investigate early trait curiosity. The absence of research on infants' trait curiosity may be attributed to the prevailing lack of applicable theoretical approaches. However, research has demonstrated that observations of specific exploration behaviours are not particularly stable over time (e.g., Muentener et al., 2018) and are costly to collect, rendering them unreliable and inefficient as a trait measure. In contrast, trait measures in adults tend to take the form of relatively brief self-report measures (e.g., reviews, Grossnickle, 2016; Jirout & Klahr, 2012). Nevertheless, the development of questionnaires is a lengthy process that typically involves numerous revisions. It is also not uncommon for there to be disagreement about theoretical assumptions and specific analytical decisions which are amplified by the likely emergence of different factor-structures across independent samples (e.g., Eysenck, 1992). Moreover, even when a questionnaire measure has been developed, its informative value is contingent upon its capacity to explain observed behavioural variance, which has been demonstrated to be challenging, particularly early in development (e.g., Madhavan et al., 2024). Given the combination of these challenges, it is understandable that a reliable and valid measure of infant trait curiosity has yet to be developed. Chapter 3 of this thesis reports on the development of such a measure, whereas Chapters 4 and 5 explore its explanatory and predictive strength regarding observed exploration behaviours and language development.

1.3 Why is early curiosity important to investigate?

Despite the absence of a consensus regarding the definition of curiosity from infancy onwards, the majority of theoretical frameworks concur that curiosity is associated with an intrinsic drive to learn about our environment. It is therefore a pivotal element in how we construct our understanding of the world and in our continued development throughout our lives. Consequently, it should not be overlooked in developmental research merely because it is challenging to conceptualise. Instead, greater effort is required to bridge the gap and include infancy in this research field.

By investigating state curiosity, we gain insights into how infants process and sample information to construct their knowledge in the most efficient (Kidd et al., 2012; Poli et al., 2020; Ten et al., 2021), effective (Ackermann et al., 2020; Bazhydai et al., 2020; Twomey & Westermann, 2018), and enjoyable ways. For example, from recent research we learned that a state of curiosity is associated with enhanced information encoding (Ackermann et al., 2020; X. Chen et al., 2022; Stahl & Feigenson, 2015). Likewise, allowing infants to lead their play interactions (C. Chen et al., 2021; Pridham et al., 2000; Schatz et al., 2022; Suarez-Rivera et al., 2019; Tamis-LeMonda et al., 2013) and responding to their communicative expressions of curiosity (Begus et al., 2014; Goldstein et al., 2010; Lucca & Wilbourn, 2019) benefitted their sustained attention, positive mood, and learning achievements. Similar findings in adults (Gruber et al., 2014; Jepma et al., 2012; Kang et al., 2009) but also in children (Alan & Mumcu, 2024; Engel, 2011; Evans et al., 2023; A. Singh & Manjaly, 2022; Walin et al., 2016; Watson et al., 2018) showed that providing information in ways that sparked curiosity improved memory formation and learning experiences. Consequently, the investigation of state curiosity enables us to gain a deeper insight into how infants structure their engagement, while also elucidating the ways in which learning can be facilitated and even optimised.

In order to gain a comprehensive understanding of curiosity, it is essential to acknowledge the role of trait curiosity in modulating our experiences of such curious states. However, this mechanism is barely understood in infancy, despite the fact that this period is when the foundations are laid so that such trait differences are likely to have the greatest impact on our developmental trajectories. It is therefore recommended that this area of research receive greater attention than it has thus far. In contrast, research has been conducted on infants' specific exploration behaviours, which showed that individual differences can explain and predict vocabulary, problem-solving abilities, and academic achievement (e.g., Berg & Sternberg, 1985; Bornstein et al., 2013; Caruso, 1993; Muentener et al., 2018; Smith & Yu, 2013). This evidence suggests that trait curiosity underlying these behaviours may be a beneficial factor. Similarly, older children with higher levels of curiosity were found to explore more efficiently and learn more successfully than their less curious peers (e.g., Inagaki, 1978; van Schijndel et al., 2018). Such benefits appear to extend across development, as numerous studies on adults have demonstrated positive associations between curiosity and academic achievement, job performance, and innovation (e.g., Grossnickle, 2016; Hardy et al., 2017; Kashdan et al., 2020; Kashdan & Yuen, 2007; Mussel, 2013; Reio & Wiswell, 2000; Reio & Callahan, 2004), as well as creativity (Schutte & Malouff, 2020), adaptability (Reio & Wiswell, 2000; Van der Horst et al., 2017), and even mental and cognitive health later in life (e.g., Galli et al., 2018; Sakaki et al., 2018). Given that trait curiosity in adulthood is likely to have its origins early in development, a more comprehensive understanding of curiosity from infancy onwards could provide substantial insights into its cascading effects across the lifespan.

Finally, such a holistic account of curiosity necessitates an examination of the interplay between trait and state curiosity (Pérez-Edgar et al., 2020). Similar demands have recently been expressed for adult research due to its strong focus on trait curiosity (Reio, 2024). Contrastingly, research on curiosity in early development has almost exclusively focused on environment-driven states or individual differences in specific exploration behaviours, rather than on a stable and more global trait. It is plausible that positive experiences with exploration and learning (e.g., states of maximised learning progress) likely reinforce similar behaviours and perceptions of learning opportunities, eventually forming a more stable trait. An imbalance between tendencies to explore or exploit may result in suboptimal development. For example, insufficient exploitation may lead to premature disengagement (Piccardi et al., 2020) and inhibit robust memory formation, whereas insufficient exploration may impede the discovery of information sources that could be exploited, thereby preventing the realisation of one's developmental potential.

An analysis of one variable in isolation cannot provide an optimal understanding of the research field. In order to provide a comprehensive picture and create new opportunities for future investigations regarding these developmental mechanisms, this thesis includes empirical findings regarding both state (Chapter 2) and trait (Chapter 3) curiosity, their relation to each other (Chapter 4), as well as trait curiosity's predictive strength regarding trajectories of language development (Chapter 5) – one of the most prominent developmental research fields (Mani & Ackermann, 2018; McKean & Reilly, 2023).

1.4 How can we measure curiosity?

The preceding sections introduced the constructs of state and trait curiosity and provided an explanation for the necessity of further investigation. However, given that no previous studies have attempted to directly measure curiosity in infancy, it is clear that new methodological approaches are required. In the following sections, I will provide a brief overview of methods employed to assess infants' state and trait curiosity, and introduce the avenues chosen for this thesis.

1.4.1 How can we capture infants' state curiosity within active exploration?

The reviewed research has predominantly employed infants' looking behaviour as a means of investigating the underlying mechanisms of their state curiosity. This is due to the fact that gaze behaviour is one of the earliest skills with which infants can explore their environment. For this, one of the most widely utilised methodologies is eye-tacking where the baby's look towards the screen is captured through relating their pupil's position to an infrared light reflecting on their cornea (e.g., Holmqvist & Andersson, 2017). Across paradigms, looking durations (e.g., Kidd et al., 2012, 2014; Poli et al., 2020), gaze-shifting (e.g., Oakes et al., 2009) and pupil size (e.g., Ackermann et al., 2020) have been utilised to conceptualise infants' state curiosity indicated by their engagement, information encoding, and individual levels of arousal. Furthermore, electroencephalography (EEG) has been employed to assess the neural correlates of curious states (e.g., Begus & Bonawitz, 2020; Piccardi et al., 2020). However, these studies employed structured, passive paradigms with the main objective of investigating curiosity from an information processing standpoint.

Alternatively, unstructured study designs, such as observational and free-play studies, focus on infants' self-guided information sampling via their visual and manual exploration. These studies can then capture state curiosity (e.g., object selection, general patterns and temporal structures; e.g., C. Chen et al., 2021; Slone et al., 2019; Smith & Yu, 2013; Suarez-Rivera et al., 2019) as well as individual differences in specific exploration behaviours (e.g., Caruso, 1993; Mandler et al., 1987; Muentener et al., 2018). However, due to the vast amount of variance and individual preferences (e.g., Karmazyn-

Raz & Smith, 2023), these studies are consequently less manageable for investigations of the mechanisms underlying such dynamic information sampling.

A novel methodology utilising the strength of looking-time measures while also enabling active and dynamic information sampling in infants is gaze-contingent eye-tracking. In contrast to the response of a touchscreen to a tap of a finger pressing a button, gaze-contingent eye-tracking utilises the infant's gaze to trigger specific areas on the screen. This approach allows infants to actively explore and learn about their environment, while also enabling the experimental manipulation of the presented information, for example in terms of visual salience or stimulus differences. Wang et al. (2012) demonstrated that 6- to 8-month-old infants were able to learn that certain areas on the screen were interactive while other areas were not, resulting in the avoidance of those non-contingent areas. Furthermore, Tummeltshammer et al. (2014) showed that infants of the same age group learned cue-reward associations, which guided their gaze-contingent triggers to exploit the associated rewards. These findings collectively indicate that within gaze-contingent paradigms, infants can learn about both the environment itself and the information accessible in that environment. To date, however, no paradigm has been developed in which these two aspects are combined, allowing for intricate investigations of the dynamically evolving states of curiosity (Chapters 2 and 4).

1.4.2 How can we capture early trait curiosity?

As previously stated, trait curiosity in infants and young children is generally viewed to manifest in their exploration tendencies, which can be quantified through behavioural assessments or caregiver report questionnaires. Behavioural assessments may include observations regarding the number of objects interacted with, the specific exploration behaviours they exhibited, the number of new functions they discovered, and the duration of engagement with each object and the session overall (e.g., Caruso, 1993; Karmazyn-Raz & Smith, 2023; Muentener et al., 2018; Slone et al., 2019). Nevertheless, some studies have indicated that such specific exploration behaviours in infants are not temporally stable (e.g., Muentener et al., 2018) and that they do not conclusively relate to developmental outcomes (e.g., Nicoladis & Barbosa, 2024). Furthermore, such assessments would require the recording, coding, and analysis of a significant number of hours and various behaviours (e.g., Caruso, 1993), preferentially including a re-test. This would render them both time-consuming and costly. It should be noted that various computerised exploration assessments (e.g., games) have been developed to capture state and trait curiosity in older children (Evans et al., 2023; Jirout & Klahr, 2012; Tor &

Gordon, 2020). However, these will not be further reviewed in this context as they are not directly relevant to measures in infants due to their conceptual complexity.

An alternative approach to assess early trait curiosity might be a caregiver questionnaire. This approach could be more efficient, applicable, and informative as it can utilise the caregiver's extensive and long-term observations of the child's exploration tendencies throughout daily life. Even though there are some concerns regarding the formation of stable traits early in development (e.g., Piotrowski et al., 2014) multiple such questionnaires have demonstrated good reliability and validity from infancy onward (e.g., Hoicka et al., 2023; Jago et al., 2023; Putnam et al., 2014; Salomonsson & Sleed, 2010). Nevertheless, while there are numerous trait curiosity measures for adults (see review Grossnickle, 2016) and even a few for children (for a review, see Jirout & Klahr, 2012; Piotrowski et al., 2014), as of yet, there are no validated curiosity questionnaires specifically for infants and toddlers. Two recently reported measures are worth mentioning, however, with one being applied to children between 10 months and six and a half years of age (Lee et al., 2023), and the other consisting of a subset of various caregiver-report items as an ad hoc measure of curiosity (Shah et al., 2018). The former measure was reported to be able to associate infants' curiosity with longer looking in a *violation of expectation* paradigm. The latter found links between curiosity and children's later academic achievement in kindergarten. Collectively, these findings indicate the methodological potential of a fully developed and validated measure. However, without rigorous development and validation efforts, questionnaire measures cannot offer reliable or meaningful data (Flake & Fried, 2020). Consequently, a significant portion of this thesis will be devoted to the validation process, including the introduction of a newly developed caregiver report measure (Chapter 3) and the testing of its predictive strength by explaining variance in infants' active exploration (Chapter 4) and their language development longitudinally (Chapter 5).

1.5 How will this thesis spark your curiosity?

This general introduction has reviewed how curiosity can be understood as both a state and a trait, demonstrating its crucial role in development. It has also outlined the ways in which curiosity has been investigated, with a particular focus on infants. However, this review has also identified a lack of understanding and conceptualisations that can be applied throughout development. The following chapters present four empirical studies which aim to advance our theoretical understanding of infant curiosity by resolving methodological issues pertaining to its conceptualisation and measurement. Each of the following experimental chapters therefore intends to provide intrinsically rewarding learning progress by achieving the following goals:

1. Offer methodological innovations to measure both state and trait curiosity in infants (Chapters 2 & 3).
2. Increase our knowledge of the mechanisms underlying how infants structure their dynamic information sampling (Chapter 2).
3. Reliably and cost-efficiently capture exploration tendencies as a manifestation of trait curiosity, above and beyond temperament, early in development (Chapter 3).
4. Explore the correspondence between trait curiosity and dynamic information sampling (state curiosity) in infants (Chapter 4).
5. Explore the predictive link between trait curiosity and language development, including potential limits to curiosity's benefits (Chapter 5).
6. Further the conceptualisation and understanding of curiosity from infancy onward by considering the meaning of this thesis' findings in the larger context of development.
7. Offer a novel, holistic account of curiosity with theoretical propositions on the mechanisms underlying curiosity-based engagement and, importantly, integrating parameters of individual differences (General Discussion).

2 INFANTS' DYNAMIC INFORMATION SAMPLING

2.1 Linking Statement

In the following chapter, I provide an investigation of active information sampling in 10- to 12-month-old infants as a conceptualisation of their dynamically evolving state curiosity. Previous studies on infant curiosity showed that their engagement with passively presented stimulus sequences was guided by mechanisms to maximise their learning progress through decreasing prediction errors (Poli et al., 2020) and not waste their recources on engaging with sequences that were too predictable or too unpredictable (Kidd et al., 2012; 14). Studies on infants' active exploration, on the other hand, demonstrated exploitative tendencies to repeatedly engage with a select number of objects (e.g., Karmazyn-Raz & Smith, 2023; Smith et al., 2018). Here, we designed a new interactive paradigm utilising gaze-contingent eye-tracking, that enables infants' active information sampling within a controlled environment (e.g., Bazhydai et al., 2022; Tummeltshammer et al., 2014; Wang et al., 2012). Our focus in this experimental study was to investigate whether we would find observable patterns and systematicities in the way infants dynamically structure their sampling based on their preceding exploration history. The findings of this study have both theoretical and methodological implications regarding how state curiosity is conceptualised and captured within infants' active exploration.

This chapter is currently under review following a revise-and-resubmit in Cognition.

Altmann, E. C., Bazhydai, M., & Westermann, G. (under review 2nd round). Curious Choices: Infants' moment-to-moment information sampling is driven by their exploration history. *Cognition.*

Curious Choices: Infants' moment-to-moment information sampling is driven by their exploration history

Elena C. Altmann, Marina Bazhydai, and Gert Westermann

Funding Statement: This research was supported by the Doctoral Research Program in the Department of Psychology at Lancaster University and the Economic and Social Research Council (ESRC) International Centre for Language and Communicative Development (LuCiD) [ES/S007113/1 and ES/L008955/1].

Acknowledgements: We thank all families and babies who participated and made this study possible. We would also like to thank Barrie Usherwood for his invaluable technical support for the gaze-contingent eye-tracking MATLAB scripts.

Materials and analysis scripts presented in this manuscript are available from the OSF. The authors have no conflicts of interest to declare.

Research highlights:

- A powerful new paradigm enabling active exploration in a controlled environment.
- Infants' curiosity-driven exploration within this paradigm was non-random.
- Infants generated different sampling patterns, from explorative to exploitative.
- The largest emerging group, however, sampled information from both categories.
- Exploration history and pre-switch behaviour predicted exploratory switching.

2.2 Abstract

Infants explore the world around them based on their intrinsically motivated curiosity. However, the cognitive mechanisms underlying such curiosity-driven exploratory behaviour remain largely unknown. Here, infants could freely explore two novel categories, triggering a new exemplar from a category by fixating on either of the two associated areas on a computer screen. This gaze-contingent design enabled us to distinguish between exploration – switching from one category to another – and exploitation – consecutively triggering exemplars from the same category. Data from 10-12-month-old infants (N=68) indicated that moment-to-moment sampling choices were non-random but guided by the infants' exploration history. Self-generated sequences grouped into three clusters of brief more explorative, longer exploitative, and overall more balanced sampling patterns. Bayesian hierarchical binomial regression models indicated that across sequence patterns, infants' longer trigger time, shorter looking time, and more gaze-shifting were associated with trial-by-trial decisions to disengage from exploiting one category and making an exploratory switch, especially after consecutively viewed stimuli of high similarity. These findings offer novel insights into infants' curiosity-driven exploration and pave the way for future investigations, also regarding individual differences.

Keywords: infant curiosity, information sampling, exploration-exploitation, gaze-contingent eye-tracking

2.3 Introduction

Curiosity is considered the driving force behind exploration, discovery, and learning, motivating us to seek out new experiences, knowledge, and skills. It is, therefore, a crucial developmental factor from infancy onward, which has also been linked to positive outcomes later in life. Although there are various theoretical approaches to defining curiosity, they mostly agree that it reflects an intrinsic motivation to acquire information to enhance our understanding of the world (see reviews Bazhydai et al., 2021; Begus & Southgate, 2018; Kidd & Hayden, 2015; Reio et al., 2006; but see also Dubey & Griffiths, 2020). It manifests itself in exploratory behaviours; however, little is known about what drives moment-to-moment choices of such curiosity-based exploration in infants. In this study, we aimed to capture infants' active exploration within a controlled environment employing state-of-the-art gaze-contingent eye-tracking methodology.

2.3.1 Infants explore actively

Infants are active explorers who help shape their own learning experiences (e.g., Piaget, 1970; Smith et al., 2018). These behaviours manifest themselves in, for example, visual and tactile exploration, but also in requesting information from others by pointing and later through verbal communication. Such exploration opportunities dramatically evolve throughout the first two years of life with infants developing a variety of new skills – gross-motor, fine-motor, and communicative – supporting ever more sophisticated exploratory behaviours and offering new perspectives on their immediately accessible physical (Adolph & Hoch, 2019) and social (Karasik et al., 2014) environments. In fact, infants autonomously adapt their exploration strategies to characteristics of their environment, such as employing different actions on objects based on their properties (e.g., Bourgeois et al., 2005; Fontenelle et al., 2007), selectively preferring an action that previously provided new information, travelling farther in a room with toys than without (Hoch et al., 2019), and selectively referring to the more informative adult when seeking an answer in a situation of referential uncertainty (Bazhydai et al., 2020). Infants also showed increased focus, longer-lasting exploration, and better learning when the course of play or interactive exploration followed their attention (C. Chen et al., 2021; Schatz et al., 2022; Suarez-Rivera et al., 2019; Tamis-LeMonda et al., 2013) rather than the caregiver's redirection (Bono & Stifter, 2003; Mendive et al., 2013; Pridham et al., 2000). Similarly, there seems to be a learning advantage for novel labels when these are presented in response to the infant's pointing gesture (Begus et al., 2014; Lucca &

Wilbourn, 2019) and object-directed vocalisations (Goldstein et al., 2010) which are interpreted as communicative indices of information-seeking. Together, these studies highlight how infants use their available skills to explore the world on their own terms and benefit from doing so (see also Mani & Ackermann, 2018). An important question within developmental research which has only recently started to gain much-needed attention is to understand the mechanisms underlying infants' dynamic exploration as well as why it leads to these advantages (Begus & Southgate, 2018; Kidd & Hayden, 2015).

2.3.2 Exploration as a function of environment knowledge and learning mechanism

To better understand infant exploration, we need to consider which factors may guide infants' exploratory choices dynamically. This includes both previous experience with the environment as well as the mechanism by which that knowledge affects subsequent behaviour. Findings from looking-time studies suggest both novelty (e.g., Fantz, 1964; Siqueland & DeLucia, 1969; Stahl & Feigenson, 2015) and familiarity (e.g., Bushnell, 2001; DeCasper & Spence, 1986; Gaither et al., 2012) to be key characteristics to predict infants' engagement. Studies investigating infants' preferences for complexity found that infants were most likely to stay engaged at intermediate complexity levels ("Goldilocks effect", e.g., Berlyne, 1960; Kidd et al., 2012, 2014; Kidd & Hayden, 2015) whereas infants disengaged from sequences which were too predictable (Addyman & Mareschal, 2013) or unlearnable (Gerken et al., 2011).

A mechanism proposed to explain these findings is learning progress maximisation (e.g., Altmann et al., 2021 (See also Chapter 6); Oudeyer et al., 2007; Twomey & Westermann, 2018) where exploration is driven by making intrinsically rewarding learning progress. Findings from adult populations where higher levels of curiosity have been linked to stronger activation in the dopaminergic brain circuits (Gruber et al., 2014; Kang et al., 2009) support the notion of its intrinsically rewarding nature. Computational models have shown that learning progress can predict infants' looking and looking away above and beyond predictability or surprise alone (Poli et al., 2020). They have also highlighted the importance of a moment-to-moment perspective because what maximises learning progress is dependent on the learner's current knowledge and changes dynamically with every learning experience and knowledge update (Twomey & Westermann, 2018). It is to be noted that learning progress thereby offers a comparatively lean approach to interpreting curiosity as a psychological construct (Goupil & Proust, 2023; Poli et al., 2024). Furthermore, how much learning progress is being made by engaging with something is not only based on the available information in the environment but also on the degree to which it is being encoded. This is in line with previous research that found infants' looking preferences to be best explained by the degree of exposure and encoding rather than the distinction between novelty or familiarity alone (e.g., Hunter & Ames, 1988; Oakes et al., 1991; Rose et al., 1982). Thus, to understand infants' dynamic, curiosity-driven exploration we need to consider the interplay between what information the environment offers but also how the infant engages with that information in order to predict and understand their successive sampling choices.

2.3.3 Need for a new paradigm

Studies on infant exploration have thus far followed one of two main methodological approaches: either employing largely unstructured designs such as free play sessions, using observation and video recordings or head-mounted cameras and eye-tracking (e.g., Hoch et al., 2019; Rodriguez & Tamis-LeMonda, 2011; Slone et al., 2019; Yu & Smith, 2012), or controlled laboratory settings to capture visual exploration and engagement across predefined groups of stimuli and sequences (Addyman & Mareschal, 2013; X. Chen et al., 2022; Kidd et al., 2012; Poli et al., 2020). While both allow for invaluable insights into infant exploration, they do represent two ends of a continuum. Free play studies provide rich data on more descriptive characteristics of infants' curiosity-driven exploration, but the emerging variability poses difficulties in deriving precise mechanistic accounts. On the other hand, structured studies allow for precise manipulation of the provided information to disentangle underlying factors explaining exploration behaviour, such as predictability or stimulus similarities, but do not capture the active choices infants would make in more natural settings. Here we propose a paradigm which combines these approaches by using gaze-contingent eye-tracking – where the visual display changes in response to the infant's fixation. This approach enables infants to determine the sequence and timing of their exploration within an otherwise controlled environment.

Previous studies employing gaze-contingent eye-tracking have shown that infants quickly learn the association between looking towards a specific area on the screen and certain types of information or stimuli being presented (Bazhydai et al., 2022; Keemink et al., 2019; Miyazaki et al., 2015; Sučević et al., 2021; Tummeltshammer et al., 2014; Wang et al., 2012; Zettersten, 2020). It is therefore a powerful method to implement an active component into a structured study design. In fact, similar to our conceptualisation, recent studies (Bazhydai et al., 2022; Zettersten, 2020) also employed gaze-contingent eye-tracking as a way to investigate infants' active sampling and exploratory behaviours.

In our new 'Curious Choices' paradigm, infants can discover interactive information sources in the environment and thereby freely explore two novel categories by fixating on an associated area on the screen, triggering the presentation of a novel exemplar from the respective category. In this way, infants can self-generate exploratory sequences which provide data for more general characteristics of the emerging exploration patterns, but also allow for mechanistic investigations regarding infants' dynamic sampling choices based on the information sources they discovered and how they engaged with the encountered, varying visual information.

2.3.4 Exploration-exploitation framework

The 'Curious Choices' paradigm allows infants to create sequences for receiving information about two novel categories, where every trigger can be conceptualised as a decision to either continue viewing exemplars from one category or to switch over to the other. A useful framework to explain and predict such dynamic choices of 'staying' versus 'switching' is the exploration-exploitation trade-off (Charnov, 1976). Applied to curiosity-driven exploration, this trade-off would predict the agent to exploit an intrinsically rewarding learning opportunity (in other words the focused exploration of a known information source), but to disengage when learning progress subsides. Instead, the agent would then turn to explore the environment more broadly in pursuit of other options worth exploiting (e.g., Oudeyer & Smith, 2016). Making such an exploratory switch requires cognitive effort to redirect one's attention (Pelz et al., 2015) leading to a baseline tendency to exploit (Hayden et al., 2011). Accordingly, the new paradigm allows us to evaluate these assumptions by linking the exploration-exploitation trade-off to the mechanism of learning progress maximisation. While the exploration-exploitation framework has been applied to investigate information seeking in adults often employing a k-armed bandit paradigm where the participant can sample from k-amount of reward sources (Averbeck, 2015), these studies were mainly focused on maximising external rewards (e.g., Daw et al., 2006; Somerville et al., 2017). Furthermore, only recently work has started to study children who had long been assumed to explore un-systematically (Blanco & Sloutsky, 2020; Schulz et al., 2019). For instance, in a computerised task, Meder et al. (2021) found that 4- to 9-year-old children explored the environment in an uncertainty-directed manner to maximise their rewards, with random exploration decreasing with age. Regarding earlier emerging, manual exploration in the absence of external rewards, Karmazyn-Raz & Smith (2023) found a systematic toy selection where 21-month-olds showed exploitative engagement with a selection of objects but only rarely engaged with all others. In summary, the exploration-exploitation trade-off lends itself to predicting dynamic exploration choices and, together with the novel paradigm, offers new insights into the systematicity even of infants' active information sampling.

2.3.5 The current study

The aim of the current study was to investigate infants' curiosity-driven exploration of two unfamiliar categories within a controlled environment. For this, we developed and employed the Curious Choices paradigm, comparable to a 2-armed bandit task. Here, 10-12-month-old infants were introduced to two Fribble species (TarrLab) which are novel stimuli with animal-like features (Williams, 1998). Two identical "houses" were presented on a computer screen, and at each trial, a new exemplar from one of the categories was revealed if the infant fixated on the corresponding house. This way, we could explore how intrinsic curiosity resulted in specific exploration patterns which, in turn, captured how infants weighed exploration against exploitation. Importantly, it also allowed us to disentangle behavioural and environmental factors explaining their sampling choices. The age group was chosen on the basis that the infants would have relevant skills such as object permanence (e.g., Bremner et al., 2015) and higher-level representations guiding their looking (Kiat et al., 2022) as the novel categories would not be visible unless triggered. The research questions were as follows:

1. Do infants explore non-randomly within this new paradigm?
2. Do patterns emerge from the self-generated sequences based on how exploration was weighed against exploitation?
3. Can we predict the dynamic exploratory choices by aspects of the infant's behavioural patterns and exploration history?

3.1 And lastly, do these predictors differ between the possibly emerging exploration patterns?

2.2 Methods

2.2.1 Participants

The sample consisted of $N = 68$ typically developing infants (age range: 10-12 months, $M = 11.14$, $SD = 0.52$, 50% female) from the northwest of England. Additionally, three infants were excluded due to calibration problems and another infant due to not engaging with the study procedure. Caregivers were reimbursed £5 for their travel and the child received a small gift (book or t-shirt) for participating. Informed consent was obtained before the study commenced. The study was approved by the University Faculty's research ethics committee.

2.2.2 Materials

2.2.2.1 Stimuli

Novel visual stimuli, called Fribbles, were sourced from the open TarrLab repository[1]. Fribbles are animal-like figures with four distinct body parts, each of which comes in three variants. Two species (FA2 & FB4, see Figure 2.1) were chosen under the consideration that none of the four body-parts was dominantly salient (Barry et al., 2014; Williams, 1998). Thirty out of 81 possible stimuli per species (in the following referred to as categories) were selected to capture the possible variability in stimulus similarities (differences in one to four body-parts). The stimuli were standardised to a size of 400x300 pixels with the exemplar presented on a white background, matched in luminosity using Adobe Photoshop. For both categories, a random stimulus sequence was created determining which stimulus would be presented at any given trial, if triggered, consistent across participants but counterbalanced regarding their associated location. Additionally, 10 exemplars from two animal categories – ducks and tortoises on white background (532x531 pixels) – were selected for the warm-up phase. Per phase, two identical houses functioned as 'buttons' triggered by fixations.

2.2.2.2 Apparatus & Procedure

Prior to the appointment, caregivers were asked to complete a short infant curiosity questionnaire (Altmann et al., 2024, Chapter 3) online which will not be further analysed in the current paper as it was still in the process of validation by the time of

[1] TarrLab Stimuli at https://sites.google.com/andrew.cmu.edu/tarrlab/stimuli?pli=1

submission. At the lab, infants either sat on their caregiver's lap (77%) or in a high-chair (23%), approximately 60 cm away from the screen (24-inch, resolution of 1920x1080 pixels). Fixations were recorded using a TobiiX120 eye tracker positioned below the screen, with a gaze sampling rate of 60 Hz and a five-point calibration. Caregivers were explicitly instructed not to interrupt or influence their child's behaviour.

The experiment was structured into two parts, warm-up and exploration, each following a similar procedure: an introduction phase and a gaze-contingent phase. In the warm-up introduction, a female voice said in child-directed speech 'There are two *houses*. *Look* who lives in the houses!' while in the exploration introduction, the same voice said "Here are two *new* houses. Look who lives in *these* houses!", intended to direct the infants' attention towards the screen. This was followed by a video clip showing all exemplars (animals in the warm-up, Fribbles in the exploration phase) surrounding their respective house for one second, before synchronously moving into those houses over the duration of five seconds, accompanied by some 'squeaky' noises. Which categories were associated with which side in either part was counterbalanced across participants.

In the gaze-contingent phases, infants could then trigger new exemplars from either category by fixating on the respective house for 700ms. This threshold was based on previous gaze-contingent designs choosing between 500 and 700ms with infants aged between 6 and 23 months (Bazhydai et al., 2022; Sučević et al., 2021; Wang et al., 2012; Zettersten, 2020), choosing a more conservative threshold to ensure more robust (less incidental) triggering. When a house was triggered, the next exemplar from this category was presented for four seconds: increasing in size for one second as if it emerged from its respective house, followed by static presentation for three seconds, while the other house was still visible (Figure 2.1). Disappearance of the exemplar was followed by a gaze-contingent central attention getter which required being fixated for 250ms to start the next trial. If the infant did not fixate on either house within ten seconds, the trial was automatically terminated, registered as an empty trial, and an attention getter was presented again (following Wang et al., 2012). While the warm-up phase was constrained to 30 seconds (median number of warm-up triggers = 4, M = 3.5, SD = 1.57), the exploration phase was constrained to 30 trials (thus, a maximum of 30 Fribble exemplars could be triggered; median number of exploration triggers = 21.5, M = 19.8, SD = 9.77).

The experiment ended either after 30 trials (n = 27) if the infant had three consecutive empty trials (n = 12), or if they became fussy so that the experimenter terminated the experiment during the following attention-getter phase (n = 29). However, this termination did not lead to the participant's exclusion but captured differences in how long infants wanted to engage with the study. Overall, the experiment lasted no longer than six minutes, and the overall visit lasted up to half an hour including time to arrive, getting accustomed to the room, as well as playtime and debriefing afterwards.

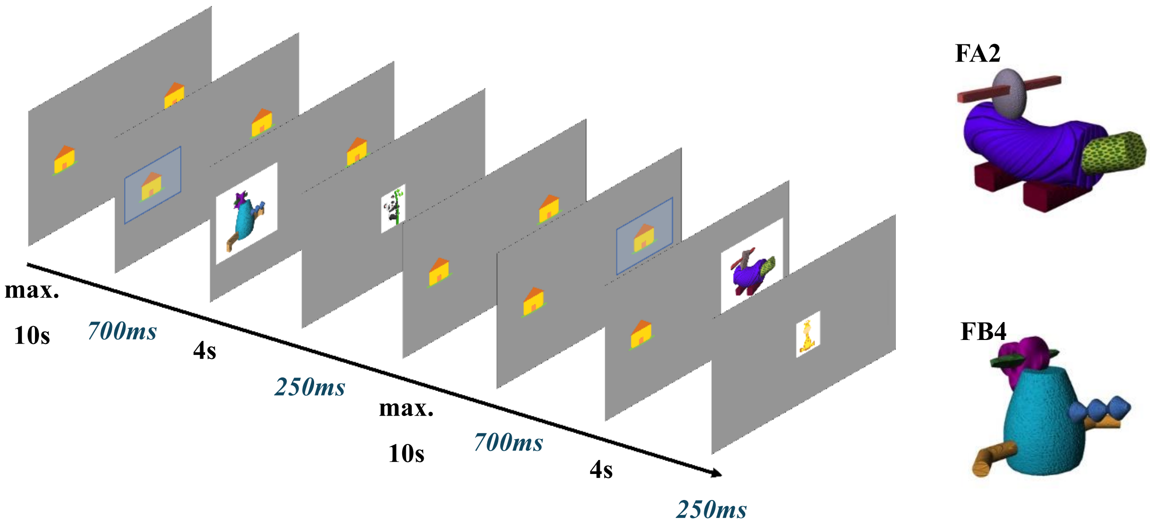


Figure 2.1 Curious Choices Trial Design**. Left**: An example sequence of two trials: when a house is triggered, an exemplar from this house is shown (coloured AOI here for illustration purposes, not visible in practice). Cursive values indicate looking time necessary to make a trigger. **Right**: Example stimuli from both novel categories: Fribble families A and B as indicated by their main body.

2.2.3 Data Processing

Data was processed and analysed using R (Version 4.1.2). Triggers were recoded as either a *stay-event* (triggering the same category as in the previous trial, e.g., A**A**) or a *switch-event* (e.g., A**B**), whereas all first triggers were coded as *start-events* from where a decision could be made to stay or switch. Then, *runs* of consecutive triggers towards each category were computed. For instance, a sequence of AABBBBA is made up of three runs: the first and third in category A (lengths of 2 and 1 respectively) and the second of length 4 in category B. Empty trials were coded to end a run as the infant disengaged for at least 10 seconds; thus, returning to exploration, even to the same category, implies renewed engagement, so the first trigger was then again coded as a *start-event*.

The eye-tracking raw data was initially pre-processed through two rounds of interpolation (e.g., Hessels et al., 2017). The first round identified blinks and smaller technical glitches by interpolating over missing samples of less than 100 ms to connect the preceding and subsequent looking coordinates (R package 'eyetools', Version 0.4.6). The second round connected fixations on certain areas of interest (AOI) if they were interrupted by fixations to another area shorter than 50ms, most likely to reflect technical glitches rather than short looks away (e.g., Hessels et al., 2017). AOIs were defined per screen phase: attention getter in the *centre*, house and stimulus *left*, as well as house and stimulus *right*, whereas fixations to non-relevant areas were coded as *screen,* and *NA* if off-screen. Continuous looks towards each AOI were computed, where looks shorter than 100 ms were excluded as the minimal window-size (e.g., Chen et al., 2022). The remaining continuous looks were then added for total looking time per AOI and trial-phase.

2.2.4 Measures

2.2.4.1 Overall Engagement

Overall engagement was defined as the number of triggers the infant made over the course of the exploration phase (min. 1, max. 30).

2.2.4.2 Switch Proportion

Switch proportion was defined as the proportion of valid triggers which were decisions to switch from the current category to the other one (e.g., a sequence of AAA**BAB**B would have a switch proportion of 3/6 or 0.5 as the decisions to switch or stay begin at the second trigger). Higher values indicate more switching, thus, stronger explorative tendencies.

2.2.4.3 Category Entropy

Shannon entropy (*H*) is an information theoretical uncertainty index which can quantify the amount of information contained in a random variable based on observed event counts (Shannon, 1948). Here, it was computed as the negative logarithm of the observed probability to trigger either category, characterising the overall systematicity of the sequence. Entropy becomes maximal (H=1) for sequences where, based on previous observations, either choice is equally likely (i.e., random) and thus, maximally informative. It becomes minimal (H=0) for perfectly predictable sequences, where each choice is minimally informative as it is expected.

Both switch proportion and category entropy provide unique information about the participant's exploration. For example, the switch proportion captures structural dynamics neglected within category entropy (e.g., same *H* for AAABB and ABABA), whereas category entropy factors in the number of observations (e.g., larger *H* for AABBBB than ABB).

2.2.4.4 Behavioural Engagement

Trigger time was the time from the moment the two houses appeared on screen (after the offset of the central attention getter) to the moment one of the houses was triggered. **Looking time** was the absolute duration the infant looked at the triggered stimulus. **Gaze-shifts** was defined as how many times during the presentation of an individual stimulus in a trial the infant shifted their gaze away from the currently displayed Fribble to the other side, that is, the untriggered house.

2.2.4.2 Stimulus Similarity

This was defined as the subjective similarity between the current stimulus and directly preceding stimulus from the same category[2] indicating the additional amount of information about the category the current stimulus offered (more similar pairs offering less new information). All variables were standardised within each participant so that trial-by-trial predictions were based on differences in the individual's behaviour.

2.2.5 Analysis Plan

While these analyses and hypotheses were not pre-registered due to the novelty of this paradigm and the generally exploratory nature of the study, the variables and general analyses were specified and decided upon before inspecting the data. The report of the behavioural switch-prediction in addition to their interaction with the stimulus similarities, however, was made ad hoc due to realising the consequently extensive reduction of observations (detailed below).

2.2.5.1 Did infants explore non-randomly?

We hypothesised that infants would explore systematically, which means that their trigger choices were different from chance. To analyse randomness in switching

[2] These scores are based on a supplementary online study with an adult sample ($N = 45$, $M_{age} = 27.41$, range = 18 to 54 years, 52.4% female) in which we obtained subjective similarity scores between all possible combinations of stimuli for each category on a scale from 1 ("not similar at all") to 7 ("extremely similar") which were significantly correlated with the number of objective differences ($r = -0.54$, $p < 0.001$); see supplementary materials S2.2 for more details.

behaviour at each trial as well as their category sampling, 1000 draws from a binomial distribution with a likelihood of .50 were simulated for each infant based on their number of triggers. Switch proportions and category entropy were computed for each draw. The simulated distributions consisted of 68000 draws for each variable, and Kolmogorov-Smirnov tests were performed to determine if simulated and observed data came from the same chance distribution or not.

2.2.5.2 Did patterns of exploration emerge?

We hypothesised that there would be variance regarding how infants structured their self-generated exploration sequences. To identify emerging patterns, a cluster analysis was computed based on overall engagement, switch proportion, and category entropy, capturing quantitative and qualitative aspects of how infants weighted exploration against exploitation. These variables were checked for clustering using the Hopkins statistic (Hopkins, 1954) where the value of 0.89 (≥0.7) indicated clustering in the data[3]. As the clustering method, we chose Partitioning Around Medoids (PAM; Kaufman & Rousseeuw, 2009) which groups the data permutationally around central data-points (medoids) minimising the pairwise dissimilarities between observations within clusters[4]. The optimal number of clusters was determined using the R package 'NbClust' (Version 3.0.1), the cluster analysis was conducted using the package 'cluster' (Version 2.1.2) and data visualisation was achieved using 'plotly' (Version 4.10.1).

2.2.5.3 Could trial-by-trial trigger decisions be predicted?

The novel paradigm allows us to investigate both, infants' engagement with information sources in their environment, and the encountered stimuli's effect on conjointly guiding their dynamic sampling choices.

2.2.5.3.1 Behavioural switch-prediction. We hypothesised that behavioural indicators – trigger time, looking time, and gaze shifts – would predict the decision to switch from exploiting the current category to exploring the other. We expected that a decrease in looking time, and an increase in number of shifts during the previous trial's stimulus presentation, as well as increased trigger time for the current trial (as an indication of a switch-cost; Daw et al., 2006; Hayden et al., 2011) would predict an

[3] It should be noted that a suggested, minimal sample of 100 observations for this statistic was not met and should therefore only be taken as an indication rather than a statistical test (Cross & Jain, 1982).
[4]Compared to k-means clustering, this method is more robust against outliers and allows better interpretation of the emerging clusters (Kaufman & Rousseeuw, 2009). However, we ran another analysis using k-means with a comparable pattern of results.

exploratory switch. A Bayesian hierarchical binomial regression model was fitted using the 'brms' package (Bürkner, 2017), with the three predictors as population-level ("fixed") effects and trial-by-trial trigger decisions (stay = 0, switch = 1) as the outcome variable. Furthermore, we included random intercepts at the individual level to reflect the structure of the data.

2.2.5.3.2 Stimulus-dependent switch-prediction. We hypothesised that characteristics of the presented stimuli would affect the likelihood to switch. For instance, experiencing two highly similar stimuli right after one another offers little new information about the category and could lead to disengagement in favour of another information source. Consequently, we would expect greater similarities (as judged by participants in the online rating study) between successive stimuli to predict a subsequent switch. Furthermore, this effect may moderate the behavioural indicators above, so that the same model was used, to which the stimulus similarities interactions were added to capture the full complexity of the task. As this measure required runs of minimum length 2, any single-trial runs and first trials of each run were excluded from this analysis. Thus, we kept these two models separate as they capture the exploration choices to different degrees.

2.2.5.3.3 Differences between clusters. If our data showed evidence of clustering with regard to how infants engaged with the paradigm, we would further explore whether the predictors above differed between the emerging clusters. Thus, we would include clusters as interaction effects in both models.

2.3 Results

Where possible, both frequentist p-values and Bayes factors (via JASP 0.16.2.0) will be reported. However, we chose to fit Bayesian models for the switch-predictions as they provide effect distributions rather than point estimates which were considered more appropriate for the inherently exploratory nature of a study employing a novel paradigm. Additional graphs for model fit comparisons can be found in the supplementary materials (S2.1.1). Data and analysis code are available on the OSF.

2.3.1 Infants explored non-randomly

First, we investigated whether infants' exploration patterns showed any systematicity different from chance. Kolmogorov-Smirnoff tests for two samples indicated for both variables, switch proportion ($D = 0.63$, $p < .001$) and category entropy ($D = 0.58$, $p < .001$), that the simulated (random) and observed data did not come from the same distribution (supplementary materials Figure S2.1). More specifically, infants showed a general exploitative tendency as the average switch proportion was significantly lower than 50% ($M = .28$, $SD = .28$, Wilcoxon signed-rank test against 0.5: $W = 362.00$, $p < .001$; $r_c = -0.67$; $BF_{10} = 279.35$). There was no systematic bias for triggering either a specific category ($W = 850.00$, $p = .205$, $r_c = -0.18$, $BF_{10} = 0.32$) or side ($W = 1214.00$, $p = .245$, $r_c = 0.16$, $BF_{10} = 0.20$).

2.3.2 Three exploration patterns

Visualisation of the average silhouette (that is, minimising within-cluster dissimilarities while maximising between-cluster dissimilarities; Rousseeuw, 1987) and within-cluster sums of squares statistics suggested the optimal number of clusters to be three. The three emerging clusters (Figure 2.2) can be labelled as *brief explorative* (n = 9), *long exploitative* (n = 22), and *more balanced* (n = 37) sampling sequences (from here on referred to more accessibly as *brief/explorers*, *exploiters,* and *balanced samplers*, however, not implying stable individual differences).

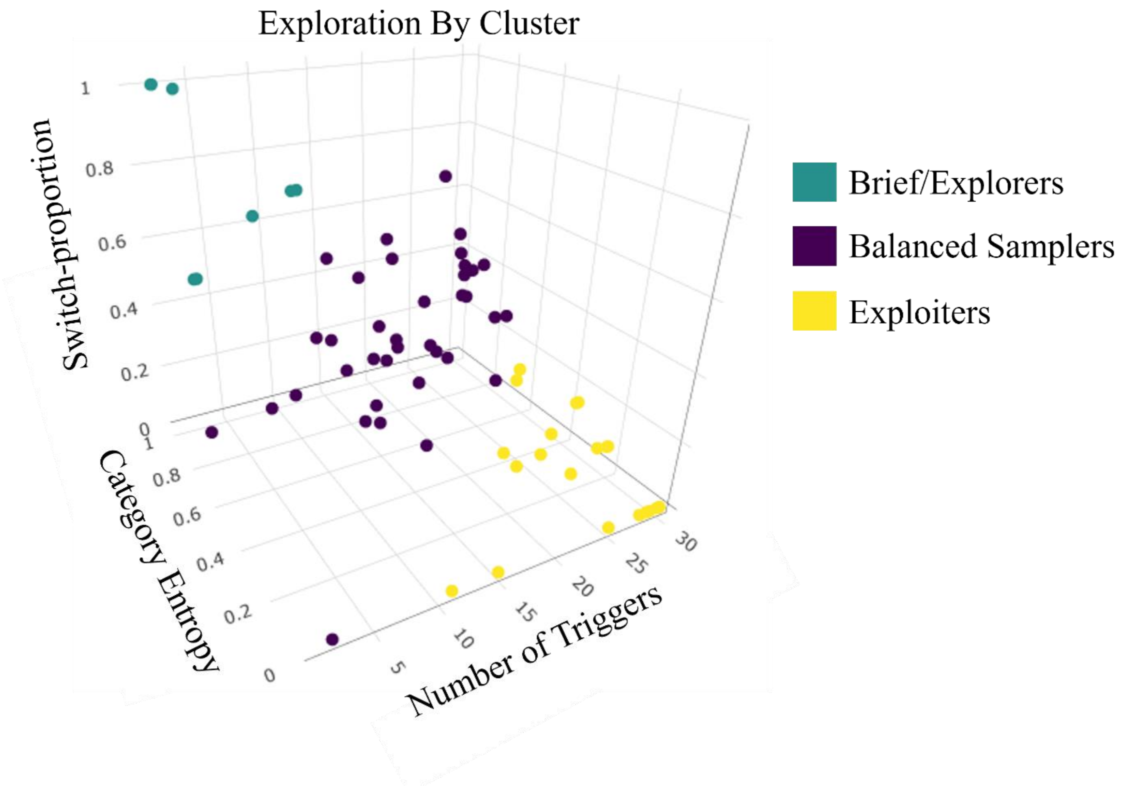


Figure 2.2 Exploration Clusters. Emerging exploration clusters based on overall engagement (number of triggers), exploitative tendencies (switch proportion) and sampling systematicity (category entropy). Each point represents an individual (or identical, overlapping data points).

While balanced samplers engaged for comparatively average length (Table 2.1), with relatively average switch proportion and high category entropy, the other two clusters captured behavioural patterns towards the opposite ends of the explore-exploit spectrum: *brief/explorers* engaged on average only very briefly, often triggered both categories at least once but lacked exploitation, whereas *exploiters* recorded on average the longest overall engagement, switched the least and focused most of their triggers towards one category, thereby lacking exploration. While a sub-sample of participants (n = 8) triggered only one side throughout the experiment, the remaining n = 60 did record triggers towards both sides. Interestingly, n = 2 of the *exploiters* triggered only one side during warm-up but then only the respective other side during the exploration phase, lending support to the notion that repeated triggering was not necessarily due to a persistent side preference established during the warm-up phase.

Furthermore, we found that on average, explorers took the longest to make a trigger and exploiters the shortest (Table 2.1), supported by a negative Spearman correlation between mean trigger time and overall engagement (r = -.38, p = .001). While infants in all three clusters looked similarly long at the triggered stimuli (which did not correlate with any of the exploration variables), higher rates of gaze-shifting were positively related to higher rates of switching (r = .38, p = .001) and category entropy meaning triggers towards both categories (r = .27, p = .024). It should be noted, however, that gaze-shifting did not occur during most stimulus presentations and thus, does not imply overall random or erratic looking behaviour (full correlation matrix of exploration and looking variables in supplementary materials).

Table 2.1 Descriptive statistics per cluster. Means (standard deviations) for each of the characterising variables.

	Brief/Explorers	**Balanced**	**Exploiters**
N	9	37	22
Sex (m:f)	6:3	19:18	9:13
Age (in months)	11.0 (0.49)	11.2 (0.56)	11.1 (0.57)
Warm-up trials	2.33 (1.32)	3.54 (1.57)	3.95 (1.50)
Overall engagement	2.89 (2.42)	19.90 (8.02)	26.50 (5.16)
Switch proportion	0.89 (0.17)	0.27 (0.15)	0.05 (0.06)
Category entropy	0.75 (0.43)	0.76 (0.22)	0.17 (0.18)
Trigger time (*ms*)	2435 (1782)	2094 (867)	1561 (451)
Looking time (*ms*)	2892 (506)	2856 (567)	2867 (890)
Gaze-shifts	.51 (.40)	.51 (.29)	.36 (.38)

Multinomial regressions revealed that cluster membership was independent of age and sex, as neither predictor reached significance (all *ps* > .05), although there seemed to be a slight tendency for the *brief/explorers* to be males and *exploiters* to be females.

2.3.3 Trial-by-trial trigger decisions were associated with behavioural and stimulus-dependent predictors

We fitted Bayesian hierarchical binomial regression models to investigate the associations between behavioural and stimulus-dependent indicators of learning progress and the likelihood of making an exploratory switch. The behavioural models included

1176 observations, whereas the stimulus-dependent models included 862 observations. In both cases, we specified a Bernoulli family likelihood (as we focus on each trial instead of an individual's distribution of switch events) and a weakly informative prior [normal(0,2)] across beta parameters. This allowed for possibility effect sizes between -4 and 4. All models fitted successfully with sufficient numbers of samples, stationary, well-mixing chains, all rhats at 1.00, and credible posterior predictive checks. Model fit comparisons (see supplementary materials for more details) found that both behavioural and stimulus-dependent models improved fit compared to their respective intercept models. Adding the cluster interactions explained some additional variance but did not greatly improve model fit.

Figures 2.3 to 2.5 illustrate the estimated effect sizes as probability distributions, with values further away from zero indicating stronger associations between predictors and outcome variable. If the distribution's mass is below zero the effect of the predictor on the outcome is negative, and if its mass is above zero the effect is positive. A distribution centred on zero indicates that predictor and outcome are not associated.

2.3.3.1 Switches were predicted by behavioural measures

The first model investigated the associations between behavioural predictors and the trial-by-trial likelihood to switch to the other category. It showed that the effects were in line with our expectations (Fig. 2.3): there was a positive association between *trigger time* and the likelihood to switch as most of the variable's distribution's mass was above zero (estimated mean effect ^b = 0.17, 95%-Credible Interval(CI)[0.02; 0.32]). Thus, longer times to trigger one of the houses indicated that this trigger would likely be a switch to the other category. Furthermore, there was a marginally negative association between *looking time* and the likelihood to switch (^b = -0.04, 95%-CI[-0.20; 0.13]), indicating that decreased looking time at the presented stimulus marginally predicted switching to the other category on the following trial. Lastly, there was a positive association between *gaze-shifts* and the likelihood to switch, as its distribution's mass was above zero (^b = 0.16, 95%-CI[0.00; 0.31]). This suggests that increased gaze-shifting towards the other, not currently triggered side predicted switching towards that side on the next trial.

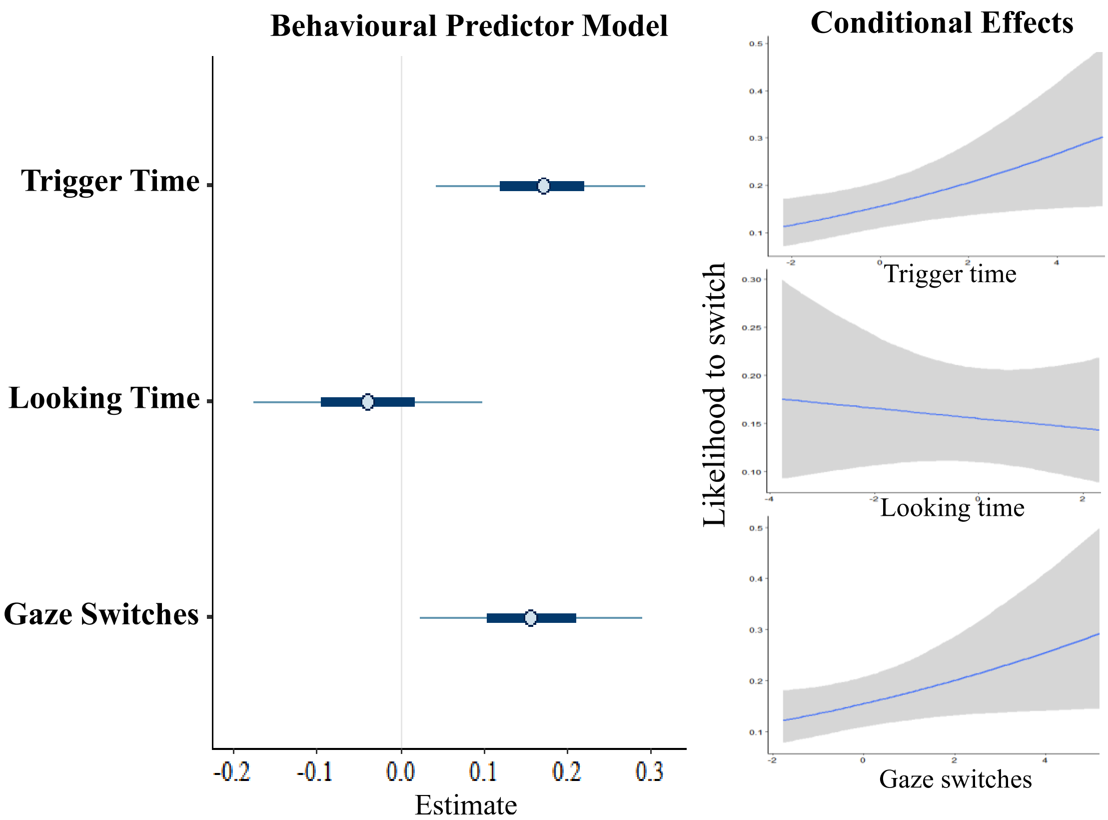


Figure 2.3 Behavioural Predictors for Switching.

Note. **Left:** probability distributions of effects for each of the behavioural predictors (mean, 50% probability interval, and 95%CI). **Right:** Conditional effects of each predictor on the likelihood to make an exploratory switch.

2.3.3.2 Stimulus similarities interacted with behavioural predictors

This model investigated whether infants' exploratory decisions were sensitive to environmental measures of learning progress as indicated by the similarities between consecutively observed stimuli (Fig. 2.4).

Both effects for *trigger time* (positive) and *looking time* (negative) were consistent with the previous model's findings (trigger time: ^b = 0.24, 95%-CI[0.04; 0.44]; looking time: ^b = -0.16, 95%-CI[-0.39; 0.07]), albeit strengthened, as their mean estimates were now further away from zero. However, the *gaze-shift* effect was now marginally negative (compared to positive at 2.3.3.1), meaning that, after reduction of observations and controlling for stimulus similarities, fewer gaze shifts were associated with a higher likelihood to switch (^b = -0.10, 95%-CI[-0.37; 0.15]). *Stimulus similarities* as a main effect had the smallest direct, negative, association with the likelihood to switch, where the probability distribution is almost centred on zero (^b = -0.01, 95%-CI[-0.26; 0.23]).

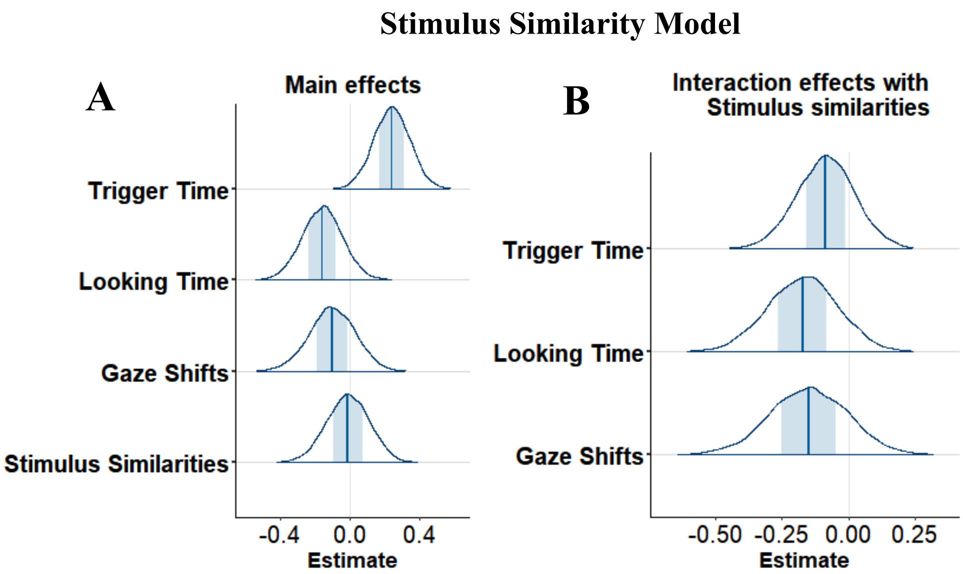


Figure 2.4 Interactions between Stimulus Properties and Behavioural Markers.

Note. Main effects (A) and interactions (B) of the predictors on the likelihood to switch. A: Probability distributions for each main effect of the predictors on the outcome variable, including stimulus similarities. B: Probability distributions for each interaction effect between the stimulus similarities and each predictor. The dark, vertical line indicates the estimate's mean, the shaded area surrounding the mean represents the 50% probability interval, and the distributions' tails cover the 99% probability interval.

With regards to interactions (Fig. 2.4B), all three effects were found to be negative and of similar strength. As the interaction effect for *trigger time* was of opposite polarity to its main effect, this indicated a weakening of the main effect for higher similarity (slopes became less steep). In contrast, interactions were of the same polarity (negative) as the main effects for *looking time* and *gaze-shift*, indicating a strengthening of those effects for higher stimulus similarities (slopes became steeper). In practice, this can be interpreted, that after seeing two very similar stimuli, it took comparatively less time to make a switch (^b = -0.09, 95%-CI[-0.30; 0.13]), possibly suggesting a reduction in switch cost (compare Daw et al., 2006; Hayden et al., 2011). Then, even smaller decreases in looking time (^b = -0.17, 95%-CI[-0.43; 0.08]) and fewer gaze-shifts (^b = -0.15, 95%-CI[-0.45; 0.14]) were associated with a higher likelihood to switch. Overall, these findings indicate that infants showed some sensitivity to similarities between consecutively presented stimuli, but this affected their likelihood to switch only by interacting with their preceding engagement behaviour.

2.3.3.3 Cluster interactions: pulling effects apart

As the cluster analysis found three clusters of exploratory patterns – capturing brief explorative, long exploitative, and more balanced sampling – we wanted to investigate whether the previously found associations between behavioural and stimulus-dependent indicators would differ between the clusters. Thus, we included interaction effects in both models and also looked at the balanced samplers in isolation (see supplementary materials S.12 and S.13).

We found that *behaviourally*, adding cluster interactions could explain additional variance making the looking time effect more pronounced ($\hat{b}$ = -0.10, 95%-CI[-0.28; 0.09]) which seemed to be mainly driven by the balanced samplers as the interaction indicated weaker effects for exploiters (opposite polarity: $\hat{b}$ = 0.48, 95%-CI[0.02; 0.25]; Figure S3 in supplementary materials). Contrastingly, the positive effects of trigger time ($\hat{b}$ = 0.13, 95%-CI[-0.04; 0.09]) and gaze-shifts ($\hat{b}$ = 0.05, 95%-CI[-0.13; 0.09]) were stronger for the exploiters than balanced samplers (same polarity for trigger time: $\hat{b}$ = 0.14, 95%-CI[-0.23; 0.19] and gaze-shifting: $\hat{b}$ = 0.43, 95%-CI[0.06; 0.19]). Effects were overall weaker for the group of explorers due to low numbers of observations.

Further analyses showed that stimulus-similarity interactions were also mainly driven by balanced samplers where we found very similar patterns of the predictors (looking time: $\hat{b}$ = -0.18, 95%-CI[-0.43; 0.06]); trigger-time: $\hat{b}$ = 0.18, 95%-CI[-0.05; 0.12]; gaze-shifts: $\hat{b}$ = -0.10, 95%-CI[-0.37; 0.14]; similarity: $\hat{b}$ = -0.05, 95%-CI[-0.31; 0.13]), with stimulus interactions strengthening the looking time effect for balanced samplers ($\hat{b}$ = -0.18, 95%-CI[-0.47; 0.15]) but marginally weakening it for exploiters ($\hat{b}$ = 0.02, 95%-CI[-0.63; 0.34]). Conversely, stimulus interactions weakened the trigger time effect for balanced samplers ($\hat{b}$ = -0.14, 95%-CI[-0.39; 0.13]) but strengthened it for exploiters ($\hat{b}$ = 0.19, 95%-CI[-0.31; 0.26]) but with larger margins (see supplementary materials S1.2 & S1.3 for more details and additional figures).

2.4 Discussion

We present a powerful new paradigm enabling infants' active exploration within an otherwise controlled environment. Infants triggered the presentation of exemplars from two novel categories via their fixations on screen, allowing them to generate their own sampling sequences. We found a general exploitative tendency with most infants more likely to make consecutive triggers towards the currently sampled information source, representing a category, than to switch to the other. Furthermore, self-generated sequences clustered into three sampling patterns, characterised by length of engagement and balance between exploration and exploitation of either category. The largest emerging group of infants sampled information from both categories in a more balanced way than the other two, who respectively presented shorter, more explorative tendencies (lacking exploitation), and longer, more exploitative tendencies (lacking exploration). Importantly, infants' pre-switch engagement behaviour (longer trigger time, less looking, and more gaze-shifting) was associated with infants' increased likelihood to make an exploratory switch at the next trial and interacted with experienced stimulus similarities.

The overall exploitative tendency to consecutively sample from one information source is crucial for knowledge acquisition especially early in development (e.g., Smith et al., 2018) and can be compared to a familiarity preference leading to full encoding of the encountered information (e.g., Rose et al., 1982). Indeed, more naturalistic studies have found similar exploitative tendencies in the way infants engage with objects in their daily lives (Bambach et al., 2018; Smith et al., 2018) and how they structure their engagement with novel toys during free play (Karmazyn-Raz & Smith, 2023). Due to their developing memory capacities, infants may be especially prone to exploiting information, while its reduction across development could be attributed to exploration becoming more flexible and efficient (Meder et al., 2021; Pelz & Kidd, 2020; Ruggeri et al., 2016).

Furthermore, we observed that infant-generated sequences grouped into three clusters capturing brief explorative, long exploitative, and more balanced sampling, the latter being characterised by exploration and exploitation of both categories. While the *brief|explorers* may not have been curious enough about revealing the exemplars in the two houses, or possibly found the setting too unfamiliar and thus only engaged shortly, they nevertheless tended to discover both categories but did not exploit their information potential by creating longer within-category runs. In contrast, *exploiters* engaged the longest but mainly focused on one category and thus missed the opportunity to explore and exploit the second category's information potential. While 36% of *exploiters* did stick to one side throughout the experiment, the remaining 64% also discovered the other side as an information source but did not exploit its potential. This could either indicate a prevailing familiarity preference with which the discovery of the other, unfamiliar category could not compete, or a preferential engagement with the same, repeated motor behaviour.

However, in studies with toddlers (14-30 months of age) on manual exploration of objects from different categories, Mandler and colleagues (1987, 1991) found similar patterns, characterised as either exhaustive categorisers who, similar to our *balanced samplers*, generated runs of touching exemplars from one or the other category in turn, single categorisers who focused on one category, similar to our *exploiters*, or non-categorisers who did not systematically engage with either category, similar to our *brief/explorers*. Thus, our results present converging evidence with these findings, indicating that similar exploratory patterns can be found across age groups and exploration modalities. Although group membership in our study was not significantly related to age or sex, these exploration patterns may be associated with aspects of cognitive development such as processing speed (manifesting in habituation paradigms: Cao et al., 2023; Feldman & Mayes, 1999), cognitive control (Daw et al., 2006; Hayden et al., 2011; Pelz et al., 2015), or personality traits such as temperament (Rothbart, 2007; van den Boom, 1994). Yet, the current paper makes no assumptions of these patterns directly reflecting stable individual differences as no test-retest reliability or comparative behaviour was assessed. Future work will address these questions.

Lastly, we found that infants' engagement behaviour in interaction with stimulus similarities (but not smaller or larger similarities directly; compare Twomey & Westermann, 2018) was associated with their likelihood to re-engage or make an exploratory switch. This indicates that it is not only the information the environment offers that predicts disengagement (Kidd et al., 2012; Poli et al., 2020) but also to what degree the agent engages with said information. For instance, longer looking was predictive of re-engagement with the current information source as would be expected from habituation paradigms and familiarity preferences, indicating that the infant still has more information to encode (e.g., Rose et al., 1982). Conversely, infants were more likely to make a switch on the following trial after looking less at the presented stimulus, and especially so if it was visually highly similar to the previously encountered exemplar, thus, not offering additional information about the category. This looking time effect was most pronounced for the cluster of *balanced samplers*, which may indicate that their behaviour was most in line with the mentioned habituation paradigms and theoretical assumptions made by the explore-exploit framework if the engagement is mainly driven by the sampled and encoded information.

In contrast, the other clusters may have been more affected by dynamics such as the cognitive switch cost attributed to inhibiting repeated sampling behaviour and redirecting one's attention (Daw et al., 2006; Hayden et al., 2011; Pelz et al., 2015). This cost was observed here as the trigger time effect with longer durations predicting a switch and was most pronounced in the cluster of *exploiters,* suggesting that if they did manage to inhibit their exploitative tendency, they were very likely to make a switch. Lastly, we observed that, before making a switch at the next trial, infants shifted their gaze more towards the non-triggered side during stimulus presentation. This effect, however, disappeared when including the stimulus similarities. Due to the nature of consequently excluded observations (e.g., switch trials), this may indicate that infants were especially likely to shift their gaze in a comparative manner after making a switch (Kovack-Lesh et al., 2008; Oakes et al., 2009) and then returned to the previously triggered category.

Together these findings are also in line with assumptions of the learning progress hypothesis (Altmann et al., 2021 (see also Chapter 6); Oudeyer et al., 2007; Poli et al., 2024; Twomey & Westermann, 2018) while offering exciting new insights into the systematicity of infants' exploration history guiding their active sampling behaviour previously only shown for engagement in fully structured infant studies (e.g., Poli et al., 2020).

2.4.1 Methodological Considerations

Twenty-nine per cent of infants in this study fell into the cluster of *exploiters*, who triggered mostly or even exclusively one of the two novel categories. As suggested, this behaviour may either be indicative of a prevailing familiarity preference or a lack of cognitive control to overcome the cost of disengaging from a repeated behaviour and could be a remnant of the developmental phenomenon of low-level, visual stickiness (Colombo, 2001; Kulke et al., 2015; Wass & Smith, 2014). Such stickiness itself should, however, disappear by about nine months of age (e.g., Wass & Smith, 2014) and would, by definition, be interrupted here by the central, gaze-contingent attention-getter. Thus, rather than continued staring, exploitation of a category required active re-engagement at each trial, making the other explanations more likely.

While we aimed to keep the warm-up phase as unstructured as possible to truly gauge infants' self-guided exploration, future studies may want to include controls ensuring at least three warm-up triggers to realise the mechanism (Wang et al., 2012), as well as at least one trigger towards all gaze-contingent areas on the screen. This could avoid the possibility that some infants remain ignorant of other potential information sources they could engage with. Nevertheless, by enhancing ecological validity but also accepting the thereby increased variance in the data, our study provides important insights into infants' active sampling behaviours reflecting that exploration is also a skill and might require initial guidance (Matas et al., 1978; McQuillan et al., 2020; Vygotsky & Cole, 1978).

The stimuli being complex visual categories did not allow us to compute trial-based learning progress in a more straightforward way as was possible in previous studies investigating improvements in anticipation of a target's location (Poli et al., 2020, 2022). Nevertheless, we were able to show convergent evidence for the association between infants' engagement behaviour and information sampling behaviour in interaction with the experienced stimulus characteristics as proximal indicators of learning progress. Future studies could seek to gather differentiating insights into predominantly environmental exploration (e.g., number of/cost associated with interactive information sources; Wang et al., 2012; Bazhydai et al., 2022) compared to predominantly information-based exploration (e.g., manipulating stimulus similarities or reward value; Tummeltshammer et al., 2014).

2.4.2 Conclusion

In this study, 10-12-month-old infants self-generated exploration sequences within the novel Curious Choices paradigm. This allowed us to gather new insights into both, general patterns of curiosity-driven exploration in infants, e.g., exploitative tendencies, but also the mechanisms underlying such dynamic behaviour. Importantly, for the first time, we showed that moment-to-moment sampling choices were not spontaneous but associated with the infant's preceding engagement behaviour modulated by the information offered from the presented stimuli. However, we also observed a large variance within infants' curiosity-based information sampling which may be constrained by their developing exploration skills. A remaining question is whether the observed exploration tendencies are stable and related to other aspects of development, which we are currently investigating. Together, we offer new methodological avenues for future research into infants' active exploration and present novel insights converging with and expanding the current literature regarding this crucial aspect of human development.

2.5 References

Addyman, C., & Mareschal, D. (2013). Local Redundancy Governs Infants' Spontaneous Orienting to Visual-Temporal Sequences. *Child Development*, *84*(4), 1137–1144. https://doi.org/10.1111/cdev.12060

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*, 141–164.

Altmann, E. C., Bazhydai, M., Karadağ, D., & Westermann, G. (2024). *The Infant and Toddler Curiosity Questionnaire: A validated caregiver-report measure of curiosity in children from 5 to 24 months*. OSF. https://doi.org/10.31234/osf.io/9swaf

Altmann, E. C., Bazhydai, M., & Westermann, G. (2021, November 30). *'Let me see that':Self-directed Exploration in Infants tested in the context of a new theoretical framework*. https://eprints.lancs.ac.uk/id/eprint/172308/

Averbeck, B. B. (2015). Theory of Choice in Bandit, Information Sampling and Foraging Tasks. *PLOS Computational Biology*, *11*(3), e1004164. https://doi.org/10.1371/journal.pcbi.1004164

Bambach, S., Crandall, D., Smith, L., & Yu, C. (2018). Toddler-Inspired Visual Object Learning. *Advances in Neural Information Processing Systems*, *31*. https://proceedings.neurips.cc/paper_files/paper/2018/hash/48ab2f9b45957ab574cf005eb8a76760-Abstract.html

Bazhydai, M., Jones, S. D., & Westermann, G. (2022, January 26). *Does curiosity enhance word learning in 18-month-old infants? A Registered Report.* [Other]. https://doi.org/10.31219/osf.io/bm5a9

Bazhydai, M., Twomey, K., & Westermann, G. (2021). Curiosity and Exploration. In J. B. Benson (Ed.), *Encyclopedia of Infant and Early Childhood Development* (2nd ed; Issue 2nd ed). Elsevier. https://eprints.lancs.ac.uk/id/eprint/136590/

Bazhydai, M., Westermann, G., & Parise, E. (2020). "I don't know but I know who to ask": 12-month-olds actively seek information from knowledgeable adults. *Developmental Science*, *23*(5), e12938. https://doi.org/10.1111/desc.12938

Begus, K., Gliga, T., & Southgate, V. (2014). Infants Learn What They Want to Learn: Responding to Infant Pointing Leads to Superior Learning. *PLoS ONE*, *9*(10), e108817. https://doi.org/10.1371/journal.pone.0108817

Begus, K., & Southgate, V. (2018). Curious Learners: How Infants' Motivation to Learn Shapes and Is Shaped by Infants' Interactions with the Social World. In M. M. Saylor & P. A. Ganea (Eds.), *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms* (pp. 13–37). Springer International Publishing. https://doi.org/10.1007/978-3-319-77182-3_2

Berlyne, D. E. (1960). *Conflict, arousal, and curiosity* (pp. xii, 350). McGraw-Hill Book Company. https://doi.org/10.1037/11164-000

Blanco, N. J., & Sloutsky, V. M. (2020). Attentional mechanisms drive systematic exploration in young children. *Cognition*, *202*, 104327. https://doi.org/10.1016/j.cognition.2020.104327

Bono, M. A., & Stifter, C. A. (2003). Maternal Attention-Directing Strategies and Infant Focused Attention During Problem Solving. *Infancy*, *4*(2), 235–250. https://doi.org/10.1207/S15327078IN0402_05

Bourgeois, K. S., Khawar, A. W., Neal, S. A., & Lockman, J. J. (2005). Infant Manual Exploration of Objects, Surfaces, and Their Interrelations. *Infancy*, *8*(3), 233–252. https://doi.org/10.1207/s15327078in0803_3

Bremner, J. G., Slater, A. M., & Johnson, S. P. (2015). Perception of Object Persistence: The Origins of Object Permanence in Infancy. *Child Development Perspectives*, *9*(1), 7–13. https://doi.org/10.1111/cdep.12098

Bürkner, P.-C. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*, *80*, 1–28.

Bushnell, I. w. r. (2001). Mother's face recognition in newborn infants: Learning and memory. *Infant and Child Development*, *10*(1–2), 67–74. https://doi.org/10.1002/icd.248

Cao, A., Raz, G., Saxe, R., & Frank, M. C. (2023). Habituation Reflects Optimal Exploration Over Noisy Perceptual Samples. *Topics in Cognitive Science*, *15*(2), 290–302. https://doi.org/10.1111/tops.12631

Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, *9*(2), 129–136. https://doi.org/10.1016/0040-5809(76)90040-X

Chen, C., Houston, D. M., & Yu, C. (2021). Parent–Child Joint Behaviors in Novel Object Play Create High-Quality Data for Word Learning. *Child Development*, *92*(5), 1889–1905. https://doi.org/10.1111/cdev.13620

Chen, X., Twomey, K. E., & Westermann, G. (2022). Curiosity enhances incidental object encoding in 8-month-old infants. *Journal of Experimental Child Psychology*, *223*, 105508. https://doi.org/10.1016/j.jecp.2022.105508

Colombo, J. (2001). The Development of Visual Attention in Infancy. *Annual Review of Psychology*, *52*(1), 337–367. https://doi.org/10.1146/annurev.psych.52.1.337

Cross, G. R., & Jain, A. K. (1982). MEASUREMENT OF CLUSTERING TENDENCY Research supported in part by NSF Grant ECS-8007106. In A. K. Mahalanabis (Ed.), *Theory and Application of Digital Control* (pp. 315–320). Pergamon. https://doi.org/10.1016/B978-0-08-027618-2.50054-1

Daw, N. D., O'Doherty, J. P., Dayan, P., Seymour, B., & Dolan, R. J. (2006). Cortical substrates for exploratory decisions in humans. *Nature*, *441*(7095), Article 7095. https://doi.org/10.1038/nature04766

DeCasper, A. J., & Spence, M. J. (1986). Prenatal maternal speech influences newborns' perception of speech sounds. *Infant Behavior and Development*, *9*(2), 133–150. https://doi.org/10.1016/0163-6383(86)90025-1

Dubey, R., & Griffiths, T. L. (2020). Reconciling novelty and complexity through a rational analysis of curiosity. *Psychological Review*, *127*(3), 455–476. https://doi.org/10.1037/rev0000175

Fantz, R. L. (1964). Visual Experience in Infants: Decreased Attention to Familiar Patterns Relative to Novel Ones. *Science*, *146*(3644), 668–670. https://doi.org/10.1126/science.146.3644.668

Feldman, R., & Mayes, L. C. (1999). *THE CYCLIC ORGANIZATION OF AITENTION DURING HABITUATION IS RELATED TO INFANTS' INFORMATION PROCESSING*. *22*(1).

Fontenelle, S. A., Alexander Kahrs, B., Ashley Neal, S., Taylor Newton, A., & Lockman, J. J. (2007). Infant manual exploration of composite substrates. *Journal of Experimental Child Psychology*, *98*(3), 153–167. https://doi.org/10.1016/j.jecp.2007.07.001

Gaither, S. E., Pauker, K., & Johnson, S. P. (2012). Biracial and monoracial infant own-race face perception: An eye tracking study. *Developmental Science*, *15*(6), 775–782. https://doi.org/10.1111/j.1467-7687.2012.01170.x

Gerken, L., Balcomb, F. K., & Minton, J. L. (2011). Infants avoid 'labouring in vain' by attending more to learnable than unlearnable linguistic patterns. *Developmental Science*, *14*(5), 972–979. https://doi.org/10.1111/j.1467-7687.2011.01046.x

Goldstein, M. H., Schwade, J., Briesch, J., & Syal, S. (2010). Learning While Babbling: Prelinguistic Object-Directed Vocalizations Indicate a Readiness to Learn. *Infancy*, *15*(4), 362–391. https://doi.org/10.1111/j.1532-7078.2009.00020.x

Goupil, L., & Proust, J. (2023). Curiosity as a metacognitive feeling. *Cognition*, *231*, 105325. https://doi.org/10.1016/j.cognition.2022.105325

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of Curiosity Modulate Hippocampus-Dependent Learning via the Dopaminergic Circuit. *Neuron*, *84*(2), 486–496. https://doi.org/10.1016/j.neuron.2014.08.060

Hayden, B. Y., Pearson, J. M., & Platt, M. L. (2011). Neuronal basis of sequential foraging decisions in a patchy environment. *Nature Neuroscience*, *14*(7), Article 7. https://doi.org/10.1038/nn.2856

Hessels, R. S., Niehorster, D. C., Kemner, C., & Hooge, I. T. C. (2017). Noise-robust fixation detection in eye movement data: Identification by two-means clustering (I2MC). *Behavior Research Methods*, *49*(5), 1802–1823. https://doi.org/10.3758/s13428-016-0822-1

Hoch, J. E., O'Grady, S. M., & Adolph, K. E. (2019). It's the journey, not the destination: Locomotor exploration in infants. *Developmental Science*, *22*(2), e12740. https://doi.org/10.1111/desc.12740

Hunter, M. A., & Ames, E. W. (1988). A multifactor model of infant preferences for novel and familiar stimuli. *Advances in Infancy Research*, *5*, 69–95.

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T., & Camerer, C. F. (2009). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. *Psychological Science*, *20*(8), 963–973. https://doi.org/10.1111/j.1467-9280.2009.02402.x

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2014). Crawling and walking infants elicit different verbal responses from mothers. *Developmental Science*, *17*(3), 388–395. https://doi.org/10.1111/desc.12129

Karmazyn-Raz, H., & Smith, L. B. (2023). Sampling statistics are like story creation: A network analysis of parent–toddler exploratory play. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *378*(1870), 20210358. https://doi.org/10.1098/rstb.2021.0358

Kaufman, L., & Rousseeuw, P. J. (2009). *Finding Groups in Data: An Introduction to Cluster Analysis*. John Wiley & Sons.

Keemink, J. R., Keshavarzi-Pour, M. J., & Kelly, D. J. (2019). Infants' responses to interactive gaze-contingent faces in a novel and naturalistic eye-tracking paradigm. *Developmental Psychology*, *55*(7), 1362–1371. https://doi.org/10.1037/dev0000736

Kiat, J. E., Luck, S. J., Beckner, A. G., Hayes, T. R., Pomaranski, K. I., Henderson, J. M., & Oakes, L. M. (2022). Linking patterns of infant eye movements to a neural network model of the ventral stream using representational similarity analysis. *Developmental Science*, *25*(1), e13155. https://doi.org/10.1111/desc.13155

Kidd, C., & Hayden, B. Y. (2015). The Psychology and Neuroscience of Curiosity. *Neuron*, *88*(3), 449–460. https://doi.org/10.1016/j.neuron.2015.09.010

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks Effect: Human Infants Allocate Attention to Visual Sequences That Are Neither Too Simple Nor Too Complex. *PLoS ONE*, *7*(5), e36399. https://doi.org/10.1371/journal.pone.0036399

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks Effect in Infant Auditory Attention. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12263

Kovack-Lesh, K. A., Horst, J. S., & Oakes, L. M. (2008). The Cat is out of the Bag: The Joint Influence of Previous Experience and Looking Behavior on Infant Categorization. *Infancy*, *13*(4), 285–307. https://doi.org/10.1080/15250000802189428

Kulke, L., Atkinson, J., & Braddick, O. (2015). Automatic Detection of Attention Shifts in Infancy: Eye Tracking in the Fixation Shift Paradigm. *PLOS ONE*, *10*(12), e0142505. https://doi.org/10.1371/journal.pone.0142505

Lucca, K., & Wilbourn, M. P. (2019). The what and the how: Information-seeking pointing gestures facilitate learning labels and functions. *Journal of Experimental Child Psychology*, *178*, 417–436. https://doi.org/10.1016/j.jecp.2018.08.003

Mandler, J. M., Bauer, P. J., & McDonough, L. (1991). Separating the sheep from the goats: Differentiating global categories. *Cognitive Psychology*, *23*(2), 263–298. https://doi.org/10.1016/0010-0285(91)90011-C

Mandler, J. M., Fivush, R., & Reznick, J. S. (1987). The development of contextual categories. *Cognitive Development*, *2*(4), 339–354. https://doi.org/10.1016/S0885-2014(87)80012-6

Mani, N., & Ackermann, L. (2018). Why Do Children Learn the Words They Do? *Child Development Perspectives*, *12*(4), 253–257. https://doi.org/10.1111/cdep.12295

Matas, L., Arend, R., & Sroufe, L. A. (1978). Continuity of Adaptation in the Second Year: The Relationship between Quality of Attachment and Later Competence. *Child Development - CHILD DEVELOP*, *49*, 547–556. https://doi.org/10.1111/j.1467-8624.1978.tb02354.x

McQuillan, M. E., Smith, L. B., Yu, C., & Bates, J. E. (2020). Parents Influence the Visual Learning Environment Through Children's Manual Actions. *Child Development*, *91*(3), e701–e720. https://doi.org/10.1111/cdev.13274

Meder, B., Wu, C. M., Schulz, E., & Ruggeri, A. (2021). Development of directed and random exploration in children. *Developmental Science*, *24*(4), e13095. https://doi.org/10.1111/desc.13095

Mendive, S., Bornstein, M. H., & Sebastián, C. (2013). The role of maternal attention-directing strategies in 9-month-old infants attaining joint engagement. *Infant Behavior and Development*, *36*(1), 115–123. https://doi.org/10.1016/j.infbeh.2012.10.002

Miyazaki, M., Takahashi, H., Rolf, M., Okada, H., & Omori, T. (2015). The image-scratch paradigm: A new paradigm for evaluating infants' motivated gaze control. *Scientific Reports*, *4*(1), 5498. https://doi.org/10.1038/srep05498

Oakes, L. M., Kovack-Lesh, K. A., & Horst, J. S. (2009). Two are better than one: Comparison influences infants' visual recognition memory. *Journal of Experimental Child Psychology*, *104*(1), 124–131. https://doi.org/10.1016/j.jecp.2008.09.001

Oakes, L. M., Madole, K. L., & Cohen, L. B. (1991). Infants' object examining: Habituation and categorization. *Cognitive Development*, *6*(4), 377–392. https://doi.org/10.1016/0885-2014(91)90045-F

Oudeyer, P.-Y., Kaplan, F., & Hafner, V. V. (2007). Intrinsic Motivation Systems for Autonomous Mental Development. *IEEE Transactions on Evolutionary Computation*, *11*(2), 265–286. https://doi.org/10.1109/TEVC.2006.890271

Oudeyer, P.-Y., & Smith, L. B. (2016). How Evolution May Work Through Curiosity-Driven Developmental Process. *Topics in Cognitive Science*, *8*(2), 492–502. https://doi.org/10.1111/tops.12196

Pelz, M., & Kidd, C. (2020). The elaboration of exploratory play. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*(1803), 20190503. https://doi.org/10.1098/rstb.2019.0503

Pelz, M., Piantadosi, S. T., & Kidd, C. (2015). The dynamics of idealized attention in complex learning environments. *2015 Joint IEEE International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob)*, 236–241. https://doi.org/10.1109/DEVLRN.2015.7346147

Piaget, J. (n.d.). *Piaget's theory* (Vol. 1).

Poli, F., Meyer, M., Mars, R. B., & Hunnius, S. (2022). Contributions of expected learning progress and perceptual novelty to curiosity-driven exploration. *Cognition*, *225*, 105119. https://doi.org/10.1016/j.cognition.2022.105119

Poli, F., O'Reilly, J. X., Mars, R. B., & Hunnius, S. (2024). Curiosity and the dynamics of optimal exploration. *Trends in Cognitive Sciences*, *0*(0). https://doi.org/10.1016/j.tics.2024.02.001

Poli, F., Serino, G., Mars, R. B., & Hunnius, S. (2020). Infants tailor their attention to maximize learning. *Science Advances*, *6*(39), eabb5053. https://doi.org/10.1126/sciadv.abb5053

Pridham, K., Becker, P., & Brown, R. (2000). Effects of infant and caregiving conditions on an infant's focused exploration of toys. *Journal of Advanced Nursing*, *31*(6), 1439–1448. https://doi.org/10.1046/j.1365-2648.2000.01448.x

Reio Jr., T., Petrosko, J., Wiswell, A., & Thongsukmag, J. (2006). The Measurement and Conceptualization of Curiosity. *The Journal of Genetic Psychology*, *167*(2), 117–135. https://doi.org/10.3200/GNTP.167.2.117-135

Rodriguez, E. T., & Tamis-LeMonda, C. S. (2011). Trajectories of the Home Learning Environment Across the First 5 Years: Associations With Children's Vocabulary and Literacy Skills at Prekindergarten. *Child Development*, *82*(4), 1058–1075. https://doi.org/10.1111/j.1467-8624.2011.01614.x

Rose, S. A., Gottfried, A. W., Melloy-Carminar, P., & Bridger, W. H. (1982). Familiarity and novelty preferences in infant recognition memory: Implications for information processing. *Developmental Psychology*, *18*(5), 704–713. https://doi.org/10.1037/0012-1649.18.5.704

Rothbart, M. (2007). Temperament, Development, and Personality. *Current Directions in Psychological Science*, *16*, 207–212. https://doi.org/10.1111/j.1467-8721.2007.00505.x

Rousseeuw, P. J. (1987). Silhouettes: A graphical aid to the interpretation and validation of cluster analysis. *Journal of Computational and Applied Mathematics*, *20*, 53–65. https://doi.org/10.1016/0377-0427(87)90125-7

Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2016). Sources of developmental change in the efficiency of information search. *Developmental Psychology*, *52*(12), 2159–2173. https://doi.org/10.1037/dev0000240

Schatz, J. L., Suarez-Rivera, C., Kaplan, B. E., & Tamis-LeMonda, C. S. (2022). Infants' object interactions are long and complex during everyday joint engagement. *Developmental Science*, *25*(4), e13239. https://doi.org/10.1111/desc.13239

Schulz, E., Wu, C. M., Ruggeri, A., & Meder, B. (2019). Searching for Rewards Like a Child Means Less Generalization and More Directed Exploration. *Psychological Science*, *30*(11), 1561–1572. https://doi.org/10.1177/0956797619863663

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Siqueland, E. R., & DeLucia, C. A. (1969). Visual Reinforcement of Nonnutritive Sucking in Human Infants. *Science*, *165*(3898), 1144–1146. https://doi.org/10.1126/science.165.3898.1144

Slone, L. K., Smith, L. B., & Yu, C. (2019). Self-generated variability in object images predicts vocabulary growth. *Developmental Science*, *22*(6), e12816. https://doi.org/10.1111/desc.12816

Smith, L. B., Jayaraman, S., Clerkin, E., & Yu, C. (2018). The Developing Infant Creates a Curriculum for Statistical Learning. *Trends in Cognitive Sciences*, *22*(4), 325–336. https://doi.org/10.1016/j.tics.2018.02.004

Somerville, L. H., Sasse, S. F., Garrad, M. C., Drysdale, A. T., Abi Akar, N., Insel, C., & Wilson, R. C. (2017). Charting the expansion of strategic exploratory behavior during adolescence. *Journal of Experimental Psychology: General*, *146*(2), 155–164. https://doi.org/10.1037/xge0000250

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*(6230), 91–94.

https://doi.org/10.1126/science.aaa3799
Suarez-Rivera, C., Smith, L. B., & Yu, C. (2019). Multimodal parent behaviors within joint attention support sustained attention in infants. *Developmental Psychology*, *55*(1), 96–109. https://doi.org/10.1037/dev0000628

Sučević, J., Althaus, N., & Plunkett, K. (2021). The role of labels and motions in infant category learning. *Journal of Experimental Child Psychology*, *205*, 105062. https://doi.org/10.1016/j.jecp.2020.105062

Tamis-LeMonda, C. S., Kuchirko, Y., & Tafuro, L. (2013). From Action to Interaction: Infant Object Exploration and Mothers' Contingent Responsiveness. *IEEE Transactions on Autonomous Mental Development*, *5*(3), 202–209. https://doi.org/10.1109/TAMD.2013.2269905

Tummeltshammer, K. S., Mareschal, D., & Kirkham, N. Z. (2014). Infants' Selective Attention to Reliable Visual Cues in the Presence of Salient Distractors. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12239

Twomey, K. E., & Westermann, G. (2018). Curiosity-based learning in infants: A neurocomputational approach. *Developmental Science*, *21*(4), e12629. https://doi.org/10.1111/desc.12629

van den Boom, D. C. (1994). The Influence of Temperament and Mothering on Attachment and Exploration: An Experimental Manipulation of Sensitive Responsiveness among Lower-Class Mothers with Irritable Infants. *Child Development*, *65*(5), 1457–1477. https://doi.org/10.2307/1131511

Vygotsky, L. S., & Cole, M. (1978). *Mind in Society: Development of Higher Psychological Processes*. Harvard University Press.

Wang, Q., Bolhuis, J., Rothkopf, C. A., Kolling, T., Knopf, M., & Triesch, J. (2012). Infants in Control: Rapid Anticipation of Action Outcomes in a Gaze-Contingent Paradigm. *PLoS ONE*, *7*(2), e30884. https://doi.org/10.1371/journal.pone.0030884

Wass, S. V., & Smith, T. J. (2014). Individual Differences in Infant Oculomotor Behavior During the Viewing of Complex Naturalistic Scenes. *Infancy*, *19*(4), 352–384. https://doi.org/10.1111/infa.12049

Williams, P. (1998). *Representational Organization of Multiple Exemplars of Object Categories*. 21.

Yu, C., & Smith, L. B. (2012). Embodied attention and word learning by toddlers. *Cognition*, *125*(2), 244–262. https://doi.org/10.1016/j.cognition.2012.06.016

Zettersten, M. (2020). *Seeking New Words: Active Word Learning in Infants and Children* [Ph.D., The University of Wisconsin - Madison]. https://search.proquest.com/docview/2408896456/abstract/E02DABE6983D46B2PQ/1

S2.1 Supplementary materials

These supplementary materials are made up of two parts. The first part (S2.1) provides additional detail about reported results, whereas the second part (S2.2) reports the additional adult study based on which stimulus similarities were computed. Data and analysis code for all results are available on the OSF.

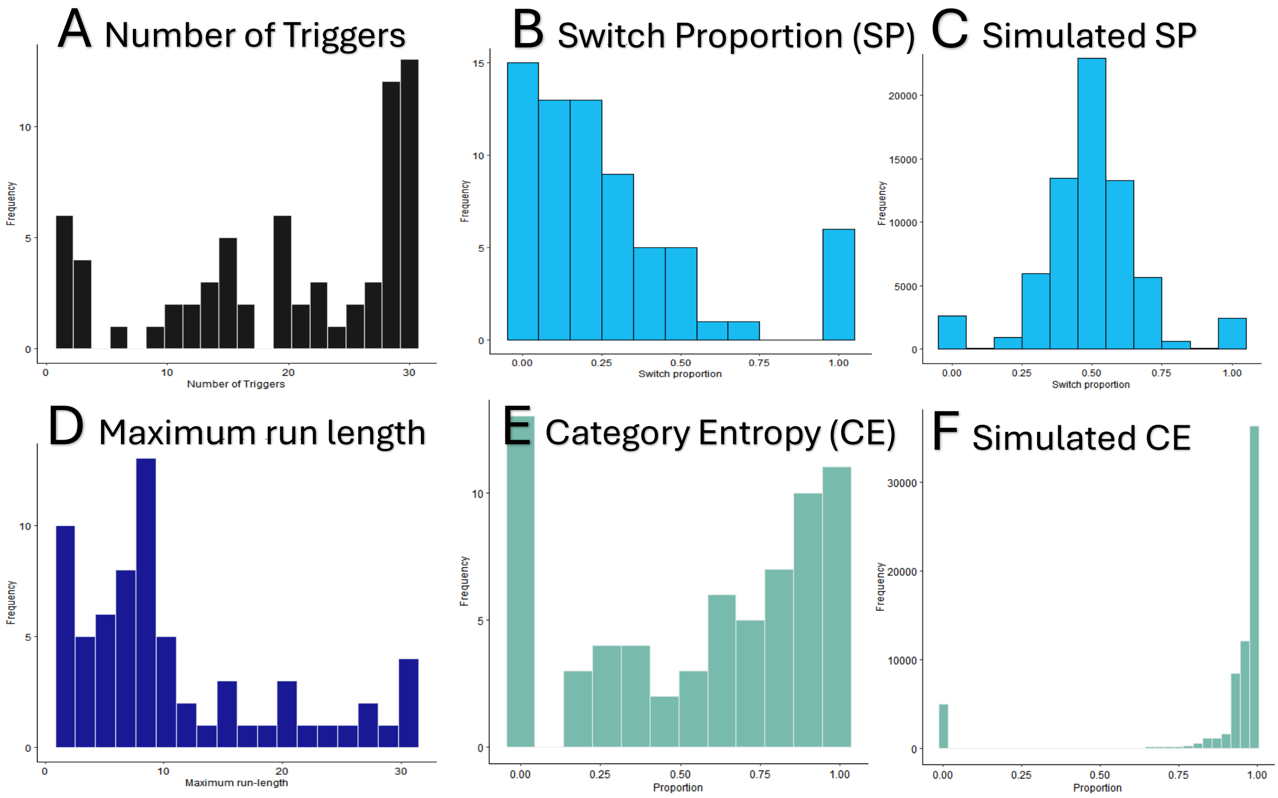


Figure S2.1. Distributions of observed and simulated exploration variables.

Note. **A:** Overall engagement as illustrated by the distribution of triggers across participants **B:** Exploitative tendencies as indicated by majority of switch proportions being below 50% (vertical line), **C:** Simulated switch proportions based on a chance mechanism (1000 draws per participant based on their number of triggers) **D:** Distribution of longest continuous runs (consecutively triggering the same category) per participant, **E:** Category entropies across participants, where higher values indicate more similar number of triggers towards both categories and the minimum of 0 indicates that all triggers were towards only one category, and **F**: Simulated category entropies based on a chance mechanism.

Table S2.1. Differential correlations between exploration variables by cluster.

	Brief/Explorers	Balanced	Exploiters
Correlations (Spearman)			
Overall engagement ~ Switch proportion	**-.70 (*p* = .034)**	**.48 (*p* = .003)**	.04 (*p* = .865)
Overall engagement ~ Category Entropy	.24 (*p* = .528)	**.47 (*p* = .003)**	-.09 (*p* = .692)
Switch proportion ~ Category Entropy	.14 (*p* = .730)	.29 (*p* = .085)	**.89 (*p* < .001)**

Note. Correlations of *explorers* should be considered with caution due to a very small sample size.

Table S2.2. Correlations between exploration and looking variables.

	Overall Engagement	Switch Proportion	Category Entropy
Mean Trigger Time	**-.38 (*p* = .001)**	.10 (*p* = .411)	.22 (*p* = .072)
Mean Looking Time	.06 (*p* = .653)	-.12 (*p* = .319)	-.11 (*p* = .359)
Mean Gaze-shifts	.-.01 (*p* = .915)	**.38 (*p* = .001)**	**.27 (*p* = .024)**

S2.1 Trial-by-trial trigger decision predictions

S2.1.1 Model comparisons

S2.1.1.1 Behavioural Models. Model fit comparison based on the leave-one-out cross validation values (looic) measure (Fig. S2.2, left) showed that the main model greatly improved the fit compared to the intercept model as its looic value is substantially smaller and standard errors are not overlapping. Adding the interaction terms for clusters did improve the fit further, however, the standard errors are widely overlapping suggesting that the added complexity may not be worth the fit improvement.

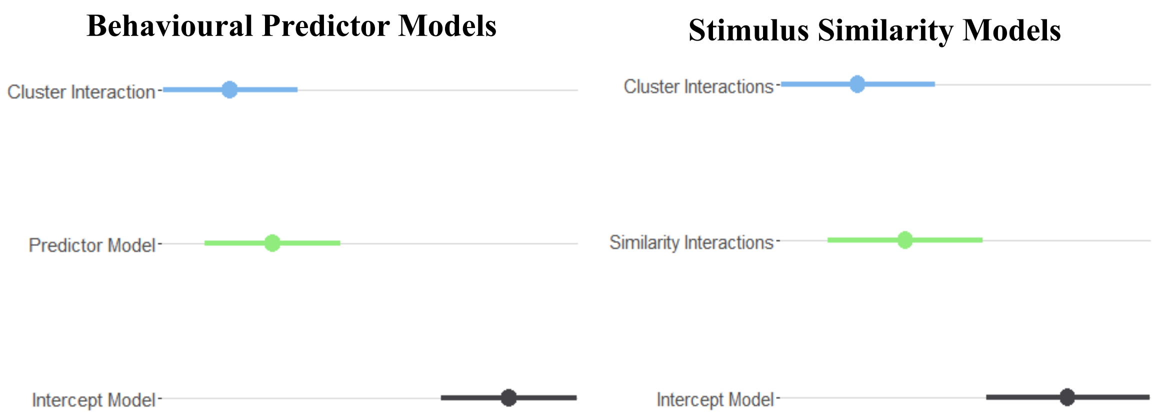


Figure S2.2. Model Comparisons.

Note. Based on the leave-one-out cross validation (looic) values on the x-axis. Smaller looic values suggest better fit. Standard errors are indicated. Left: Behavioural models (with reference to 2.3.3.1 and 2.3.3.3). Right: Stimulus-dependent models (with reference to 2.3.3.2).

S2.1.1.2 Stimulus-dependent Models. Model fit comparison based on the looic measure (Fig. S2.2, right) showed that the main model improved the fit compared to the intercept model as its looic value is substantially smaller and standard errors are not overlapping. Adding the interaction terms for clusters did improve the fit further, however, the standard errors are widely overlapping suggesting that the added complexity may not be worth the fit improvement.

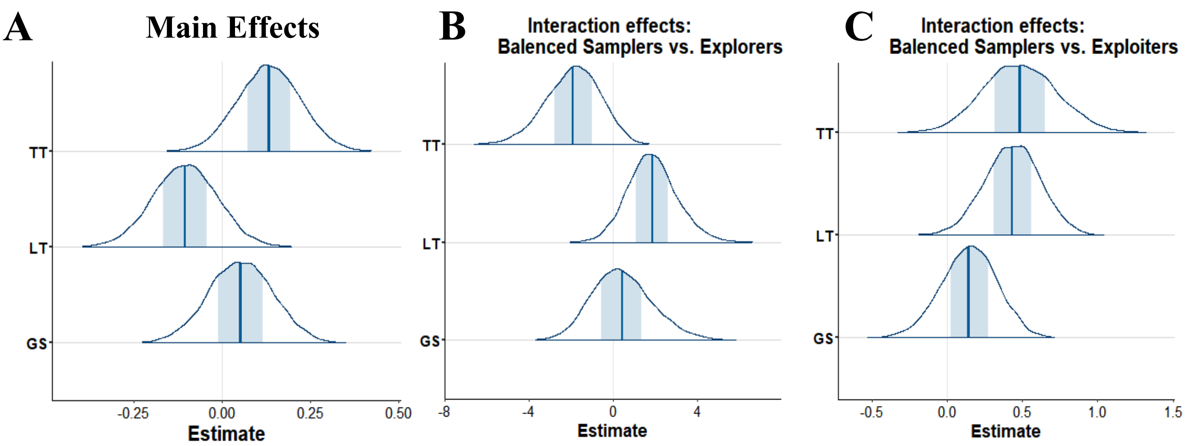


Figure S2.3. Behavioural switch prediction between Clusters.

Note. Probability distributions for each of the behavioural predictors on the outcome variable. A: main effects. B: Interaction effects comparing the balanced samplers to the explorers. C: Interaction effects comparing the balanced samplers to the exploiters.

If the interaction effect is of the same polarity as the main effect (e.g., both negative), it indicates a strengthening of that effect in the comparative group (slopes become steeper). If the interaction effect is of opposing polarity, the effect is weaker in the comparative group (slopes become less steep).

S2.1.2 Three-way interactions

In more detail, the main effects are still the same in polarity and look mostly like the main model (Fig. S2.4A). The three stimulus similarity interaction effects reported above have strengthened with slightly more negative values (Fig. S2.4B). The 3-way-interactions then indicate to what degree these interaction effects differ between clusters (Figures S2.4C, S2.4D). If the terms have the same polarity, the comparison cluster seems to have a stronger effect, whereas opposite polarities suggest a weaker interaction effect for that cluster. Regarding looking time, interaction terms for both explorers and exploiters are centred around zero indicating that there are no differences between clusters in the way that stimulus similarities affect looking time and in turn the likelihood to switch. In contrast, the interaction effects for the other two predictors are positive across clusters indicating that there are differences between the clusters. As noted above, the simple interactions are all negative which means they are of opposing polarity to these 3-way-interactions. This indicates that both, the effect of stimulus similarity on trigger time and on gaze-shifts is weaker for explorers and exploiters compared to the balanced samplers. This suggests that the main effects and interaction effects may be stronger if we had only looked at the balanced samplers.

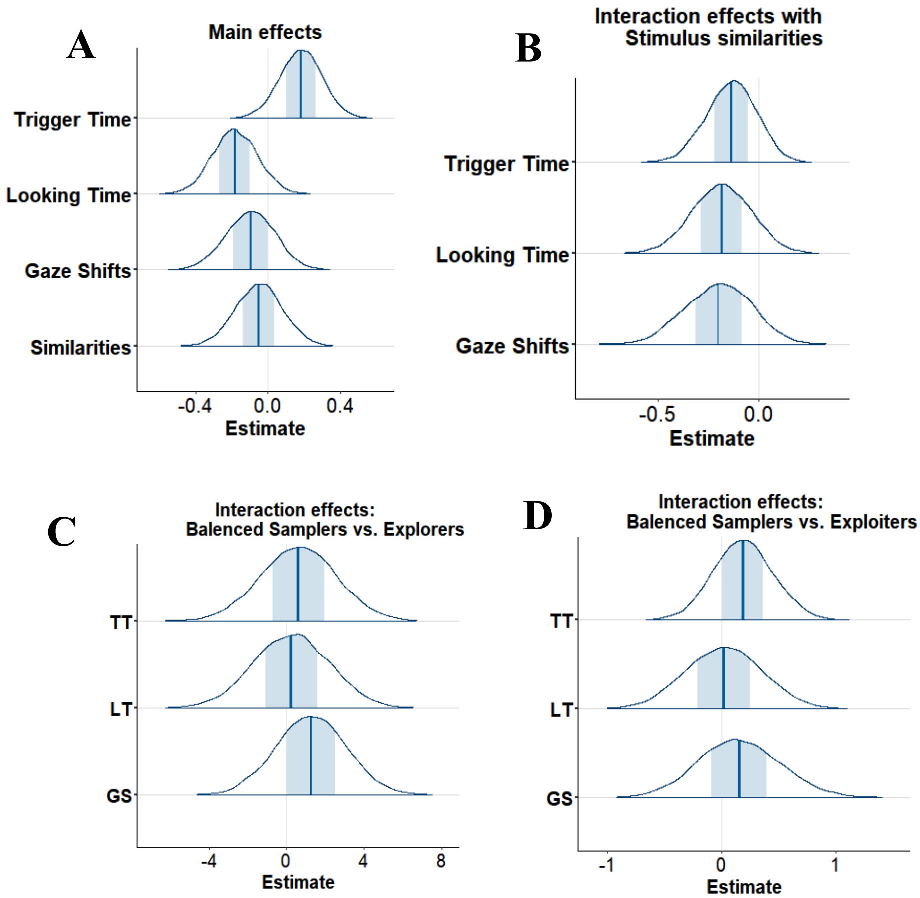


Figure S2.4. Effects for 3-way interaction model.

Note. Probability distributions for each of the behavioural predictors on the outcome variable. A: main effects of the behavioural predictors on likelihood to switch. B: Simple interaction effects of stimulus similarities on the behavioural predictors. C: 3-way-interaction comparing how similarity interaction effects differ between *explorers* compared to *balanced samplers*. D: 3-way-interaction comparing how similarity interaction effects differ between *exploiters* compared to *balanced samplers*. Note the scale difference for the *explorer* plot, which is likely due to the limited number of observations in the cluster of explorers.

S2.1.3 Balanced samplers in isolation

As the 3-way interactions suggested that the effects were mostly driven by the balanced samplers, we decided to look at this group in isolation. This model included 405 observations and fit successfully. Indeed, main effects and interaction effects were comparable to the other two stimulus-dependent models, and therefore in line with the notion that those were mostly driven by this group. Here, looking time (^b = -0.18, 95%-

CI[-0.43; 0.06]) and trigger time (^b = 0.18, 95%-CI[-0.05; 0.42]) had similarly strong effects, whereas both, gaze-shifts (^b = -0.09, 95%-CI[-0.37; 0.18]) and stimulus similarities (^b = -0.04, 95%-CI[-0.31; 0.21]) were only marginally negatively associated with higher likelihood to switch. All three interaction effects are again negative, meaning a strengthening of looking-time and gaze-shift effects and a weakening of the trigger-time effect for higher stimulus similarities.

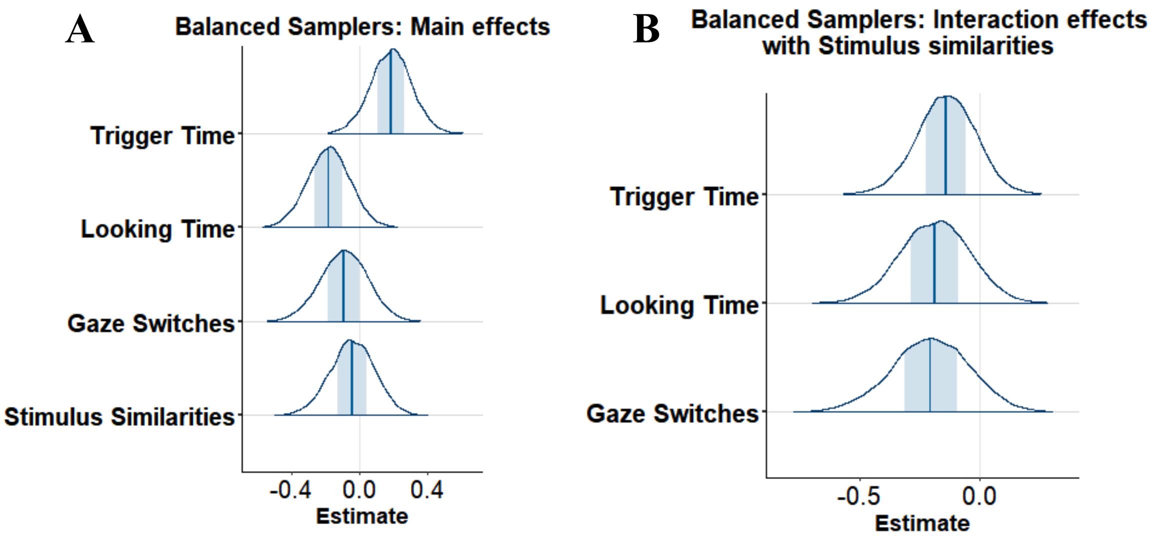


Figure S2.5. Effects for Balanced Samplers in isolation.

Note. Main effects (A) and interactions (B) of the predictors on the likelihood to switch when isolating the cluster of balanced samplers. **A**: Probability distributions for each main effect of the predictors on the outcome variable, including stimulus similarities. **B**: Probability distributions for each interaction effect between the stimulus similarities and each predictor.

S2.2 Supplementary materials - Adult Experiment

S2.2 Similarity Ratings Introduction

The novel stimuli used in the reported infant study were taken from the open TarrLab[1] repository. Two species of *Fribbles* from different families were chosen, under the consideration of not having a dominantly salient, variable body part (Barry et al., 2014). Perceptual differences between two stimuli from the same species, then, are mainly defined by counting the body parts in which they differ (0 to 4) as the variations are nominally different (Williams, 1998). However, it may be that subjective similarity between the stimuli does not perfectly map onto this objective way of categorising the differences (see Barry et al., 2014 with different stimulus sets) but could allow for more nuanced, perceptual measures of similarity. Thus, the aim of this supplementary study was to collect similarity ratings for each possible pair of the 30 stimuli for each category to account for subjective rather than objective measures. We collected the ratings for each possible pair as the presentation of stimuli in the study was randomised without repetition. This led to 465 possible pairs per category. To minimise fatigue effects, each participant was asked to only rate 155 pairs from one category.

S2.3 Methods

S2.3.1 Participants

Participants were recruited over Prolific (www.prolific.co) [2021] and the final sample consisted of 45 participants who completed the study (Mean age = 27.41, range = 18 to 54 years, 52.4% female) so that each individual pair would be rated seven times. One additional participant was excluded has they left the experiment after 12 trials. Prolific suggests to shortly inspect the data visually before accepting or rejecting submissions as one shortcoming of these online platforms is that participants sometimes do not submit high quality data. Based on such inspection, three further participants were messaged about their very short rating times suggesting a lack of attention necessary for conscious assessments. They admitted to these worries based on fatigue from earlier experiments and returned their submissions voluntarily.

S2.3.2 Materials

S2.3.2.1 Stimuli. Novel stimuli were taken from the open TarrLab[1] repository. Species FA2 and FB4 were chosen from which 30 stimuli were semi-randomly selected each, in alternating triplets to sample from the full range of body-part variations including objective differences of all four distances (0-4, Williams, 1998; the full list of included stimuli can be found in the appendix and supplementary online materials).

S2.3.2.2 Design & Measures. The study was created with PsychoPy3 and online conducted via Pavlovia. First, a list of all possible combinations of stimuli per category was created. Each list was randomly ordered and separated into three equal sets of 155 pairs. This was based on the consideration to not ask for too many ratings per participant to ensure high quality data. Each pair then was presented in random order, where the two stimuli were presented next to each other on grey background for 2 seconds to allow only for a subjective impression of the similarities rather than counting the differences (Barry et al., 2014). Each pair was then rated on a scale from 1 (not similar at all) to 7 (extremely similar). After every 52 stimuli (roughly each third), the participant could take a little break which they could terminate by pressing 'space' but which also automatically ended after 20 seconds.

S2.3.2.3 Exclusion criteria. Besides the ratings for each pair, the reaction times for each rating was recorded. This was used as a rough indication of data quality as reaction times below 200ms are typically viewed as too short to be conscious and even more so if two stimuli had to be compared. Thus, if the reaction times were too often in the area of 0.1-0.4 seconds when roughly inspecting the data visually, we suspected a lack of attention and contacted the anonymous participant for a follow up. This kind of inspection was only conducted if the completion time was suspiciously low or high – in accordance with Prolific's data quality check suggestion. Out of 45 participants, only three were inspected and contacted this way leading to them returning their submissions voluntarily after admitting they had not completed the study giving their full attention. While this was a subjective exclusion criterion, it did allow for economical recruitment where submissions of clearly lacking data quality were not paid for, but the participants were also not reprimanded by having their submission rejected.

S2.3.3 Analysis

21 ratings with a reaction time of below 200ms were excluded as these could not be assumed to have been made consciously. Each of these ratings belonged to a different stimulus pair leading to 21 out of 930 pairs receiving six instead of seven scores included in their aggregates. We computed the objective difference count for each pair, as well as the mean score, standard deviation, and range. To investigate the relation between objective and subjective scores, a correlation analysis was conducted and plotted.

S2.4 Results

The Shapiro-Wilk normality tests indicated that the data for both variables – objective differences and mean rating scores – were not normally distributed ($p < 0.001$). Thus, a parametric Kendall rank correlation test was computed. This analysis estimated the rank-based measure of association between the two variables to be significantly correlated, so that the mean similarity scores decreased with the number of differing body parts ($r_{tau} = -0.54$, $p < 0.001$). In other words, stimuli were perceived as more similar the more body parts they had in common (Figure 2.6). As the relation, however, was not exactly one to one, we chose to include these subjective mean scores in any further analyses instead of the objective nominal values as they were deemed more indicative of the perceived differences between consecutively presented stimuli.

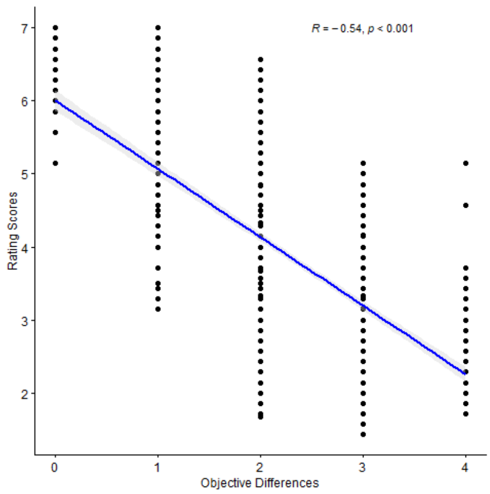


Figure 2.6 Correlation between objective stimulus differences (x-axis) and subjective similarity judgements (y-axis).

S2.5 Discussion

We conducted this supplementary study of collecting similarity ratings between every possible pairing amongst the stimuli included in the related exploration studies. We found that the number of objective differences significantly correlated with the subjective similarity ratings so that mean scores decreased with increasing objective differences. This confirms that objective differences were also subjectively perceived. However, as the relation was not perfect – for instance, pairs of identical stimuli received a number of scores different from the maximum score (7) – this also shows that including the subjective scores may better represent the subjective perception of consecutively presented stimuli more so than referring to the objective measure. The findings of this study are in accordance with Barry et al. (2014) who also found a strong relation between the two whilst suggesting that the objective scores cannot perfectly indicate subjective perception.

3 CAPTURING TRAIT

CURIOSITY IN INFANCY

3.1 Linking Statement

In the following chapter, I describe the development and initial validity testing of a new caregiver report measure of trait curiosity in infants and toddlers. While trait curiosity is an extensive area of research in adults, it becomes less so the earlier in development we look. No measure of the trait has yet been developed specifically for this very young age group. Nevertheless, it is highly likely that some of the variance observed in studies of infant exploration (e.g., Bornstein et al., 2013; Colombo et al., 1991; Franchak et al., 2016; Mandler et al., 1987; Muentener et al., 2018; Piccardi et al., 2020; Wass & Smith, 2014), as well as studies on state curiosity (e.g., Kidd et al., 2012; Poli et al., 2020), including the findings in Chapter 2, can be attributed to differences in their underlying trait curiosity. However, until now there has been no way to control for these differences. Here, we designed a new questionnaire to fill this gap. Our focus in this experimental study was to provide evidence for the reliability and validity of the new measure to capture infants' exploration tendencies as a manifestation of their trait curiosity. The results of this study have both theoretical and methodological implications for how trait curiosity is conceptualised and expressed in infants' active exploration.

This chapter is currently under review in Infancy.

Altmann, E. C., Bazhydai, M., Karadağ, D., & Westermann, G. (under review 1st round). The Infant and Toddler Curiosity Questionnaire: A validated caregiver report measure of curiosity in children from 5 to 24 months. *Infancy*.

The Infant and Toddler Curiosity Questionnaire: A validated caregiver-report measure of curiosity in children from 5 to 24 months

Elena C. Altmann, Marina Bazhydai, Didar Karadağ, and Gert Westermann

Funding Statement: This research was supported by the Doctoral Research Program in the Department of Psychology at Lancaster University and the Economic and Social Research Council (ESRC) International Centre for Language and Communicative Development (LuCiD) [ES/S007113/1 and ES/L008955/1].

Acknowledgements: We thank all families who participated and made this study possible. We would also like to thank the following Babylabs for their support in our online recruitment efforts: Camebridge Babylab, Birkbeck Babylab & Toddlerlab, Birmingham Babylab, University of Essex Babylab, Liverpool Language Lab, Oxford University Babylab, Oxford Brooks Babylab, Plymouth Babylab, UoM Child Study Centre.

Materials and analysis scripts presented in this manuscript are available from the OSF. The authors have no conflicts of interest to declare.

Research highlights:

- The first validated caregiver report to measure individual differences in trait curiosity in infants and toddlers.
- Twenty-three items were found to reliably capture a general factor of curiosity as well as three emergent curiosity subfactors.
- The scale had good test-retest reliability and correlated with temperament at medium effect sizes, offering evidence of its validity as a trait measure.
- A powerful new measure enabling new research avenues for better understanding trajectories of early cognitive and language development.

3.2 Abstract

Humans are curious. Especially children are known for their drive to explore and learn, which is crucial for developing in and navigating through our complex world. Naturally, some children may be more curious than others, leading to differences in how they structure their own learning experiences, subsequently impacting their developmental trajectories. However, there is a gap in the research field for a reliable measure of such differences early in development. Across three studies, we present the development and assessment of the Infant and Toddler Curiosity Questionnaire (ITCQ), the first caregiver report measure to fill this gap. Items cover observable exploration behaviours in 5- to 24-month-olds to capture general tendencies of their desire to actively explore their immediate surroundings and are evaluated on a 7-point Likert-scale. Exploratory factor analyses and structural equation modelling on a sample of $N = 370$ UK caregivers led to the final selection of 23 items and provided evidence that the scale is unidimensional enough to allow for an overall curiosity score, whereas three emergent subscales of curiosity types (*sensory, investigative*, and *social curiosity*) showed acceptable internal consistency explaining additional variance in the data. Furthermore, the scale had good test-retest reliability after 7 to 14 days ($N = 67$) and related to the child's temperament ($N = 75$; positively with surgency and effortful control, negatively with negative affect) offering evidence of its validity as a trait measure. Together, these results support the scale's reliability and validity, showcasing the ITCQ as a powerful tool for developmental research.

Keywords: infant curiosity, individual differences, psychometrics, exploration, early development, trait curiosity

3.3 Introduction

While the study of curiosity and its effects on learning has a long history in adults (Berlyne, 1960; Gruber et al., 2014; Kang et al., 2009; Rossing & Long, 1981), only in recent years has infant curiosity become a focus of research and has provided insights into how infants actively engage in their own learning. Studies have shown, for example, that infants prefer to engage with information of intermediate complexity (Kidd et al., 2012, 2014) and that they alternate between visual exploration and exploitation driven by their active learning experience (Chapter 2; Altmann, et al., 2023) in the pursuit of maximizing their learning progress (Poli et al., 2020; Twomey & Westermann, 2018), that they actively request information from adults through social orienting (Bazhydai et al., 2020) and pointing (Liszkowski et al., 2007), with learning benefits shown for actively requested information (Begus et al., 2014) but also from being in a state of curiosity more generally (Chen et al., 2022; Stahl & Feigenson, 2015). What is common to all of these studies is that they assume infants to be curious learners by definition and that they investigate the implications of such inherent trait curiosity on in-the-moment behaviours. Only a few studies, however, have considered how differences in infants' individual interests (Ackermann et al., 2020) and sensory seeking (Piccardi et al., 2020) affect their preference to engage with specific information. Overall, there has been no systematic investigation on individual differences in trait curiosity on infants' exploratory behaviour, learning, and later outcomes. To enable such research, it is necessary to have validated measures of infant curiosity.

This is different from research in adults where multiple scales exist to assess variation in trait curiosity (for reviews, see Grossnickle, 2016; Jirout & Klahr, 2012; Wagstaff et al., 2021), measuring general accounts of curiosity (e.g., Day, 1971; Kashdan et al., 2020; Litman & Jimerson, 2004; Litman & Spielberger, 2003; Naylor, 1981; Spielberger, 1979) but also more specific domains (e.g., social curiosity, Renner, 2006; work-related curiosity, Mussel et al., 2012) in the form of self-report questionnaires. These measures typically ask responders how commonly or intensely they experience a desire for knowledge and learning, thereby requiring meta-cognitive awareness (e.g., Goupil & Proust, 2023; Loewenstein, 1994). However, some questionnaires also conceptualised curiosity as the intrinsic motivation behind exploration in the pursuit of knowledge, leading to items focusing on more observable behaviours (e.g., Kashdan et al., 2009). Research using such trait measures has shown positive associations between curiosity and job performance as well as academic achievement (e.g., Grossnickle, 2016; Hardy et al., 2017; Kashdan & Yuen, 2007; Mussel, 2013; Reio & Wiswell, 2000; Reio & Callahan, 2004), highlighting its impact on life outcomes.

To investigate trait curiosity in children, some self-report measures designed for school-aged cohorts do exist (Byman, 2005; Maw & Maw, 1968; Olson, 1986; Penney & McCann, 1964) but their validity may be limited by the children's lack of motivation to self-reflect and reliably answer numerous repetitive items (Jirout & Klahr, 2012). An alternative to self-reports, especially relevant for younger children, are *other*-reports (primarily caregivers and teachers, e.g., Harty & Beall, 1984; Lee et al., 2023; Maw & Maw, 1970; Piotrowski et al., 2014). Other-reports enable measurement without age-restriction but do require another person to assess a latent (not directly observable) construct in the child, bringing its own challenges. Yet, extensive research from infancy onward has shown that such measures can generate reliable, valid, and longitudinally informative data by, for instance, having items address observable behaviours in which the latent construct manifests itself. Prominent examples include the Ages and Stages questionnaire (e.g., Klamer et al., 2005; Lepine et al., 2022; Richter & Janson, 2007; Salomonsson & Sleed, 2010), the MacArthur-Bates Communicative Development Inventory (CDI; Bornstein & Putnick, 2012; Can et al., 2013; Feldman et al., 2005; Fenson, 2002; Fenson et al., 1994, 2006; Marchman & Fernald, 2008), and temperament scales from infancy to early childhood (e.g., Putnam et al., 2008; Rothbart, 1986, 2011; Slagt et al., 2016; Wright & Jackson, 2022). However, there is a clear gap in the scientific literature regarding infant trait curiosity. Even though some emerging work has aimed to assess differences in early curiosity through caregiver reports (Lee et al., 2023; Piotrowski et al., 2014) the target group of infants and toddlers has thus far been neglected.

As mentioned, for other-reports it is important to create items based on observable behaviour in which the construct manifests. Regarding curiosity, this manifestation is commonly assumed to be active exploration and interaction with the environment (for review see Bazhydai et al., 2021). Previous research across the first two years of life has found individual differences in exploration throughout various experimental paradigms, such as visual exploration (e.g., Colombo et al., 1991; Franchak et al., 2016; Piccardi et al., 2020; Wass & Smith, 2014), manual exploration (e.g., Fortner-wood & Henderson, 1997; Mandler et al., 1987; Muentener et al., 2018) and free play exploration (e.g., Bornstein et al., 2013; Slone et al., 2019; Smith & Yu, 2013), letting us plausibly assume that infants already differ in their trait curiosity. Some of these studies also found that exploration differences were predictive of variability in learning, later vocabulary, cognitive development, and academic achievement (e.g., Berg & Sternberg, 1985; Bornstein et al., 2013; Muentener et al., 2018; Smith & Yu, 2013) highlighting its role in and importance across development. In fact, one study used a subset of various caregiver-report items as an ad hoc measure of curiosity and was able to find a positive relation with academic achievement in kindergarten (Shah et al., 2018). While it is important to stress that measures used in psychological research need to be reliable and structurally validated (e.g., Flake & Fried, 2020), this finding does hint at the impact a systematically developed and validated caregiver report measure of curiosity could have.

3.3.1 The current paper

We present the Infant and Toddler Curiosity Questionnaire (ITCQ) applicable for 5-24-month-old infants and toddlers as a new caregiver-report measure for capturing individual differences in trait curiosity. Considering the lack of consensus for a functional definition of curiosity especially early in development (Jirout & Klahr, 2012; Kidd & Hayden, 2015), we decided to base our approach on a folk psychology definition of curiosity, that is, *a keen desire or tendency to actively explore one's immediate surroundings*. Here we report three studies on the ITCQ's development and assessment, evidencing its reliability and validity in line with rigorous practices (e.g., Downing, 2003; Flake & Fried, 2020; Messick, 1995). Study 1 describes the questionnaire development, including its content and structural validity (sample size and general analysis aims pre-registered at https://aspredicted.org/19J_291). Study 2 supports the ITCQ's test-retest reliability after 7-14 days, and study 3 explores the measure's criterion validity via its relation to the well-established trait measure of temperament. Studies were given ethical approval by the University Faculty's research ethics committee, and data as well as analysis scripts are available on the OSF.

3.4 Study 1: Questionnaire Development & Structural Validity

3.4.1. Introduction

In this first study we describe the principles underlying the ITCQ's creation, a reduction of items to generate coherent and reliable responses, as well as offering evidence for its content and structural validity (Downing, 2003; Messick, 1995). Content validity concerns whether the items are representative and well formulated, and whether ambiguities were resolved, which was largely the focus of the item development and an initial pilot study. Structural validity, on the other hand, concerns the scale's dimensionality and internal consistency, which was the focus of the main analysis of this study. While we created the items with the purpose of measuring a single factor of general curiosity, it is recommended for new scales to explore and consider the best fitting emerging factor structure to explain additional variance in the data (e.g., McCoach et al., 2013). Furthermore, we aimed to provide evidence supporting our intention of one general factor (Artino et al., 2014) to justify the computation of an overall mean score (Dunn & McCray, 2020).

3.4.1.1 Questionnaire development

We developed an initial set of 34 statements capturing a wide range of behaviours infants can produce to interact with their physical and social environment as the manifestation of their curiosity. For this, we reviewed the exploration behaviours children typically express throughout their first two years of life (looking, grabbing, mouthing, pointing, etc.; Adolph & Hoch, 2019; Lockman, 2000) as well as everyday situations and locations in which they could be observed (e.g., at home or in new environments). Items covered behaviours such as interacting with objects, enjoyment of new discoveries, and observation to gain information (for a full list of final items, see Figure 3.2).

Due to the necessarily developmental perspective, some behaviours may not yet be observable in younger infants such as interacting socially (e.g., "When reading a picture book together, my child directs me (e.g., by pointing) towards what they want to know more about.") whereas other items were expected to be equally applicable across ages (e.g., "When my child encounters an object, they typically seem interested in its properties (e.g., how it feels, tastes or sounds like, etc.)"). To constrain the variance in applicability of items, we decided to focus on an age range from five to 24 months. The minimum of five months was chosen based on a notable expansion in behaviours infants can produce, whereas 24 months was chosen as the upper limit because from around the second birthday onwards verbal expressions of curiosity, such as question asking, become more prevalent.

Three of the items were reverse coded and described non-curious behaviour (e.g., "My child does not typically engage with (look at, point at, reach for, inspect) a lot of things in their environment."). While it is recommended to include such items to enhance data quality by making the reader slow down (Boley et al., 2021), they can also reduce the scale's overall reliability due to inattentive responses and lack of clarity (Rossiter, 2002; Salazar, 2015; Weijters & Baumgartner, 2012), often leading to their exclusion during the structural validity investigations. With this in mind, we included two additional items which were the mirrored versions of other positive items, solely meant to increase the responders' attention but not to be analysed as part of the final dataset (see Supplementary Materials).

We chose a 7-point Likert-scale from 1 ("strongly disagree") to 7 ("strongly agree") as the response scale, with an option of "not applicable (NA)" if they could not think of any recent situation allowing them to rate a specific item or because their child had not yet been able to show such behavior. Items were created in English initially targeting British caregivers and were repeatedly reviewed and improved based on the topical expertise of the authors, as well as through discussions with parents and native speakers to ensure their content validity. For further considerations regarding the response scale and online presentation, see Supplementary Materials.

3.4.1.2 Piloting

A pilot sample (N = 22, age in months: M = 11.5, SD = 1.6, 41% female; £5 travel reimbursement given), collected from families participating in an in-person study with typically developing 10- to 12-month-olds in the north-west of England, provided the first support for the questionnaire's construction. After excluding two items (items 21 and 25) indicated to improve the scale's homogeneity, the measure had very good coefficients commonly used to indicate internal consistency (Cronbach's alpha = .87, Guttman's lambda-6 = .93), suggesting that the scale was constructed sensibly enough (a set of around 30 items resulting in an $\alpha \geq .80$; Nunnally & Bernstein, 1994) to continue wider data collection. At the end of the survey, caregivers were also invited to provide qualitative responses of additional behaviours capturing curiosity. These responses were found to reflect very similar behaviours and situations already covered in the questionnaire items (e.g., being interested in how things feel, trying to see what objects are on the table, etc.). They also supported our conceptualisation of curiosity being in line with how parents intuitively understand the construct; thus together, these findings evidenced the scale's content validity. In-person comments received from caregivers after completing the questionnaire offered additional insights as they mentioned that the questionnaire was clearly formulated and easy to complete. Some parents mentioned that the items let them easily differentiate between behavioural tendencies of their youngest child and their older siblings which they found fascinating. Due to these overall promising preliminary results, we continued with wider data collection across the full age-range, making no changes to the scale. Based on this decision, the pilot data was deemed suitable to be included in the following main analyses.

3.4.2 Methods

3.4.2.1 Participants

A minimum sample size of *N*=360 was preregistered following a rule of thumb with 10 participants per item (e.g., Nunnally, 1978). A total of *N* = 370 responses were included in the final analyses (age range in months: 4.5-24.4, *M* = 13.5, *SD* = 5.2, see Figure 3.1; 51% female). Of these, *n* = 243 were recruited via social media, *n* = 72 attended in-lab visits, and *n* = 54 were contacted from the Babylab's database (which includes contact details for families willing to take part in infancy studies in the north-west of England) to directly complete the questionnaire alongside a temperament questionnaire (see study 3). Fifty-five additional responses were excluded due to being outside the preregistered age-range (*n* = 16), not being from the UK (*n* = 5), prematurity (*n* = 17), developmental concerns (*n* = 14), or poor data quality (*n* = 2, where all responses were either NA or the exact same response including reverse coded items). From the final sample, 97% indicated their child to be monolingual English, 82% of caregivers indicated to have achieved a degree in higher education (e.g., bachelor's degree and above), 50% of children were said to be the first born, 40% second born, and 10% were reported to have at least 2 older siblings (including stepsiblings). Participants provided informed consent prior to answering any questions and those recruited online via social media were invited to complete the survey without reimbursement. The sub-samples directly recruited from the Babylab's database received reimbursement as per university guidelines: in-lab visiting participants received £5 for their travel, and the sample which completed the longer version including the temperament scale received a £5 online gift voucher of their choice (via express.giftpay.com).

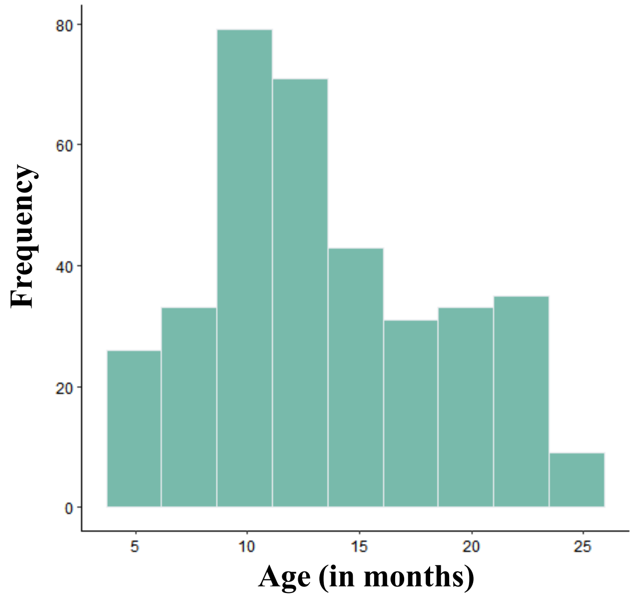


Figure 3.1. Age distribution of the sample.

3.4.2.2 Materials

Aside from the piloted 34 items, the questionnaire also included two items directly addressing the construct: an item asking about the child's curiosity directly ("I would describe my child as curious") and one item about the child's curiosity in comparison to their peers (on an ad-hoc five-point scale from 1 ("a lot less curious") to 5 ("a lot more curious")). Additionally, respondents were asked to provide demographic information (prematurity, developmental concerns, country, languages spoken, birth order, and socio-economic status (SES) via their educational level; Singh et al., 2023), and could optionally contribute qualitative responses regarding additional behaviours in which they see their child's curiosity manifested.

3.4.2.3 Procedure

Primary caregivers across the UK were invited to complete this online questionnaire on Qualtrics (Qualtrics, Provo, UT). Participating caregivers were provided with an information sheet before giving informed consent and received instructions to think about their child's typical behaviour to evaluate each statement. They indicated their child's age and sex after which the items were presented in a randomised order with four to five items per page. These were followed by the two items assessing direct curiosity, optional qualitative responses, and demographic questions. Lastly, caregivers were given the opportunity to sign up to receive an automatic email a week later for a re-test. It took most respondents under 15 minutes ($M = 11.43$, $SD = 5.45$) to complete the survey.

3.4.2.4 Analyses

3.4.2.4.1 Item reduction and emerging sub-factors. The scale was designed to measure infants' and toddlers' trait curiosity as one general construct represented in the tendencies with which the infant explores their surroundings. Thus, the aim of the exploratory factor analysis was to reduce the item list to coherently capture this construct, as well as to better understand the additional variance in the data. This analysis required initial steps (following Pett et al., 2003) of identifying possibly ill-fitting items and assessing the scale's sampling adequacy and factorability. We then fitted a unidimensional structure eliminating items which did not sufficiently load onto the general curiosity factor. Subsequently, we explored how many sub-factors the items grouped into to further investigate the scale's dimensionality (Dunn & McCray, 2020), where the number of sufficient factors was indicated using a scree plot and a parallel analysis. For the two latter steps, we conducted Exploratory Factor Analyses (function "fa" from the *psych* package) using default minimum residual factoring (*minres*) and oblique rotation allowing for sub-factors to correlate. The *minres* factoring method is recommended for questionnaire data (Fabrigar et al., 1999) since it gives robust estimates even for skewed items, whereas correlation among emerging sub-factors was justified by our theoretical assumption of one underlying construct.

3.4.2.4.2 Structural validity. Having multiple items can lead to an emergent sub-factor structure if item topics and wordings result in correlated response behaviour. The current scale, however, was constructed to measure a general factor of trait curiosity due to lacking a strong theoretical basis for assuming multi-dimensionality of curiosity in early childhood. Here, we explored the scale's dimensionality to support the computation of an overall curiosity mean score (following Dunn & McCray, 2020) by fitting the previously identified sub-factor structure using Structural Equation Modelling (SEM; function "sem" from the *lavaan* package; Rosseel, 2012). This allowed us to compare three possible ways of defining the scale's dimensionality: a unidimensional model, a correlate model of sub-factors, and a bi-factor model in which each item loads onto a general factor beyond which the subfactors capture additional variance among the items. Due to the expected occurrence of missing values (N/A responses for not yet or not recently observed behaviours), models were specified to estimate the 'full information maximum likelihood' across all observations. Furthermore, due to heavily skewed responses, we included a robust maximum likelihood estimator, which corrects the standard errors and test statistics but does not change the estimates. Model comparison included standard indices such as chi-square, comparative fit index (CFI), Root Mean Square Error of Approximation (RMSEA), and Bayesian Information Criterion (BIC), to inform whether the scale was unidimensional enough to allow for the valid computation of an overall mean score in future empirical applications.

3.4.2.4.3 Internal consistency. For the final set of items, commonly reported measures of internal consistency were computed, namely Cronbach's alpha, Revelle's Omega total, and Guttman's lambda (McNeish, 2018, using "omega" from the *psych* package), as well as Revelle's coefficient Beta. Revelle's Beta estimates how much variation in the data can be attributed to some general underlying factor (Cooksey & Soutar, 2006), so that a general factor can be argued at beta values above .50, whereas values above .70 are recommended (John & Roedder, 1981; Revelle, 1979; Rossiter, 2002). Regarding the other three measures, values above .80 are considered good (but are said to be acceptable above .70 when not meant for diagnostic decisions; Pett et al., 2003) and the average Inter-item correlation is ideally between .20 and .40 (Piedmont, 2014).

3.4.2.4.4 Exploration of mean scores. We explored whether mean scores systematically differed across sex and age to inform future applications of the scale. Mean scores were only computed across the remaining, applicable items, so that unobserved items (N/A responses) did not affect them. To test the difference between sexes, we first identified and removed nine outliers based on group specific interquartile range (IQR method; identifying five male responses and four female responses) and checked the assumptions of normality and homogeneity of variance. While the score distribution did not meet the assumption of normality, the independent samples t-test in large samples such as this is considered robust against departures from normality. Furthermore, the assumption of homogeneity of variance between the groups was met, so that we computed an independent samples t-test, expecting no systematic difference. We then computed, due to non-normality, a non-parametric Spearman rank correlation between the mean score and infant age, expecting no significant relationship. Lastly, we computed Spearman correlations between the overall mean scores and the two additional curiosity items as an initial indication of construct validity, expecting positive relationships. All analyses were conducted in R (Version 4.1.2).

3.4.3 Results

3.4.3.1 Item reduction and emerging sub-factors

We first reverse coded the three negatively formulated items and computed a correlation matrix (using Spearman's rho) to investigate ill-fitting ones (e.g., Prett et al., 2003). This led to the exclusion of two items (5 and 21) which correlated negatively with many of the rest. Then we ensured that the data was adequately sampled and factorable as indicated by a significant Bartlett's test of sphericity ($X^2(496) = 3474.50$, $p < .001$), a non-zero, positive matrix's determinant (.00006), and the Kaiser-Meyer-Olkin statistic above 0.70 for both, the overall sample (KMO = 0.89) as well as each individual item (lowest measure of sampling adequacy (MSA) = 0.82).

We then fitted a one-factor model on the remaining 32 items to further reduce the item list to only those loading onto a general factor. In this way, six additional items (1, 4R, 9, 14, 29R, and 36) with loadings below the recommended .32 (Tabachnick & Fidell, 2007) were eliminated. The subsequent exploration of emerging factors only included the 26 remaining items that loaded strongly and positively onto this general factor. Drawing a line through the lower values in the scree plot (Cattell, 1966; Pett et al., 2003; Figure in Supplemental Materials) suggested 3 or 4 factors. Similarly, the parallel analysis indicated four factors, whereas the "elbow" of both graphs already occurred at factor 3. Accordingly, we fitted a 3-factor and a 4-factor model.

The 4-factor model had overall better fit values (TLI = .89, RMSEA = .048, BIC = -921.22) than the 3-factor model (TLI = .87, RMSEA = .052, BIC = -978.39). However, upon inspection of the emerging sub-factors, both models were highly similar except for an additional two-item factor in the 4-factor model. As it has been argued that a meaningful factor should consist of at least three items (Hair et al., 2010), we decided to continue with the 3-factor model. Table 3.1 shows the items' sub-factor-loadings in comparison to their loadings on the general factor (item content can be found in Figure 3.2; excluded items in Supplementary Materials).

Table 3.1. Exploratory Factor loadings in a 1-Factor and 3-Factor structure.

	General Factor	3-Factor Model		
Item	1	1	2	3
Item 2	.39	.39		
Item 3	.40	.44		
Item 6	.34	**.61**		
Item 7	.41	.52		
Item 8	.40	.50		
Item 10	.42	.37		
Item 11	.44	.51		
Item 12	.54		.64	
Item 13	.57		**.70**	
Item 15	.32			
Item 17	.53	.45		
Item 18	.51			
Item 20	.32		.40	
Item 22	.54			.36
Item 24	.55			
Item 25	.42			
Item 26	.53			.66
Item 27	.43	.51		
Item 28	.47	.43		
Item 30	.54			.71
Item 31	.62		.33	
Item 32	.53			.38
Item 33	.46			.61
Item 34	.55			**.77**
Item 35	**.64**		.66	
Item 19R	.43	.36		

Notes. Loadings smaller than .32 are not reported, the strongest loading per factor is marked in bold. Italicised items are those that loaded onto the general factor but did not load sufficiently onto any sub-factor.

The first sub-factor (11 items) could be labelled as *Sensory Curiosity* as it includes items regarding more general manual and visual exploratory behaviours. The second sub-factor (5 items) could be labelled as *Investigative Curiosity* including items indicating a tendency to autonomously manipulate objects in their environment to gain information.

The third sub-factor (6 items) could be labelled as *Social Curiosity* capturing to what degree the child uses and interacts with social partners to receive additional information.

Four items did not sufficiently load onto any of these sub-factors. On inspection, three of these (15, 18, 25) concerned play behaviour more so than exploration which may explain their distinctness. However, item 24 (looking at others for help when confused) had one of the strongest loadings toward the general factor and also loaded onto the social exploration factor in the 4-factor model (at .41). As exploratory factor analysis is not meant to be a purely data-driven process, we decided to keep this item given its strong contribution to the general factor and its contextual fit with the social sub-factor (now 7 items) while excluding the other three. Thus, from here on analyses were conducted on the final set of 23 items (see Figure 3.1).

3.4.3.2 Structural validity

We fitted three structural equation models as described above to investigate the scale's dimensionality. Table 3.2 shows fit indices for model comparison. The bi-factor model had the best fit with the commonly reported fit indices having acceptable values (Dunn & McCray, 2020). The chi-square test was significant in all three models which is expected at larger sample sizes (Schermelleh-Engel et al., 2003; Vandenberg, 2006). The standardised factor loadings of the bi-factor model are presented in Figure 3.2 (see supplementary materials S3.2.2 for additional details). These results overall support the computation of a general mean score in line with the bi-factor model.

Table 3.2. Indices for the three specified models using Structural Equation Modelling (SEM).

Model	Unidimensional	Correlational	Bi-Factor
Chi-Square	$X^2(230, 370)=703.98^{***}$	$X^2(227,370)=457.14^{***}$	$X^2(207, 370)=373.57^{***}$
CFI[a]	.71	.86	.90
RMSEA[b]	.075[.069; .080]	.052[.046; .059]	.047[.039; .054]
AIC[c]	22468.58	22174.50	22103.66
BIC[d]	22738.61	22456.27	22463.70
adj. BIC[e]	22519.69	22227.84	22171.82

Note: *** p < .001; **a:** Comparative Fit Index (preferably ≥ .90); **b:** Root Mean Square Error of Approximation (preferably ≤ .060) and [95% Confidence Intervals]; **c:** Akaike Information Criterion; **d:** Bayesian Information Criterion; **e:** Sample-size adjusted BIC (all: smaller better)

A. Bi-Factor Model

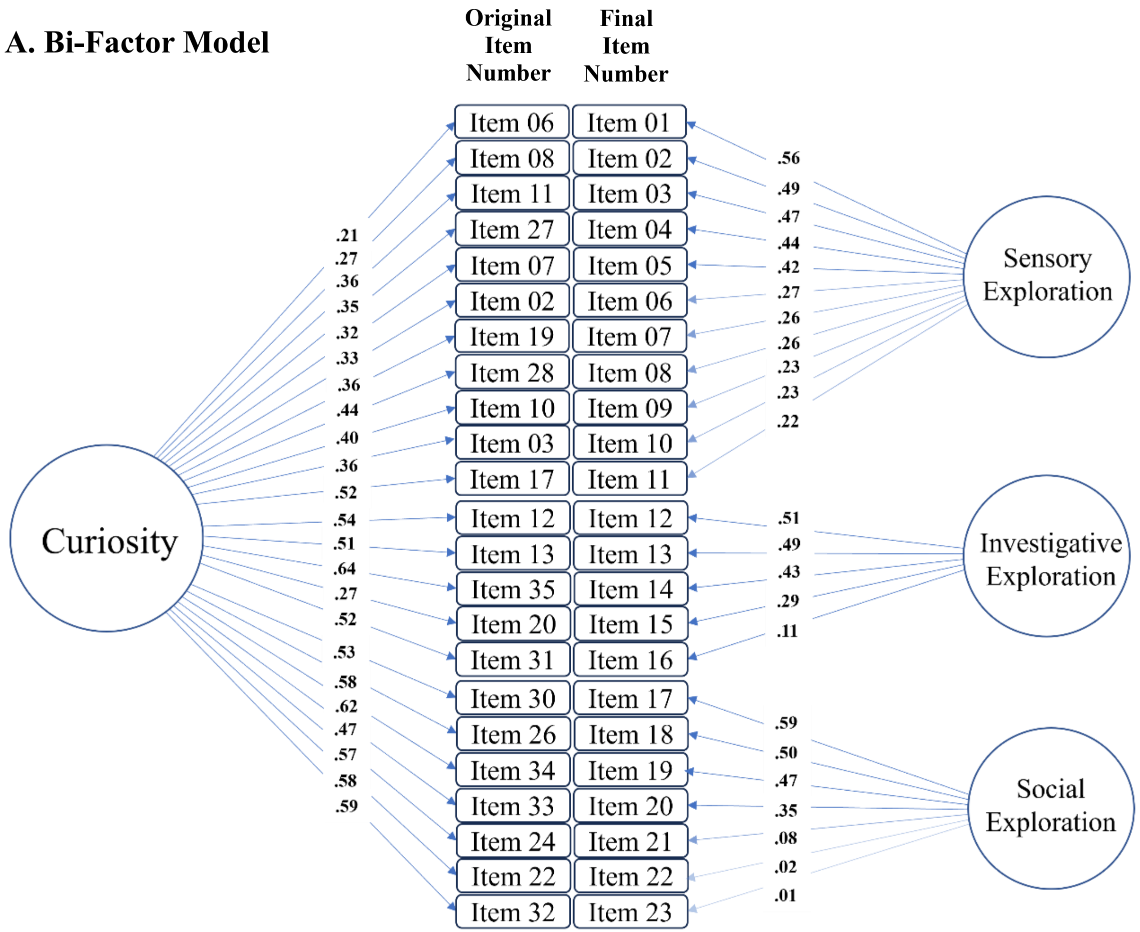


Figure 3.2. Final item list structured as **A**. the best fitting bi-factor model in order of their loadings on the emergent subfactors, providing original item number corresponding to the available analysis script, and **B.** the full items based on the final order as shown in **A.**

B. Final Item List

1. When my child encounters an object, they typically seem interested in its properties (e.g., how it feels, tastes, or sounds like, etc.).
2. My child actively inspects a variety of objects, whether it be toys or ordinary household items.
3. My child usually inspects objects from all angles and sides.
4. My child pokes at and probes objects to see how they feel.
5. My child is interested in a wide variety of objects.
6. My child likes to look around, scanning the environment for something new.
7.R My child does ***not*** typically engage with (look at, point at, reach for, inspect) a lot of things in their environment.
8. My child enthusiastically explores new environments (e.g., a new house, the beach, etc.).
9. My child is interested in what other people next to them are doing. For example, when someone prepares food, my child closely observes their every move.
10. My child shows visible enjoyment (e.g., smiling, gurgling, babbling) when discovering something new.
11. My child actively seeks out and enjoys new experiences.
12. When I open my bag in front of my child, they will come and peek into it.
13. When my child looks into a container (e.g., a bag, kitchen drawer, etc.), they take out and inspect each of its contents.
14. When something is hidden from my child (e.g., in closed boxes, rooms, cupboards etc.), they will actively try to uncover it.
15. My child often bangs objects to see what noise they make.
16. If a toy has multiple functions, my child will typically discover and play with more than one of them.
17. When reading a picture book together, my child directs me (e.g., by pointing) towards what they want to know more about.
18. When we are in a new environment (e.g., the zoo, a shop, etc.), my child keeps pointing at all the things they find interesting.
19. My child often leads me to/brings me things that they want to know more about.
20. When faced with a problem, my child will seek the help of others in order to solve it.
21. When my child is confused by something, they look at me/another person for additional information.
22. When someone shows my child how something works, they watch with continuous interest.
23. When faced with a problem (e.g., fitting a block into its respectively shaped hole), my child typically keeps trying to figure it out until they have solved it.

3.4.3.3 Internal consistency

We computed common measures of internal consistency for both the complete scale and the emergent sub-factors (Table 3.3). The overall scale was found to have high internal consistency, where a Revelle's beta of >.70 additionally supports our assumption of a general underlying factor. Furthermore, the separate subfactors also had good (>.70) indices supporting these data-driven options to explore additional variance in the sample. Consequently, we will consider them from here on out as subscales.

Table 3.3. Measures of internal consistency for the full scale and the emergent subscales.

Scale	Number of Items	Cronbach's α	Guttman's λ	Revelle's omega total	Revelle's β
General	23	.87	.90	.89	.71
Sensory	11	.78	.78		
Investigative	5	.74	.71		
Social	7	.81	.80		

3.4.3.4 Exploration of mean scores across sex and age

The mean curiosity scores were distributed around an average of $M = 5.87$ ($SD = .52$), evidencing that the scale captures variance in reported exploration tendencies (Figure 3.3). An independent samples t-test, in line with our expectations, did not find a significant differences between male ($M = 5.91$, $SD = .49$) and female ($M = 5.84$, $SD = .55$) curiosity scores ($t(359) = -1.20$, $p = .233$, $d = .13$). We then correlated the scores to age and found a significant positive correlation ($r_s = .35$, $p < .001$) so that older children received on average higher scores. As this was not in line with our expectations, we exploratorily correlated age with each of the subscales which revealed that this age relation was strongest for social curiosity scores ($r_s = .48$, $p < .001$), somewhat smaller for investigative curiosity scores ($r_s = .34$, $p < .001$), and non-significant for sensory curiosity scores ($r_s = .08$, $p = .129$). Additionally, we found that the age relation with the overall mean score disappeared from the age of 13 months ($r_s = .12$, $p = .146$). Lastly, the overall mean scores and the two single curiosity items were positively correlated (direct item: r_s = .41, $p < .001$; comparative item: r_s = .24, $p < .001$), offering a first indication of construct validity.

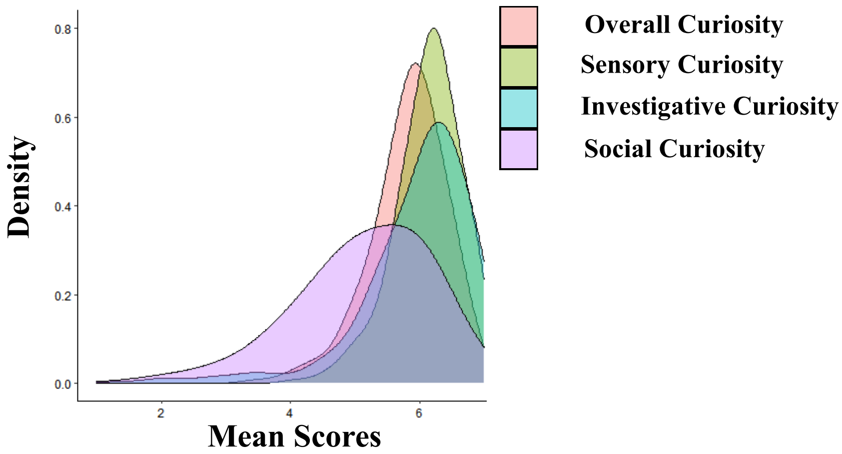


Figure 3.3. Density plots of overall curiosity mean scores as well as the curiosity subscale scores.

3.4.4 Interim Discussion

In this first study, we described the development of the ITCQ: from creating an initial set of items capturing various behaviours with which infants and toddlers can explore and interact with their environment to the final set of 23 items comprising this internally consistent and structurally valid measure of trait curiosity. An initial pilot study provided evidence for the scale's content validity. The subsequent main analysis included 370 responses across an age range from 5 to 24 months and offered sufficient evidence for the scale's unidimensionality to justify the computation of an overall mean score, along with three emergent subscales which could explain additional variance in the data. These subscales seemed to capture different types of curiosity based on their manifestation in broader, sensory exploration, more focused, investigative exploration, and exploration by using social others to gain information. While high internal consistency for the full scale further supported the computation of an overall curiosity score, good indicators for the subscales also made those an option for exploratory analyses.

We then investigated the distribution of mean scores which did not systematically differ between males and females. However, they did increase with age, specifically in very young infants between the ages of 5 and 12 months. This could be due to the items covering various exploratory behaviours which develop across the first two years of life and are thus bound to increase with time, making parental observations more robust and caregivers more confident in their indicated agreement with the scale's items. The differential correlations between age and the subscales (sensory < investigative < social) and disappearance of the effect for ages from 13 months lend support to this notion. Therefore, this effect should be controlled for in cross-sectional studies including younger infants. In longitudinal studies, we would expect to find rank stability in curiosity scores across development (more curious children stay more curious) which would also validate the scale's temporal consistency.

3.5 Study 2: Test-retest Reliability

Another important aspect of a scale's validation is test-retest reliability which indicates the clarity of the items via the responses' temporal stability (Crocker & Algina, 1986). If items are well constructed to capture observable behaviour that reflects the child's general tendencies, the responses should be consistent with each other. Here, the retest timeframe was set to 7 to 14 days so that participants were unlikely to remember their previous responses and the child would not have experienced a leap in behavioural development.

3.5.1 Methods

3.5.1.1 Participants

As mentioned previously, participants who provided consent and email address at the end of the survey were automatically contacted through Qualtrics one week after their initial response. From the participants included in the main analysis in Study 2, we collected $N = 67$ test-retest responses completed within 7-14 days ($M = 7.61$, $SD = 1.19$) of the first measurement. Three additional responses were excluded due to longer timeframes (18, 46, and 144 days, respectively). Babies of the final 67 responders were typically developing and representative of the full sample (age in months at first timepoint: $M = 12.7$, $SD = 5.1$, range: 5.1 – 24.2; 58% female). Caregivers provided consent to proceed to the questionnaire items and completed this second measurement without any additional reward or compensation. Responses were matched via anonymous identification numbers, imbedded in the automatic emails.

3.5.1.2 Materials

The test-retest version of the full questionnaire included the original 36 items as well as the two curiosity questions. However, we conducted all analyses using only the final 23 items based on the results from Study 1.

3.5.1.2.1 Analyses. Test-retest reliability was investigated in two ways: how consistently participants responded to each item (using the function "testRetest" from the *psych* package; (Revelle, 2023), as well as the Intraclass Correlation Coefficient (ICC) of mean scores (using the function "icc" from the *irr* package; Gamer et al., 2019). The first analysis implemented the data's multi-level structure to provide reliability indices for items and participants over time and indicated variance for each of these components and their interactions. Furthermore, we specified the ICC of mean scores as a two-way mixed effect model with absolute agreement and single unit analysis as suggested by the literature (e.g., Koo & Li, 2016). Historically, ICC scores have been considered as *poor* at values smaller than .5, as *moderate* between .5 and .75, as *good* between .75 and .9, and as *excellent* above .9.

3.5.2 Results

We found good internal consistency at both timepoints (T1: Cronbach's $\boldsymbol{\alpha}$ = .87, Guttman's $\boldsymbol{\lambda}$ = .94; T2: $\boldsymbol{\alpha}$ = .88, $\boldsymbol{\lambda}$ = .96), indicating that the items correlated with each other to a similar extent. Furthermore, item scores were correlated across measurements at $r = .86$ ($p < .001$). The mean within-subject test-retest reliability of response patterns over items and time was good ($rqq = .79$) as was the reliability of all ratings across items and times ($RkF = .97$) (Revelle, 2023; Shrout & Lane, 2012). Multilevel components of variance further showed that most of the variance in scores could be attributed to the items (44%), participants (13%), and the interaction between items and participants (23%). Little to no variance, however, was attributed to time effects (time: 0%; participant*time interaction: 0.1%; items*time interaction: 0%). This suggests that participants responded to items with sufficient temporal stability to support the scale's test-retest reliability. A good ICC of mean scores seconded this finding (ICC(A, 1) = .82; $F(66,47.9) = 11.3$, $p < .001$; 95%CI=[0.72; 0.89]).

3.5.3 Interim Discussion

Both measures supported the scale's temporal stability indicating that the items were well constructed to allow for reliable responses. Future research should increase the timespan between measurements to investigate the measure's longitudinal rank stability.

3.6 Study 3: Criterion Validity

Another source of validity evidence (Downing, 2003) is the measure's relationship to other variables. This includes correlating them with scores of other existing measures with well-known characteristics. Therefore, we decided to compare the new scale to facets of temperament as we would expect them to be related yet distinct. It had furthermore previously been stated that an established relation between a curiosity measure and temperament would support the notion of it capturing curiosity as a trait (Piotrowski et al., 2014).

Temperament is viewed as an early equivalent to adult personality traits, and its measures (Infant Behavior Questionnaire or IBQ; Early Child Behavior Questionnaire or ECBQ) have been shown to be reliable, valid, and informative both in personality related research but also for predicting behavioural outcomes (e.g., Putnam et al., 2008; Rothbart, 1986, 2011), making them appropriate measures for exploring the ITCQ's criterion validity. Here, we related the curiosity responses to the age-specific version of the temperament measure as our age-range covered both the IBQ and the ECBQ's age ranges.

3.6.1 Methods

3.6.1.1 Participants

Caregivers of a sample of N = 75 children (age in months: M = 14.1, SD = 4.5, range: 6.5-24.2; 50.7% female) completed the survey, two thirds of which indicated to have a degree in higher education. A subsample of respondents was recruited directly from the Babylab's database, and thus, received £5 as reimbursement in the form of an online gift voucher of their choice (n = 55). The rest (n = 20) completed the temperament survey without additional rewards after their in-person study visit for which they had received £5 travel reimbursement and a book for the child. Participants provided written consent prior to answering any questions.

3.6.1.2 Materials

While the full temperament measure consists of around 200 items across multiple facets of temperament, the "very short form" versions (IBQ-vsf and ECBQ-vsf) each consists of 36 items evaluated on a 7-point Frequency-scale from 1 ("Never") to 7 ("Always") and an option of "NA - not applicable", which have been validated to capture three broader dimensions: Surgency, Negative Affect, and Effortful Control (e.g., Putnam et al., 2010, 2014). Surgency items capture facets such as Approach, High Intensity Pleasure, Activity Level, and Perceptual Sensitivity, making this factor comparable to the personality dimension of *Extraversion*. Negative Affect items capture levels of Sadness, Distress to Limitations, and Fear, making this factor comparable to the personality dimension of *Neuroticism*. Lastly, Effortful Control items capture Duration of Orienting, and levels of Low Intensity Pleasure, Cuddliness, and Soothability, making this factor comparable to the personality dimension of *Conscientiousness*.

Participants first completed the full ITCQ, followed by either the very short form of the IBQ or ECBQ depending on the child's age: IBQ if the child was between 5 and 12 months old and the ECBQ for ages 13 months and over.

3.6.1.3 Hypotheses

The temperament scales mostly capture how the child typically reacts to certain situations, whereas the ITCQ mostly captures infant-initiated exploratory behaviours. As behavioural expressions may well be affected by how the child reacts to certain situations, we expected the temperamental facets to differentially correlate with the curiosity scores, while also being distinct from one another – meaning that at most we would observe moderate effect sizes (e.g., Nunnally & Bernstein, 1994). First, we expected Surgency to positively correlate with curiosity, as a more extraverted child may exhibit more exploratory behaviours across contexts. Second, we expected Negative Affect to negatively correlate with curiosity, as a more fearful and distressed child may exhibit fewer exploratory behaviours across contexts. Lastly, we did not have a clear prediction on how Effortful Control may correlate with curiosity but could hypothesise a positive relation with longer exploratory engagement.

3.6.1.4 Analyses

We computed mean scores for all scales (exploratorily also for the curiosity subscales) and conducted Spearman correlations between the temperament and curiosity scores. We treated scores from the IBQ and ECBQ equally, as items form into the same three dimensions and because of their assessed longitudinal stability (Putnam et al., 2008; Rothbart, 1986).

3.6.2 Results

Correlations between the facets of temperament and curiosity are shown in Table 3.4. We found significant, positive correlations of moderate effect sizes between both surgency as well as effortful control and the mean curiosity score. Exploratory correlations with the curiosity subscales revealed these to be strongest for the sensory exploration tendencies.

Additionally, we found a negative correlation between curiosity and negative affect scores. This relation seemed to be mainly driven by lower social exploration tendencies so that young children reported to be more fearful and distressed were especially unlikely to interact with social others in the pursuit of information.

Table 3.4. Spearman correlation matrix between curiosity and temperament mean scores.

	Overall Curiosity	**Sensory Exp.**	**Investigative Exp.**	**Social Exp.**
Surgency	**0.39*****	**0.47*****	**0.31****	0.16
Negative Affect	-0.27*	-0.24*	-0.14	**-0.3****
Effortful Control	0.25*	**0.3****	0.17	0.08

Note. $p < .001$ '***', $p < .01$ '**', $p < .05$ '*'

3.6.3 Interim Discussion

We investigated how the ITCQ related to other early traits measures, more specifically facets of temperament, to obtain evidence of its criterion validity. We found significant correlations of moderate effect size between all three temperament dimensions and overall curiosity, where the subscales offered additional insights. The negative correlation between curiosity and negative affect, that is, being more fearful and distressed, is in line with previous research in adults that showed anxiety to be negatively associated with epistemic curiosity (Collins et al., 2004; Kashdan & Roberts, 2004;

Litman & Jimerson, 2004; Litman & Spielberger, 2003; Naylor, 1981). Additionally, we observed the strongest negative correlation with social exploration which is consistent with the idea that neuroticism may specifically inhibit social interactions and respective exploratory behaviours (Green & Campbell, 2000). Together, these results provide evidence that curiosity and facets of temperament are related but still capture unique characteristics of the child's personality.

3.7 General Discussion

Recognising the need to measure individual differences in trait curiosity in infants and toddlers, we developed the Infant and Toddler Curiosity Questionnaire (ITCQ) as the first caregiver report measure to assess trait curiosity in this targeted age group, with items capturing observable exploration behaviours specific to infants and toddlers between 5 and 24 months of age. Across three studies we reported evidence for the scale's reliability and validity, suggesting that the ITCQ could become a powerful tool for developmental research.

The first study focused on the initial questionnaire development leading to a final set of 23 items, selected based on internal consistency and exploratory factor analyses. Three methodologically emergent sub-factors captured additional co-variance among the items and developmental exploration skills: sensory curiosity, investigative curiosity, and using social others to gain new information. The well-fitting bi-factor model using structural equation modelling offered sufficient evidence that the scale is unidimensional enough (Dunn & McCray, 2020) to justify the computation of an overall mean score. As both the full scale but also each of the sub-factors had good measures of internal consistency, we considered these sub-factors as curiosity subscales. Together, this work offers multiple avenues to disentangle effects of trait curiosity but also of specific types of curiosity. The second study then showed that the final scale had good test-retest reliability after 7 to 14 days.

Lastly, study three indicated criterion validity as the ITCQ scores were significantly related to the well-established trait measure of temperament (Putnam et al., 2014). Here, we found positive correlations between curiosity and surgency, which is considered a precursor of extraversion, as well as curiosity and effortful control, a precursor of conscientiousness. In contrast, curiosity negatively correlated with negative affect, a precursor of neuroticism. Together, these findings are in line with theoretical considerations as well as previous adult research (e.g., Collins et al., 2004; Kashdan & Roberts, 2004; Litman & Jimerson, 2004; Litman & Spielberger, 2003; Naylor, 1981), so that a child who is more extraverted would score more highly across the wide variety of exploration behaviours captured in the new scale compared to a child who is generally more fearful. Crucially, the correlations were of only medium effect sizes, supporting the constructs to be related yet distinct.

3.7.1 Limitations & future research

Questionnaire development is a strenuous process for which there is no gold-standard as evidenced by numerous open discussions. Using the best practices as a guide, we created and assessed the ITCQ to be a reliable and valid measure (Downing, 2003; Dunn & McCray, 2020; Pett et al., 2003). Yet, future studies are needed to collect multiple independent samples replicating these findings as well as longitudinal data to establish temporal stability of the trait measure, and its convergent validity to other measures of early curiosity (Lee et al., 2023), problem solving (Hoicka et al., 2023) or observation-based curiosity scores (Fortner-wood & Henderson, 1997). Nevertheless, our reported studies here suggest that the ITCQ is a promising measure for application in psychological research to potentially explain variance in observed exploration behaviours (e.g., Mandler et al., 1987; Piccardi et al., 2020; Slone et al., 2019; Smith & Yu, 2013) as well as developmental trajectories (e.g., Berg & Sternberg, 1985; Bornstein et al., 2013; Muentener et al., 2018; Shah et al., 2018). In fact, preliminary reports of our measure have already gained international interest so that a German and Dutch version of the ITCQ are currently undergoing validation, and a child version for 2–5-year-olds is also being developed (Altmann, et al., 2023b).

3.7.2 Conclusion

In this paper, we present the development of a newly constructed caregiver report questionnaire (ITCQ) and showcase that it effectively captures early exploration tendencies as a manifestation of individual differences in infants' and toddlers' trait curiosity. Importantly, the ITCQ fills an important gap in the scientific landscape of infancy research. Across three studies we demonstrated evidence for the measure's reliability and validity following rigorous practice to ensure that future applications of the ITCQ will offer new and powerful insights into early human development.

3.8 References

Ackermann, L., Hepach, R., & Mani, N. (2020). Children learn words easier when they are interested in the category to which the word belongs. *Developmental Science*, *23*(3). https://doi.org/10.1111/desc.12915

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*, 141–164.

Altmann, E. C., Bazhydai, M., & Westermann, G. (2023). *Curious Choices: Infants' moment-to-moment information sampling is driven by their exploration history*. PsyArXiv. https://doi.org/10.31234/osf.io/7d28k

Altmann, E. C., de Boer, E., Eiteljoerge, S., Bazhydai, M., Hunnius, S., Bounia-Mastrogianni, P., Meyer, M., Karadağ, D., Braithwaite, E. K., & Westermann, G. (2023b, August 23). *The Development of the Early Child Curiosity Questionnaire (ECCQ)*. [Poster Presentation] 8th Lancaster Conference on Infant & Early Child Development, Lancaster, UK.

Artino Jr, A. R., La Rochelle, J. S., Dezee, K. J., & Gehlbach, H. (2014). Developing questionnaires for educational research: AMEE Guide No. 87. *Medical Teacher*, *36*(6), 463–474.

Bazhydai, M., Twomey, K., & Westermann, G. (2021). Curiosity and Exploration. In J. B. Benson (Ed.), *Encyclopedia of Infant and Early Childhood Development* (2nd ed; Issue 2nd ed). Elsevier. https://eprints.lancs.ac.uk/id/eprint/136590/

Bazhydai, M., Westermann, G., & Parise, E. (2020). "I don't know but I know who to ask": 12-month-olds actively seek information from knowledgeable adults. *Developmental Science*, *23*(5), e12938. https://doi.org/10.1111/desc.12938

Begus, K., Gliga, T., & Southgate, V. (2014). Infants Learn What They Want to Learn: Responding to Infant Pointing Leads to Superior Learning. *PLoS ONE*, *9*(10), e108817. https://doi.org/10.1371/journal.pone.0108817

Berg, C. A., & Sternberg, R. J. (1985). Response to novelty: Continuity versus discontinuity in the developmental course of intelligence. *Advances in Child Development and Behavior*, *19*, 1–47.

Berlyne, D. E. (1960). *Conflict, arousal, and curiosity* (pp. xii, 350). McGraw-Hill Book Company. https://doi.org/10.1037/11164-000

Boley, B. B., Jordan, E., & Woosnam, K. M. (2021). Reversed polarity items in tourism scales: Best practice or dimensional pitfall? *Current Issues in Tourism*, *24*(4), 466–478.

Bornstein, M. H., Hahn, C.-S., & Suwalsky, J. T. D. (2013). Physically Developed and Exploratory Young Infants Contribute to Their Own Long-Term Academic Achievement. *Psychological Science*, *24*(10), 1906–1917. https://doi.org/10.1177/0956797613479974

Bornstein, M. H., & Putnick, D. L. (2012). Stability of Language in Childhood: A Multi-Age, -Domain, -Measure, and -Source Study. *Developmental Psychology*, *48*(2), 477–491. https://doi.org/10.1037/a0025889

Byman, R. (2005). Curiosity and sensation seeking: A conceptual and empirical examination. *Personality and Individual Differences*, *38*(6), 1365–1379. https://doi.org/10.1016/j.paid.2004.09.004

Can, D. D., Ginsburg-Block, M., Golinkoff, R. M., & Hirsh-Pasek, K. (2013). A long-term predictive validity study: Can the CDI Short Form be used to predict language and early literacy skills four years later? *Journal of Child Language*, *40*(4), 821–835. https://doi.org/10.1017/S030500091200030X

Cattell, R. B. (1966). The Scree Test For The Number Of Factors. *Multivariate Behavioral Research*, *1*(2), 245–276. https://doi.org/10.1207/s15327906mbr0102_10

Chen, X., Twomey, K. E., & Westermann, G. (2022). Curiosity enhances incidental object encoding in 8-month-old infants. *Journal of Experimental Child Psychology*, *223*, 105508. https://doi.org/10.1016/j.jecp.2022.105508

Collins, R. P., Litman, J. A., & Spielberger, C. D. (2004). The measurement of perceptual curiosity. *Personality and Individual Differences*, *36*(5), 1127–1141. https://doi.org/10.1016/S0191-8869(03)00205-8

Colombo, J., Mitchell, D. W., Coldren, J. T., & Freeseman, L. J. (1991). Individual Differences in Infant Visual Attention: Are Short Lookers Faster Processors or Feature Processors? *Child Development*, *62*(6), 1247–1257. https://doi.org/10.2307/1130804

Cooksey, R. W., & Soutar, G. N. (2006). Coefficient beta and hierarchical item clustering: An analytical procedure for establishing and displaying the dimensionality and homogeneity of summated scales. *Organizational Research Methods*, *9*(1), 78–98.

Crocker, L., & Algina, J. (1986). *Introduction to Classical and Modern Test Theory.* Holt, Rinehart and Winston, 6277 Sea Harbor Drive, Orlando, FL 32887 ($44.75). https://eric.ed.gov/?id=ed312281

Day, H. I. (1971). *Intrinsic Motivation: A New Direction in Education.*

Downing, S. M. (2003). Validity: On the meaningful interpretation of assessment data. *Medical Education*, *37*(9), 830–837.

Dunn, K. J., & McCray, G. (2020). The Place of the Bifactor Model in Confirmatory Factor Analysis Investigations Into Construct Dimensionality in Language Testing. *Frontiers in Psychology*, *11*. https://www.frontiersin.org/articles/10.3389/fpsyg.2020.01357

Fabrigar, L. R., Wegener, D. T., MacCallum, R. C., & Strahan, E. J. (1999). Evaluating the use of exploratory factor analysis in psychological research. *Psychological Methods*, *4*(3), 272.

Feldman, H. M., Dale, P. S., Campbell, T. F., Colborn, D. K., Kurs-Lasky, M., Rockette, H. E., & Paradise, J. L. (2005). Concurrent and Predictive Validity of Parent Reports of Child Language at Ages 2 and 3 Years. *Child Development*, *76*(4), 856–868. https://doi.org/10.1111/j.1467-8624.2005.00882.x

Fenson, L. (2002). *MacArthur Communicative Development Inventories: User's guide and technical manual*. Paul H. Brookes.

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., Pethick, S. J., Tomasello, M., Mervis, C. B., & Stiles, J. (1994). Variability in Early Communicative

Development. *Monographs of the Society for Research in Child Development*, *59*(5), i–185. https://doi.org/10.2307/1166093

Fenson, L., Marchman, V. A., Thal, D. J., Dale, P. S., Reznick, J. S., & Bates, E. (2006). *MacArthur-Bates Communicative Development Inventories, Second Edition*. https://doi.org/10.1037/t11538-000

Flake, J. K., & Fried, E. I. (2020). Measurement Schmeasurement: Questionable Measurement Practices and How to Avoid Them. *Advances in Methods and Practices in Psychological Science*, *3*(4), 456–465. https://doi.org/10.1177/2515245920952393

Fortner-wood, C., & Henderson, B. B. (1997). Individual Differences in Two-Year-Olds' Curiosity in the Assessment Setting and in the Grocery Store. *The Journal of Genetic Psychology*, *158*(4), 495–497. https://doi.org/10.1080/00221329709596686

Franchak, J. M., Heeger, D. J., Hasson, U., & Adolph, K. E. (2016). Free Viewing Gaze Behavior in Infants and Adults. *Infancy*, *21*(3), 262–287. https://doi.org/10.1111/infa.12119

Gamer, M., Lemon, J., & Singh, I. F. P. (2019). *irr: Various Coefficients of Interrater Reliability and Agreement* (0.84.1) [Computer software]. https://cran.r-project.org/web/packages/irr/index.html

Goupil, L., & Proust, J. (2023). Curiosity as a metacognitive feeling. *Cognition*, *231*, 105325. https://doi.org/10.1016/j.cognition.2022.105325

Green, J. D., & Campbell, W. K. (2000). Attachment and Exploration in Adults: Chronic and Contextual Accessibility. *Personality and Social Psychology Bulletin*, *26*(4), 452–461. https://doi.org/10.1177/0146167200266004

Grossnickle, E. M. (2016). Disentangling Curiosity: Dimensionality, Definitions, and Distinctions from Interest in Educational Contexts. *Educational Psychology Review*, *28*(1), 23–60. https://doi.org/10.1007/s10648-014-9294-y

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of Curiosity Modulate Hippocampus-Dependent Learning via the Dopaminergic Circuit. *Neuron*, *84*(2), 486–496. https://doi.org/10.1016/j.neuron.2014.08.060

Hair, J. F., Black, W. C., & Babin, B. J. (2010). *Multivariate Data Analysis: A Global Perspective*. Pearson Education.

Hardy, J. H., Ness, A. M., & Mecca, J. (2017). Outside the box: Epistemic curiosity as a predictor of creative problem solving and creative performance. *Personality and Individual Differences*, *104*, 230–237. https://doi.org/10.1016/j.paid.2016.08.004

Harty, H., & Beall, D. (1984). Toward the development of a children's science curiosity measure. *Journal of Research in Science Teaching*, *21*(4), 425–436. https://doi.org/10.1002/tea.3660210410

Hoicka, E., Powell, S., Rose, S. E., Reindl, E., & Tennie, C. (2023). The Early Independent Problem Solving Survey (EIPSS): Its psychometric properties in children aged 12–47 months. *Cognitive Development*, *68*, 101366. https://doi.org/10.1016/j.cogdev.2023.101366

Jirout, J., & Klahr, D. (2012). Children's scientific curiosity: In search of an operational definition of an elusive concept. *Developmental Review*, *32*(2), 125–160. https://doi.org/10.1016/j.dr.2012.04.002

John, G., & Roedder, D. L. (1981). Reliability assessment: Coefficients alpha and beta. *The Changing Marketing Environment: New Theories and Applications*, 354–357.

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T., & Camerer, C. F. (2009). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. *Psychological Science*, *20*(8), 963–973. https://doi.org/10.1111/j.1467-9280.2009.02402.x

Kashdan, T. B., Disabato, D. J., Goodman, F. R., & McKnight, P. E. (2020). The Five-Dimensional Curiosity Scale Revised (5DCR): Briefer subscales while separating overt and covert social curiosity. *Personality and Individual Differences*, *157*, 109836. https://doi.org/10.1016/j.paid.2020.109836

Kashdan, T. B., Gallagher, M. W., Silvia, P. J., Winterstein, B. P., Breen, W. E., Terhar, D., & Steger, M. F. (2009). The curiosity and exploration inventory-II: Development, factor structure, and psychometrics. *Journal of Research in Personality*, *43*(6), 987–998. https://doi.org/10.1016/j.jrp.2009.04.011

Kashdan, T. B., & Roberts, J. E. (2004). Trait and State Curiosity in the Genesis of Intimacy: Differentiation From Related Constructs. *Journal of Social and Clinical Psychology*, *23*(6), 792–816. https://doi.org/10.1521/jscp.23.6.792.54800

Kashdan, T. B., & Yuen, M. (2007). Whether highly curious students thrive academically depends on perceptions about the school learning environment: A study of Hong Kong adolescents. *Motivation and Emotion*, *31*(4), 260–270. https://doi.org/10.1007/s11031-007-9074-9

Kidd, C., & Hayden, B. Y. (2015). The Psychology and Neuroscience of Curiosity. *Neuron*, *88*(3), 449–460. https://doi.org/10.1016/j.neuron.2015.09.010

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks Effect: Human Infants Allocate Attention to Visual Sequences That Are Neither Too Simple Nor Too Complex. *PLoS ONE*, *7*(5), e36399. https://doi.org/10.1371/journal.pone.0036399

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks Effect in Infant Auditory Attention. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12263

Klamer, A., Lando, A., Pinborg, A., & Greisen, G. (2005). Ages and Stages Questionnaire used to measure cognitive deficit in children born extremely preterm. *Acta Paediatrica*, *94*(9), 1327–1329. https://doi.org/10.1111/j.1651-2227.2005.tb02095.x

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Lee, N., Lazaro, V., Wang, J. J., Şen, H. H., & Lucca, K. (2023). Exploring individual differences in infants' looking preferences for impossible events: The Early Multidimensional Curiosity Scale. *Frontiers in Psychology*, *13*. https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1015649

Lépine, J., Gagnon, K., Prud'homme, J., Vinay, M. C., Doussau, A., Fourdain, S., Provost, S., Belval, V., Bernard, C., Gallagher, A., Poirier, N., & Simard, M.-N. (2022). Utility of the Ages and Stages Questionnaires 3rd Edition for Developmental Screening in Children with Surgically Repaired Congenital Heart Disease. *Developmental Neurorehabilitation*, *25*(2), 125–132. https://doi.org/10.1080/17518423.2021.1960918

Liszkowski, U., Carpenter, M., & Tomasello, M. (2007). Pointing out new news, old news, and absent referents at 12 months of age. *Developmental Science*, *10*(2), F1–F7. https://doi.org/10.1111/j.1467-7687.2006.00552.x

Litman, J. A., & Jimerson, T. L. (2004). The Measurement of Curiosity As a Feeling of Deprivation. *Journal of Personality Assessment*, *82*(2), 147–157. https://doi.org/10.1207/s15327752jpa8202_3

Litman, J. A., & Spielberger, C. D. (2003). Measuring Epistemic Curiosity and Its Diversive and Specific Components. *Journal of Personality Assessment*, *80*(1), 75–86. https://doi.org/10.1207/S15327752JPA8001_16

Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Development*, *71*(1), 137–144.

Loewenstein, G. (n.d.). *The Psychology of Curiosity: A Review and Reinterpretation*. 24.

Mandler, J. M., Fivush, R., & Reznick, J. S. (1987). The development of contextual categories. *Cognitive Development*, *2*(4), 339–354. https://doi.org/10.1016/S0885-2014(87)80012-6

Marchman, V. A., & Fernald, A. (2008). Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. *Developmental Science*, *11*(3), F9–F16. https://doi.org/10.1111/j.1467-7687.2008.00671.x

Maw, W. H., & Maw, E. W. (1968). Self-appraisal of Curiosity. *Journal of Educational Research*, *61*(10), 462–465. https://www.proquest.com/docview/1290479073/citation/8DA93BAA53CC409FPQ/1

Maw, W. H., & Maw, E. W. (1970). Self-Concepts of High- and Low-Curiosity Boys. *Child Development*, *41*(1), 123–129. https://doi.org/10.2307/1127394

McCoach, D. B., Gable, R. K., & Madura, J. P. (2013). Evidence Based on the Internal Structure of the Instrument: Factor Analysis. In D. B. McCoach, R. K. Gable, & J. P. Madura (Eds.), *Instrument Development in the Affective Domain: School and Corporate Applications* (pp. 109–161). Springer. https://doi.org/10.1007/978-1-4614-7135-6_4

McNeish, D. (2018). Thanks coefficient alpha, we'll take it from here. *Psychological Methods*, *23*(3), 412.

Messick, S. (1995). Validity of psychological assessment: Validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist*, *50*(9), 741.

Muentener, P., Herrig, E., & Schulz, L. (2018). The efficiency of infants' exploratory play is related to longer-term cognitive development. *Frontiers in Psychology*, *9*, 635.

Mussel, P. (2013). Intellect: A theoretical framework for personality traits related to intellectual achievements. *Journal of Personality and Social Psychology*, *104*(5), 885–906. https://doi.org/10.1037/a0031918

Mussel, P., Spengler, M., Litman, J. A., & Schuler, H. (2012). Development and validation of the German Work-Related Curiosity Scale. *European Journal of Psychological Assessment*, *28*(2), 109–117. https://doi.org/10.1027/1015-5759/a000098

Naylor, F. D. (1981). A State-Trait Curiosity Inventory. *Australian Psychologist*, *16*(2), 172–183. https://doi.org/10.1080/00050068108255893

Nunnally, J. C. (1978). An overview of psychological measurement. *Clinical Diagnosis of Mental Disorders: A Handbook*, 97–146.

Nunnally, J. C., & Bernstein, I. H. (1994). Psychometric Theory New York. *NY: McGraw-Hill*.

Olson, E. (1986). *Measurement of curiosity in junior high school students*.

Penney, R. K., & McCann, B. (1964). The Children's Reactive Curiosity Scale. *Psychological Reports*, *15*(1), 323–334. https://doi.org/10.2466/pr0.1964.15.1.323

Pett, M. A., Lackey, N. R., & Sullivan, J. J. (2003). *Making sense of factor analysis: The use of factor analysis for instrument development in health care research*. sage.

Piccardi, E. S., Johnson, M. H., & Gliga, T. (2020). Explaining individual differences in infant visual sensory seeking. *Infancy*, *25*(5), 677–698. https://doi.org/10.1111/infa.12356

Piedmont, R. L. (2014). Inter-item Correlations. In A. C. Michalos (Ed.), *Encyclopedia of Quality of Life and Well-Being Research* (pp. 3303–3304). Springer Netherlands. https://doi.org/10.1007/978-94-007-0753-5_1493

Piotrowski, J. T., Litman, J. A., & Valkenburg, P. (2014). Measuring Epistemic Curiosity in Young Children: Brief Report. *Infant and Child Development*, *23*(5), 542–553. https://doi.org/10.1002/icd.1847

Poli, F., Serino, G., Mars, R. B., & Hunnius, S. (2020). Infants tailor their attention to maximize learning. *Science Advances*, *6*(39), eabb5053. https://doi.org/10.1126/sciadv.abb5053

Putnam, S. P., Helbig, A. L., Gartstein, M. A., Rothbart, M. K., & Leerkes, E. (2014). Development and Assessment of Short and Very Short Forms of the Infant Behavior Questionnaire–Revised. *Journal of Personality Assessment*, *96*(4), 445–458. https://doi.org/10.1080/00223891.2013.841171

Putnam, S. P., Jacobs, J. F., Gartstein, M. A., & Rothbart, M. K. (2010). *Development and Assessment of Short and Very Short Forms of the Early Childhood Behavior Questionnaire*. [Poster] Annual International Conference on Infant Studies, Baltimore, MD.

Putnam, S. P., Rothbart, M. K., & Gartstein, M. A. (2008). Homotypic and heterotypic continuity of fine-grained temperament during infancy, toddlerhood, and early childhood. *Infant and Child Development*, *17*(4), 387–405. https://doi.org/10.1002/icd.582

Reio Jr., T. G., & Wiswell, A. (2000). Field investigation of the relationship among adult curiosity, workplace learning, and job performance. *Human Resource Development Quarterly*, *11*(1), 5–30.

Reio Jr., T. G., & Callahan, J. L. (2004). Affect, curiosity, and socialization-related learning: A path analysis of antecedents to job performance. *Journal of Business and Psychology*, *19*, 3–22.

Renner, B. (2006). Curiosity About People: The Development of a Social Curiosity Measure in Adults. *Journal of Personality Assessment*, *87*(3), 305–316. https://doi.org/10.1207/s15327752jpa8703_11

Revelle, W. (1979). Hierarchical cluster analysis and the internal structure of tests. *Multivariate Behavioral Research*, *14*(1), 57–74.

Revelle, W. (2023). *psych: Procedures for Psychological, Psychometric, and Personality Research* (2.3.9) [Computer software]. https://cran.r-project.org/web/packages/psych/index.html

Richter, J., & Janson, H. (2007). A validation study of the Norwegian version of the Ages and Stages Questionnaires. *Acta Paediatrica*, *96*(5), 748–752. https://doi.org/10.1111/j.1651-2227.2007.00246.x

Rosseel, Y. (2012). lavaan: An R package for structural equation modeling. *Journal of Statistical Software*, *48*, 1–36.

Rossing, B. E., & Long, H. B. (1981). Contributions of Curiosity and Relevance To Adult Learning Motivation. *Adult Education*, *32*(1), 25–36. https://doi.org/10.1177/074171368103200102

Rossiter, J. R. (2002). The C-OAR-SE procedure for scale development in marketing. *International Journal of Research in Marketing*, *19*(4), 305–335.

Rothbart, M. K. (1986). Longitudinal observation of infant temperament. *Developmental Psychology*, *22*(3), 356–365. https://doi.org/10.1037/0012-1649.22.3.356

Rothbart, M. K. (2011). *Becoming who we are: Temperament and personality in development*. Guilford Press.

Salazar, M. S. (2015). The dilemma of combining positive and negative items in scales. *Psicothema*, *27*(2), 192–199.

Salomonsson, B., & Sleed, M. (2010). The Ages & Stages Questionnaire: Social–Emotional: A validation study of a mother-report questionnaire on a clinical mother–infant sample. *Infant Mental Health Journal*, *31*(4), 412–431. https://doi.org/10.1002/imhj.20263

Schermelleh-Engel, K., Moosbrugger, H., & Müller, H. (2003). *Evaluating the Fit of Structural Equation Models: Tests of Significance and Descriptive Goodness-of-Fit Measures*. *8*(2).

Shah, P. E., Weeks, H. M., Richards, B., & Kaciroti, N. (2018). Early childhood curiosity and kindergarten reading and math academic achievement. *Pediatric Research*, *84*(3), Article 3. https://doi.org/10.1038/s41390-018-0039-3

Shrout, P. E., & Lane, S. P. (2012). Psychometrics. In *Handbook of research methods for studying daily life* (pp. 302–320). The Guilford Press.

Sijtsma, K. (2009). Over misverstanden rond Cronbachs alfa en de wenselijkheid van alternatieven. *Psycholoog*, *44*(11), 561.

Singh, L., Barokova, M. D., Baumgartner, H. A., Lopera-Perez, D. C., Omane, P. O., Sheskin, M., Yuen, F. L., Wu, Y., Alcock, K. J., & Altmann, E. C. (2023). A unified approach to demographic data collection for research with young children across diverse cultures. *Developmental Psychology*.

Slagt, M., Dubas, J. S., Deković, M., & van Aken, M. A. G. (2016). Differences in sensitivity to parenting depending on child temperament: A meta-analysis. *Psychological Bulletin*, *142*(10), 1068–1110. https://doi.org/10.1037/bul0000061.supp

Slone, L. K., Smith, L. B., & Yu, C. (2019). Self-generated variability in object images predicts vocabulary growth. *Developmental Science*, *22*(6), e12816. https://doi.org/10.1111/desc.12816

Smith, L. B., & Yu, C. (2013). Visual Attention Is Not Enough: Individual Differences in Statistical Word-Referent Learning in Infants. *Language Learning and Development*, *9*(1), 25–49. https://doi.org/10.1080/15475441.2012.707104

Spielberger, C. D. (1979). *State-trait personality inventory*.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*(6230), 91–94. https://doi.org/10.1126/science.aaa3799

Tabachnick, B. G., & Fidell, L. S. (2007). *Using Multivariate Statistics. Boston, MA: Pearso n Education*. Inc.

Twomey, K. E., & Westermann, G. (2018). Curiosity-based learning in infants: A neurocomputational approach. *Developmental Science*, *21*(4), e12629. https://doi.org/10.1111/desc.12629

Vandenberg, R. J. (2006). Introduction: Statistical and Methodological Myths and Urban Legends: Where, Pray Tell, Did They Get This Idea? *Organizational Research Methods*, *9*(2), 194–201. https://doi.org/10.1177/1094428105285506

Wagstaff, M. F., Flores, G. L., Ahmed, R., & Villanueva, S. (2021). Measures of curiosity: A literature review. *Human Resource Development Quarterly*, *32*(3), 363–389. https://doi.org/10.1002/hrdq.21417

Wass, S. V., & Smith, T. J. (2014). Individual Differences in Infant Oculomotor Behavior During the Viewing of Complex Naturalistic Scenes. *Infancy*, *19*(4), 352–384. https://doi.org/10.1111/infa.12049

Weijters, B., & Baumgartner, H. (2012). Misresponse to reversed and negated items in surveys: A review. *Journal of Marketing Research*, *49*(5), 737–747.

Wright, A. J., & Jackson, J. J. (2022). Childhood temperament and adulthood personality differentially predict life outcomes. *Scientific Reports*, *12*(1), Article 1. https://doi.org/10.1038/s41598-022-14666-0

S3 Supplementary Materials

The r-script and data to reproduce the analyses, as well as a Qualtrics template and paper-pen-version for the questionnaire have been made available on the OSF.

S3.1 Final Item List

Note: These are grouped by subscale, but we recommend presenting these items to participants in a randomized order, if possible.

S3.1.1 Infant and Toddler Curiosity Questionnaire (ITCQ)

Sensory curiosity subscale:

Item.1 When my child encounters an object, they typically seem interested in its properties (e.g., how it feels, tastes, or sounds like, etc.).

Item.2 My child actively inspects a variety of objects, whether it be toys or ordinary household items.

Item.3 My child usually inspects objects from all angles and sides.

Item.4 My child pokes at and probes objects to see how they feel.

Item.5 My child is interested in a wide variety of objects.

Item.6 My child likes to look around, scanning the environment for something new.

Item.7 **(R)** My child does ***not*** typically engage with (look at, point at, reach for, inspect) a lot of things in their environment.

Item.8 My child enthusiastically explores new environments (e.g., a new house, the beach, etc.).

Item.9 My child is interested in what other people next to them are doing. For example, when someone prepares food, my child closely observes their every move.

Item.10 My child shows visible enjoyment (e.g., smiling, gurgling, babbling) when discovering something new.

Item.11 My child actively seeks out and enjoys new experiences.

Investigative curiosity subscale:

Item.12 When I open my bag in front of my child, they will come and peek into it.

Item.13 When my child looks into a container (e.g., a bag, kitchen drawer, etc.), they take out and inspect each of its contents.

Item.14 When something is hidden from my child (e.g., in closed boxes, rooms, cupboards etc.), they will actively try to uncover it.

Item.15 My child often bangs objects to see what noise they make.

Item.16 If a toy has multiple functions, my child will typically discover and play with more than one of them.

Social curiosity subscale:

Item.17 When reading a picture book together, my child directs me (e.g., by pointing) towards what they want to know more about.

Item.18 When we are in a new environment (e.g., the zoo, a shop, etc.), my child keeps pointing at all the things they find interesting.

Item.19 My child often leads me to/brings me things that they want to know more about.

Item.20 When faced with a problem, my child will seek the help of others in order to solve it.

Item.21 When my child is confused by something, they look at me/another person for additional information.

Item.22 When someone shows my child how something works, they watch with continuous interest.

Item.23 When faced with a problem (e.g., fitting a block into its respectively shaped hole), my child typically keeps trying to figure it out until they have solved it.

S3.1.2 Additional Items

Excluded Items (original numbering)

Item.1 When I hold or move a toy or object in front of my child, they follow it with their eyes.

Item.4 R When my child is introduced to something new, they are often not very interested.

Item.5 When my child encounters an object, they are likely to put it in their mouth for further inspection (e.g., to see what it feels or tastes like).

Item.9 My child is constantly reaching for objects to explore.

Item.14 Once my child was able to crawl, they used this new skill to explore their environment on their own terms.

Item.15 My child starts playing on their own, rather than waiting to be given something to play with.

Item.18 When my child plays with an assembly toy (e.g., building blocks, puzzle, a toy with detachable parts), they like to take it apart for further examination.

Item.21 My child is usually happy to try new foods they haven't eaten before.

Item.25 When playing hide and seek, my child enjoys searching for the object or person that disappeared.

Item.29 R My child does not seem to care when we go somewhere new, they still prefer to engage with familiar objects they brought from home (e.g., their pacifier or favourite toy).

Item.36 My child is usually interested in new people.

Mirrored Items for attention

Item.16 R My child usually waits to be given a toy to play with, rather than start playing by themselves. *(Excluded due to positive version being excluded)*

Item.23 R When someone shows my child how something works, they are usually not very interested.

S3.2 Additional considerations regarding the response scale

As the response scale we decided on a 7-point Likert scale from 1 (“strongly disagree”) to 7 (“strongly agree”). We considered using a frequency scale from *never* to *always* which is used in several infant and early childhood questionnaires (e.g., temperament scales IBQ and ECBQ). While both agreement (that is, Likert) and frequency scales can be used to generate aggregate scores, it was found in a systematic review that agreement scales lead to better fit and response quality and that frequency scales can be problematic in their interpretation (Brown, 2004). Thus, we decided on the format of agreement.

As the questionnaire was administered online using the secure software Qualtrics (Qualtrics, Provo, UT), we also had to consider in which way the response options would be presented. Next to the more conventional “radio-button” responses (one for each scale-point), a “slider” was discussed where caregivers could indicate their level of agreement anywhere between 0 and 100. While reviews suggest that such sliders can be more engaging with comparable data quality, they are in fact more time-intensive and can lead to frustration (Sikkel et al., 2014) and higher drop-out rates (Couper et al., 2006; Cook et al., 2001). Furthermore, they seem to add cognitive complexity which would not be recommended for wider representation of the caregiver population (e.g., Funke et al., 2014; Stanley & Jenkins, 2007). Based on these considerations, we decided to implement a conventional 7-point Likert scale with a button for each response option.

S3.2.1 Number of exploratory factors

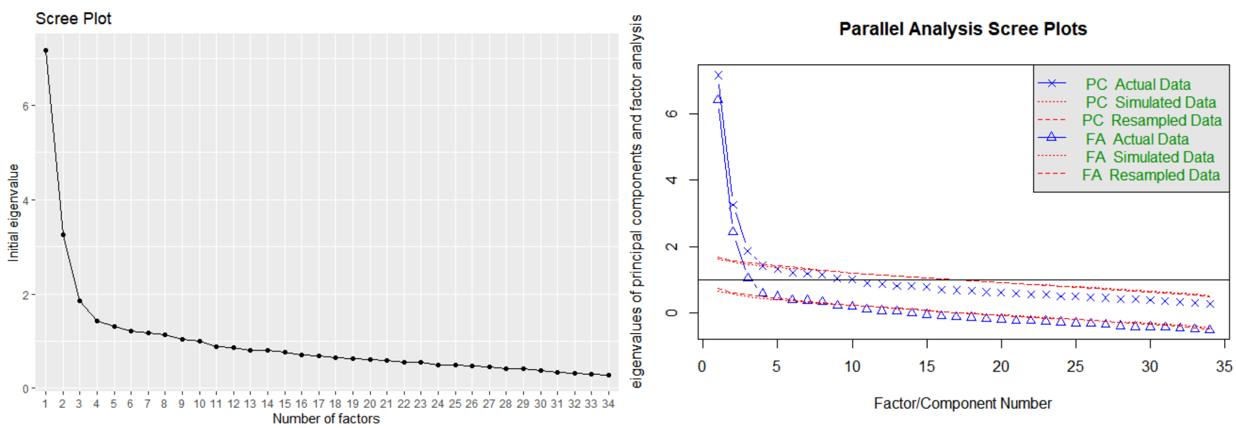


Figure S3.1 Scree plot & parallel analysis to determine the adequate number of factors suggesting 3 or 4 factors as indicated by their explanatory eigenvalues and the “elbow” in the graphs.

S3.2.2 Additionally suggested modifications to the Bi-factor model

Using structural equation modelling, one can also receive suggestions for modifications that would improve model fit even further. Here, we included suggestions with the five highest modification indices and relating to covariances among items. These were possibly due to similarities in content or wording as they included additional four covariances between items 17 and 28 (“new”), 10 and 22 (“observing others”), 26 and 30 (“pointing”), and items 24 and 33 (“help from others”). Furthermore, it suggested relating item 20 (final item 15 about “banging objects”, currently part of the investigative sub-factor) to the sensory sub-factor which also makes sense theoretically. Including these modifications, we saw a further model fit improvement with great fit indices (*CFI* = .95; *RMSEA* = .037(*CF*[.029;.046]); *BIC* = 22068.42). Note, however, that these additional parameters are mainly useful for conducting additional structural equation modelling analyses on the questionnaire and will not be considered for the discussion of which aggregate scores to compute.

4 TRAIT CURIOSITY & ACTIVE EXPLORATION

4.1 Linking Statement

In the following chapter, I describe an investigation into whether infants' trait curiosity can explain variance in their patterns of active exploration. Infant studies are notorious for the large amount of observed variance in the data, which often leads to small effect sizes. As discussed in the previous chapter, it is plausible that some of this variance - especially concerning observations of infants' curiosity-driven exploration and information sampling - can be attributed to their trait curiosity, for which we now have a measure. However, due to the novelty of this conceptualisation, it was not clear what to expect, as a more curious child might be both more explorative *and* more focused on what they are exploring, thus, more exploitative. None of the previously formulated theoretical frameworks could offer precise hypotheses in this regard. Consequently, the analyses in this chapter were generally exploratory in nature.

This experimental study followed logically from the previous two studies which conceptualised and measured infants' active exploration (Chapter 2) and their trait curiosity (Chapter 3). Our aim was then to explore how best to describe the specific relationships between trait curiosity and characteristics of infants' active exploration, and to test whether they could explain meaningful variance in the data. The results of this study have both theoretical and methodological implications for the interplay between trait and state curiosity, but also for the explanatory power of our caregiver report within experimental observations, which is not necessarily a given (e.g. Madhavan et al., 2024).

This chapter is currently being prepared for submission to Cognition.

Altmann, E. C., Bazhydai, M., & Westermann, G. (in preparation). Infants' trait curiosity shifts the balance from exploitation towards exploration. *Target submission: Cognition.*

Infants' trait curiosity shifts the balance from exploitation towards exploration

Elena C. Altmann, Marina Bazhydai, and Gert Westermann

Funding Statement: This research was supported by the Doctoral Research Program in the Department of Psychology at Lancaster University and the Economic and Social Research Council (ESRC) International Centre for Language and Communicative Development (LuCiD) [ES/S007113/1 and ES/L008955/1].

Acknowledgements: We thank all families and babies who participated and made this study possible.

Materials and analysis scripts presented in this manuscript are available from the OSF. The authors have no conflicts of interest to declare.

Research highlights:

- Infants' trait curiosity was related to their dynamic information sampling, indicating a shift from exploitation towards exploration.
- Curiosity predicted overall engagement in an inverted U-shape, driven by sensory curiosity scores.
- Curiosity positively predicted more between-category switching, driven by social curiosity scores.
- Infants' focused sampling towards one or both available information sources was, however, not related to curiosity.

4.2 Abstract

Infants actively explore their environment to construct their knowledge. This process requires the balance between exploration to discover sources of information in the environment and exploitation, that is, repeatedly engaging with the encountered information to robustly encode it into one's memory. Yet, little is known about infants' tendencies to balance exploration against exploitation in their dynamic information sampling or how their trait curiosity may impact this balance. We related infants' trait curiosity measured by the Infant and Toddler Curiosity Questionnaire (ITCQ) at 10-12 months of age to patterns in their active exploration of two novel categories as available information sources, captured by the Curious Choices paradigm. Specifically, their overall engagement formed an inverted U-shaped relationship with infants' trait curiosity which was mainly driven by their sensory curiosity scores (e.g., scanning the environment and interacting with a wide variety of objects). Additionally, curiosity positively predicted higher levels of between-category switching, which was mainly driven by their social curiosity scores (e.g., requesting information from social others by pointing). However, there was no apparent systematic relationship between curiosity and the degree to which infants focused their sampling towards either or both categories. While these patterns were found on the whole sample (N = 60), they only explained significant amount of variance in the largest emergent cluster of *balanced smaplers* (n = 34). These findings offer first insights into the specific link between infant trait curiosity and active exploration, indicating that, across such dynamic information sampling, higher levels of curiosity shift the balance towards exploration of both, the constrained environment (the two information sources) and the wider environment (earlier disengagement from the task).

Keywords: infant curiosity, active exploration, information sampling, exploration-exploitation, trait and state curiosity

4.3 Introduction

Exploration leads to new discoveries, but it also requires facing uncertainty and taking the risk of missing out on exploiting known rewards. To maximise those rewards there needs to be a balance between exploiting known sources and exploring the uncertain environment to find new sources worth exploiting (Charnov, 1976). In psychological research, this exploration-exploitation dilemma has mostly been used to characterise foraging behaviour in the pursuit of maximising external rewards (e.g., points, stickers, money; Averbeck, 2015). For this, studies showed that already young children employed reward-maximising but also uncertainty-reducing exploration strategies (Blanco & Sloutsky, 2021; Lapidow & Bonawitz, 2023; Schulz et al., 2019), with exploration becoming more efficient with age (Meder et al., 2021; Ruggeri et al., 2016) and memory capacity (Pelz et al., 2015).

However, the exploration-exploitation framework can also be employed to describe the pursuit of information in the absence of external rewards (Gottlieb & Oudeyer, 2018; Oudeyer et al., 2007). That information can be experienced as intrinsically rewarding, and thus, worth exploiting (Daw et al., 2006) has been supported by studies in adults showing that the anticipation of information as well as knowledge acquisition itself correlated with increased activity in neurological reward circuits (Gruber et al., 2014; Jepma et al., 2012; Kang et al., 2009). Then, to maximise one's knowledge construction, there needs to be a balance between exploiting encountered information sources, by engaging and repeatedly sampling from them to robustly encode that information into one's memory (e.g., Rose et al., 1982), and exploring the wider environment to discover new information sources worth exploiting.

Yet, little is known about the mechanisms underlying infants' dynamic information sampling nor about individual differences in weighting exploration against exploitation. Considering active exploration behaviours as manifestations of infants' trait curiosity (e.g., Altmann et al., 2024 (Chapter 3); Bazhydai et al., 2021), it is plausible that trait curiosity can explain variance in patterns of such exploration. Furthermore, curiosity is generally viewed as a highly positive attribute and has been related to enhanced learning (Ackermann et al., 2020; Chen et al., 2022; Engel, 2011; A. Singh & Manjaly, 2022; Stahl & Feigenson, 2015) and beneficial developmental outcomes (Reio, 2024; Shah et al., 2018) but is barely understood in infancy – especially as a trait. Consequently, it is crucial to better understand how trait curiosity may impact early exploration directly to explain those links.

4.3.1 Exploiting information to construct knowledge

Experimental studies have shown that infants' engagement with their environment is related to the information they encounter and serves their knowledge construction. For instance, their looking duration as a measure of information encoding has been shown to predict the shift from a familiarity to a novelty preference (Hunter & Ames, 1988; Kosie et al., 2023; Poli et al., 2023; Rose et al., 1982), so that information is exploitatively engaged with until fully encoded at which point they are driven to explore novel information in the wider environment. Similarly, infants were found to look longer at intermediately predictable (Kidd et al., 2012, 2014) stimulus sequences that afforded the maximising of learning progress (Poli et al., 2020). A computational model of a curious learner (Twomey & Westermann, 2018) and findings from a recently developed paradigm capturing infants' dynamic exploration choices (Altmann et al., 2023; Chapter 2) additionally highlighted the importance of taking one's information sampling history into account because what maximises learning (and the associated intrinsic reward) changes with every bit of new information and the extent to which one engages with it.

The previous findings show infants' information exploitation through their looking behaviour. A similar exploitative tendency has, however, also been observed in their repeated, manual engagement with a select few objects during free-play (Karmazyn-Raz & Smith, 2023; Slone et al., 2019; Smith et al., 2018). Indeed, studies showed such information exploitation to be beneficial if not necessary for early categorisation (e.g., Mandler et al., 1991) and word learning (e.g., Smith & Yu, 2013). Lastly, in social context, infants have been found to express states of curiosity through gestures, pointing, and verbal prompts, thereby initiating interactions about something they want to know more about (Bazhydai et al., 2020; Liszkowski et al., 2007). Reacting to such gestures with information (e.g., labels) then benefitted their sustained attention (Suarez-Rivera et al., 2019; Tamis-LeMonda et al., 2013) and learning (Begus et al., 2014; Lucca & Wilbourn, 2018, 2019; Slone et al., 2019).

Together, these findings suggest that infants' early engagement is likely driven to exploitatively sample information sources to construct their knowledge of the world (Oudeyer & Smith, 2016; Piaget, 1976; Yu et al., 2019). While little is known regarding early trait curiosity and its role in guiding infants' active information sampling, recent work has linked higher levels of curiosity to longer looking at surprising events in infants (Lee et al., 2023) but shorter engagement durations in young children (van Schijndel et al., 2018). Thus, trait curiosity seems to affect how long one engages with encountered information, but the direction of this effect remains inconclusive.

4.3.2 Exploration is necessary but costly

The literature reviewed above indicates infants' early exploitative tendency necessary to robustly construct knowledge. However, exploitation itself depletes the available resources (e.g., additional information) and its associated intrinsic reward (Hayden et al., 2011), so that exploration of the uncertain environment becomes necessary to discover new sources worth exploiting (Kaplan & Oudeyer, 2007; Oudeyer & Smith, 2016). In a constrained environment which provides several information sources (e.g., toys in front of a child, stimuli on a screen, etc.), acts of exploration can be characterised as switching between these information sources (e.g., Altmann et al., 2023 (Chapter 2); Blanco & Sloutsky, 2020; Hayden et al., 2011). Such switching has been associated with the cost of having to inhibit a positively reinforced sampling action (exploitation) and redirecting one's attention towards something more uncertain (Daw et al., 2006; Pelz et al., 2015). Very early in development, specifically in the visual exploration domain, this cost may be indicated by *sticky vision.* Sticky vision describes an infant's inability to disengage from a central stimulus and to reorient towards a peripheral distractor (Colombo, 2001; Kulke et al., 2015). It is, however, hypothesised to disappear over the first year of life due to the development of top-down cognitive control (e.g., Wass & Smith, 2014).

The notion that explorative switching requires cognitive control to overcome an exploitative tendency (see also Pelz et al., 2015) was further supported by Caruso (1993) who showed that infants' breadth of exploration was a stronger predictor of problem-solving abilities than their observed depth of exploration (exploitation). Additionally, this developmental shift towards exploration is reflected in the skills infants and toddlers develop and employ to broaden their explorable environment in search of new information (Adolph & Hoch, 2019; Hoch et al., 2019). Lastly, more sophisticated explore-exploit studies also indicated that throughout childhood, (systematic) exploration is the skill needed to develop to avoid uninformed exploitation of one reward source when other options could offer higher rewards (Blanco & Sloutsky, 2021; Lapidow & Bonawitz, 2023; Meder et al., 2021; Ruggeri et al., 2016; Schulz et al., 2019; Şen et al., 2024).

Together, these findings reiterate an existing baseline tendency for exploiting rewards of both extrinsic and intrinsic nature, whereas exploration is necessary to maximise those rewards across sequential and dynamic sampling by discovering new sources worth exploiting. However, additional cognitive effort is required to disengage and switch to exploring a less certain part of the environment, as it could possibly delay and disrupt one's reward accumulation. To our knowledge, no studies have thus far investigated how trait curiosity may affect this dynamic. One possibility is that it increases one's perception of, or sensitivity towards, learning opportunities in the environment, manifesting in a lower switch cost and thus, more explorative tendencies. Importantly, as optimal development would require a delicate balance between exploration and exploitation, such insights can help explain the vast amount of variance found in infants' active exploration and engagement with information (Bornstein et al., 2013; Caruso, 1993; Colombo et al., 1991; Fortner-wood & Henderson, 1997; Franchak et al., 2016; Mandler et al., 1987; Muentener et al., 2018; Piccardi et al., 2020; Slone et al., 2019; Smith & Yu, 2013; Wass & Smith, 2014), as well as inform the discussion about curiosity's benefits for developmental outcomes (Reio, 2024; Shah et al., 2018).

4.3.3 The current study

In this study, we investigated the links between trait curiosity and patterns of active exploration in 10-12-month-old infants by relating measures from two previously reported studies (Altmann et al., 2023, 2024; corresponding to Chapters 2, 3). We will shortly describe these measures and their conceptualisations (for an overview, see Figure 4.1) to facilitate the comprehensibility of our research questions.

First, active exploration was measured with the Curious Choices paradigm, a novel gaze-contingent eye-tracking task (Altmann et al., 2023; Chapter 2). In this computerised task, infants could freely explore two information sources, each associated with a novel category, where, at each trial, looking at the respective areas on the screen triggered a new stimulus presentation from that category (Figure 4.1 A; more details in the Method section below). Infants' self-generated exploration sequences were characterised through the number of triggers infants made throughout the task (overall engagement), the proportion of between-category switches (switch proportion), and the systematicity with which they structured their information sampling towards available information sources (category entropy).

Exploration sequences fell into three clusters (Figure 4.1 B) of brief explorative (characterised by relative short sequences with a high switch proportion and samples from both categories), long exploitative (characterised by relatively long sequences with few switches and most samples being from one category), and more balanced exploration patterns (characterised by relatively medium long sequences, higher switch proportions, and multiple samples from both categories). Thus, infants in this paradigm generated a range of exploration and exploitation tendencies, with the clusters capturing patterns of similar sampling sequences.

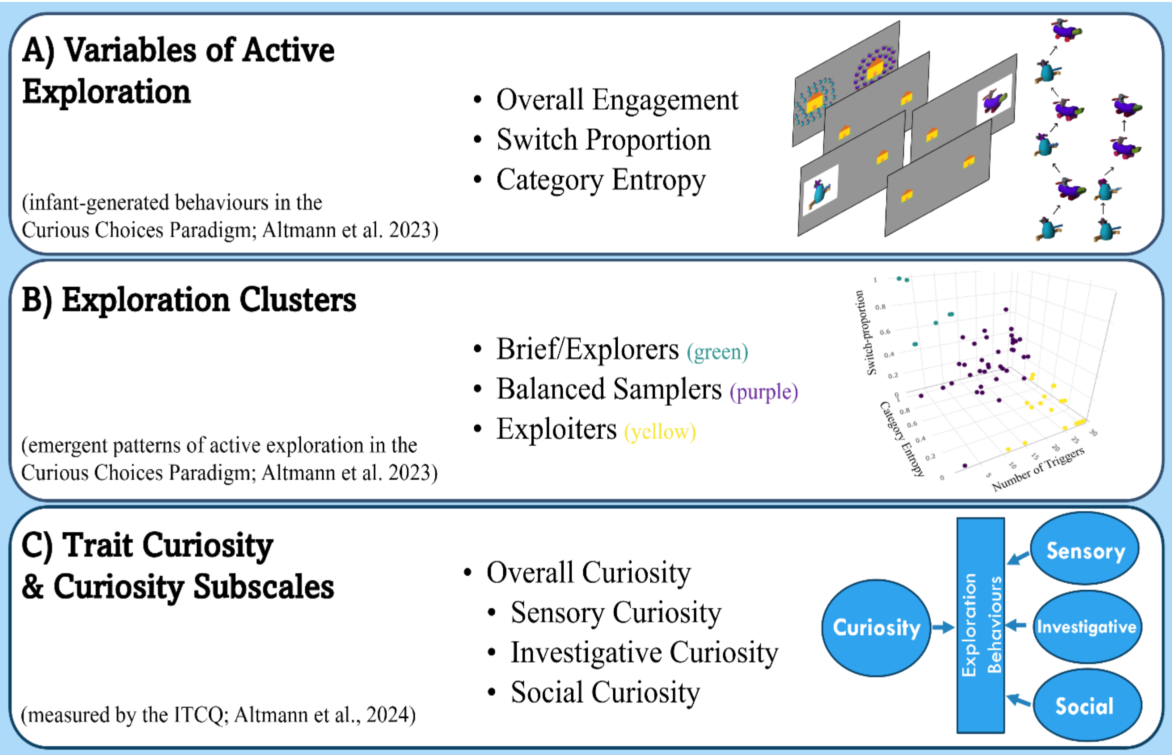


Figure 4.1. Overview of measures included as variables in the here reported analyses.

Trait curiosity was captured by the newly validated caregiver report measure, the Infant and Toddler Curiosity Questionnaire (ITCQ; Altmann et al., 2024; Chapter 3). This measure is the first questionnaire specifically developed to measure trait curiosity in infants and toddlers and does not follow any specific theoretical framework of curiosity. Instead, curiosity in the ITCQ is conceptualised as manifesting in various behaviours with which the infant explores and interacts with the environment. The authors provided evidence supporting the computation of an overall curiosity score, but also reported the emergence of three subscales of sensory (e.g., scanning the environment and interacting with a wide variety of objects), investigative (e.g., focusing on the contents of a box or a toy's functions), and social (e.g., requesting information from social others through pointing) curiosity (Figure 4.1 C).

Based on these conceptualisations and measures, we investigated whether trait curiosity could (i) predict membership of either of the three exploration clusters, (ii) whether it could predict the specific variables characterising active exploration, and (iii) whether the three trait curiosity subscales could explain additional variance beyond that. We expected that higher trait curiosity would be related to a stronger weighting of exploration against exploitation characterised by shorter engagement, more switching, and more equal sampling from both information sources. However, as this study was the first to relate trait curiosity to infants' active exploration, it is generally exploratory in nature.

4.4 Methods

4.4.1 Participants

The full sample consisted of N = 60 typically developing infants (age range: 10-12 months, M = 11.1, SD = 0.52, 45% females) from the northwest of England (previously reported in Altmann et al., 2023; Chapter 2, and Altmann et al., 2024; Chapter 3). Four participants from the original Curious Choices dataset were not included due to their caregivers not completing the ITCQ, whereas four additional observations were excluded as univariate outliers (using the IQR method) based on their mean curiosity scores compared to the whole sample (n=1) and to their respective cluster (balanced samplers: n=2; exploiters: n=1). Caregivers were reimbursed £5 for their travel to the University's Babylab, and the child received a small gift (book or t-shirt) for participating. Informed consent was obtained for each of the measurements and the study was approved by the University Faculty's research ethics committee.

4.4.2 Materials

4.4.2.1 Curious Choices Paradigm

Infants participated in a gaze-contingent eye-tracking study which employed the Curious Choices paradigm (Altmann et al., 2023; Chapter 2). Infants were presented with two identical houses in equal distance from the centre of a computer screen, associated with either of two novel categories – ducks and tortoises - during a short warm-up phase and novel, animal-like stimuli (Fribbles, TarrLab; Barry et al., 2014) during the main exploration phase (Figure 4.1). By looking at a house for 700ms infants could trigger the presentation of a novel exemplar from the respective associated category. Once triggered, the stimulus enlarged over that house for 1 second and was then presented statically for 3 seconds. A central, gaze-contingent attention getter ensured that each trial began with the infant fixating the middle of the screen. If neither house was triggered within 10 seconds, the trial was recorded as an empty trial (Wang et al., 2012) and the next trial was initiated. In this way, infants could freely trigger up to 30 trials, thereby actively generating their own exploration sequences (e.g., AABBBAB).

4.4.2.2 Behavioural measures of active exploration

Three measures were computed to characterise the sequences generated by the infants: **Overall engagement** as the number of triggers the infant made throughout the exploration phase (min. 1, max. 30; example above: 7); **Switch proportion** as the number of triggers marking a switch from the current category to the other one divided by the number of triggers minus 1 (stay/switch only possible from the second trigger onward; range: 0-1; example above: 3/(7-1)=.50); and **Category entropy** as the negative logarithm of the observed probability to trigger either category (Shannon, 1948), capturing the overall systematicity of observations (range: 0-1; example above: 0.986; maximal at equal probability of observations). Regarding the switch proportion, lower values indicate repeated triggering of the same category, and thus, stronger exploitative tendencies. Similarly, lower values for category entropy indicate more one-sided triggering, thus, more predictable sequences. A cluster analysis reported in Altmann et al. (2023) revealed patterns across these variables of exploration.

4.4.2.3 Trait curiosity

As a measure of trait curiosity, caregivers completed the Infant and Toddler Curiosity Questionnaire (ITCQ; Altmann et al., 2024; Chapter 3). The questionnaire consists of 23 items[5] about observable behaviours related to their child's early exploration tendencies. Caregivers rated their agreement on a 7-point Likert scale ranging from 1 ('strongly disagree') to 7 ('strongly agree') with an option of 'not applicable (NA)' provided

[5]Note: caregivers responded to all initial 36 items, however, based on analyses reported in Altmann et al. (2024; Chapter 3), the final set of reliable and valid items included the 23 items referred to here.

for behaviours not yet or not recently observed. Mean scores were computed for the overall curiosity score and the three subscales of sensory (e.g., "My child actively inspects a variety of objects, whether it be toys or ordinary household items."), investigative (e.g., "When my child looks into a container (e.g., a bag, kitchen drawer, etc.), they take out and inspect each of its contents."), and social (e.g., "My child often leads me to/brings me things that they want to know more about.") curiosity. All scales had good internal consistency (overall: omega total = .89, Cronbach's $\alpha = .87$; sensory: $\alpha = .78$; investigative $\alpha = .74$; social: $\alpha = .81$) and test-retest reliability (ICC(A, 1) = .82, $p < .001$).

4.4.3 Procedure

Prior to the appointment, caregivers were asked to complete the ITCQ (Altmann et al., 2024, Chapter 3) alongside demographic questions (Singh et al., 2023) online. At the lab, exploration sequences were collected via gaze-contingent eye-tracking methodology with infants viewing a screen (24-inch, resolution of 1920x1080 pixels) from approximately 60 cm away, sitting on their caregiver's lap or in a highchair. Fixations were recorded using a TobiiX120 eye tracker positioned below the screen, with a gaze sampling rate of 60 Hz and a five-point calibration. The experiment ended either after 30 trials, if the infant had three consecutive empty trials, or if they became fussy so that the experimenter terminated the experiment. All infants were included if they made any number of exploration triggers and as long as there were no concerns about technical problems (which led to the exclusion of $n = 4$ in the original sample reported in Altmann et al., 2023; Chapter 2). The total length of the experiment lasted under six minutes. Caregivers were again contacted about a year later for a follow-up on their child's developmental outcomes (not reported here).

4.4.4 Analyses

Prior to analyses, the full sample as well as each of the three clusters were inspected for univariate outliers using the IQR method on their mean curiosity scores. We conducted a multinomial regression analysis to test whether infants' trait curiosity predicted membership of these exploration clusters. We then computed multiple regression analyses with mean trait curiosity as the independent variable and overall engagement, switch proportion, and category entropy, respectively, as dependent variables, while controlling for possible age and sex differences. In order to investigate whether the three trait curiosity subscales (sensory, investigative, social) independently accounted for additional variance in infants' exploration patterns, we also conducted multiple regression analyses with infants' subscale scores as independent variables. We first conducted these analyses on the whole sample before focusing on the 'balanced samplers' to reduce the amount of additional variance originating from the very homogenous behaviour observed in the other two clusters. In this sub-sample, pairs of repeated measures were examined for influential bivariate outliers via scatter plot inspection (for non-linear relationships) and Cook's distance (for linear relationships).

Mean trait curiosity scores were centred to allow for non-linear terms while avoiding multicollinearity (e.g., Iacobucci et al., 2016). Furthermore, to test for multicollinearity between subscale scores we computed variance inflation factor (VIF) scores for each predictor variable. VIF scores of 1 indicate no correlation between the predictors whereas higher scores indicate a correlation and scores above 5-10 are generally seen as severely problematic (e.g., Thompson et al., 2017). Here, we found no concern of multicollinearity between subscales as VIF values fell into the range between 1 and 3 with the highest value for the linear sensory exploration predictor at VIF = 3.10. Model comparisons were conducted using ANOVAs and residuals were inspected to be approximately normally distributed.

Overall, as these analyses depended upon results from two previous studies (Altmann et al., 2023, 2024 corresponding to Chapters 2 and 3) and the novelty of these research questions, they could not be pre-registered. Nevertheless, variables were pre-planned before inspecting specific relations and R scripts as well as raw data are available on the OSF.

4.5 Results

4.5.1 Trait curiosity did not reliably predict cluster membership

The sample included in this analysis consisted of n = 34 *balanced samplers*, n = 19 *exploiters*, and n = 7 *brief/explorers*. Results from a multinomial regression showed that overall trait curiosity scores did not significantly predict cluster membership (Figure 4.2). Descriptively, the small cluster of explorers had on average the highest curiosity scores (M = 6.20, SD = .49) with an estimated 1.78 points higher than balanced samplers (M = 5.85, SD = .51, p = .083), while the cluster of exploiters (M = 5.89, SD = .40) scored an estimated 0.20 points higher than balanced samplers (p = .739). The cluster of balanced samplers, in comparison, showed the widest spread of scores including both the sample's maximum and minimum. Similar patterns were found for the ITCQ's three curiosity subscales (Supplementary Materials, Table S1), with the small cluster of explorers generally receiving the highest scores. It is to be noted, however, that the small group sizes, especially concerning the explorers, led to unreliable estimates that should be interpreted cautiously.

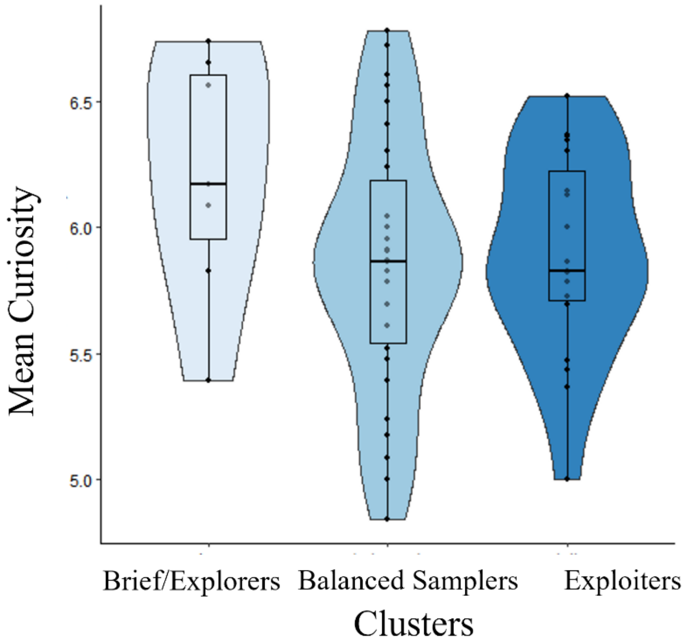


Figure 4.2. Violin plots of the mean trait curiosity scores (y-axis) by exploration cluster (x-axis).

4.5.2 Relationship between trait curiosity and overall engagement

Visual inspection of the data suggested the relationship between trait curiosity and infants' overall engagement to follow an inverted U-shape (Figure 4.3, left column). Indeed, multiple regression analysis on the full sample, controlling for age and sex, supported this as adding a quadratic term significantly improved model fit ($\Delta F(1, 55)$ = 4.06, p = .049). However, while the quadratic term reached significance (b = -8.97, p = .049), the model itself, explaining 13% of variance in the data, did not ($F(4, 55)$ = 2.07, p = .097). Visual inspection of this relation by cluster indicated that the brief/explorers introduced floor effects as they generally engaged only very briefly regardless of their curiosity, while exploiters introduced ceiling effects as they generally recorded very long engagement. We therefore focused on the largest cluster of balanced samplers for further analysis (results regarding analyses on the full sample for the other two exploration variables are reported in the supplementary materials but generally followed the same patterns, see Figure 4.3, row A).

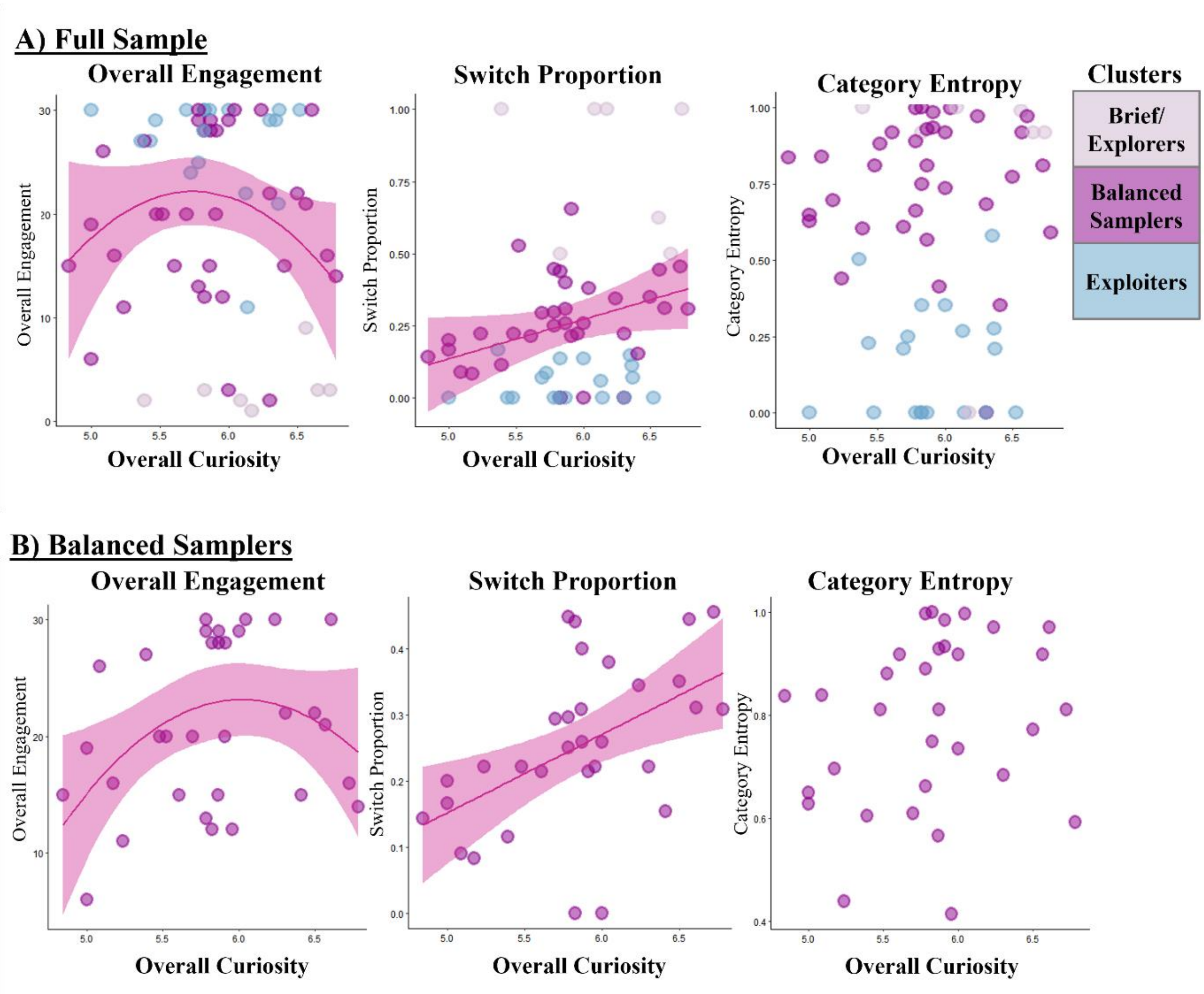


Figure 4.3. Relationships between trait curiosity and variables of active exploration. **Left:** Overall Engagement (number of triggers). **Middle:** Switch Proportion (proportion of triggers between-category switches). **Right:** Category Entropy (negative logarithm of observations towards either information source); **A)** across the whole sample, **B)** subsample of balanced samplers.

From the cluster of balanced samplers, who showed more variable behaviour in the paradigm, we first identified and excluded two bivariate outliers who only engaged very briefly. Regression analyses on the remaining n = 32 observations (M = 11.2, SD = 0.50, 15 females, 17 males), controlling for age and sex, reiterated the relationship to follow an inverted U-shape (Figure 4.3, bottom left). Adding a quadratic term significantly improved model fit ($\Delta F(1, 27) = 5.12$, p = .032) and this term was a significantly negative predictor (b = -8.81, p = .032). While this model explained 24% of variance in the data, it did not reach significance ($F(4,27) = 2.11$, p = .107). The most conservative model explaining the most variance excluded age as a non-significant predictor and could still explain the same amount of variance in infants' overall engagement (F(3,28) = 2.91, p = .052, R^2 = .24).

Regression analyses with the three subscales as independent variables indicated that this relationship was predominantly driven by infants' sensory curiosity. Even though model fit significantly improved by adding a quadratic term for each subscale separately (sensory: ΔF(1, 25) = 9.04, p = .006; investigative: (ΔF(1, 25) = 4.71, p = .040); social: (ΔF(1, 25) = 5.08, p = .033), as well as by adding all three quadratic terms at once (ΔF(3, 23) = 4.45, p = .013), in this full model (F(8,23) = 2.49, p = .041, R^2 = .47), only the quadratic term for sensory exploration remained significant (b = -8.21, p = .023). In fact, the most conservative model explaining the most variance only included the sensory terms (linear: b = -1.12, p = .651, quadratic: b = -7.69, p = .017) as well as sex as a control variable (b = -3.48, p = .136), together explaining 26% of the variance in the data (F(3,28) = 3.20, p = .038).

Together, these findings indicate that infants with comparatively average curiosity scores tended to engage with the task the longest, whereas the reportedly less and more curious babies tended to disengage earlier. This relationship was, however, mainly driven by the balanced samplers and more specifically by their sensory curiosity scores.

4.5.3 Relationship between trait curiosity and switch proportion

Visual inspection of the data suggested the relationship between trait curiosity and infants' switch proportion to be linear (Figure 4.3, middle column). We first identified and excluded three bivariate outliers in the subsample of balanced samplers based on Cook's distance. Regression analyses on the remaining n = 31 observations (M = 11.2, SD = 0.50, 15 females, 16 males), controlling for age and sex, showed that overall curiosity positively predicting switch proportion (b = 0.12, p = .006) with the model explaining 27% of the variance in the data (F(3, 27) = 3.28, p = .036).

Additional regression analyses with the three subscales as independent variables indicated that this linear relationship was predominantly driven by the infants' social curiosity scores. More specifically, the full model could explain 41% of the variance in the data (F(5, 25) = 3.46, p = .017), however only the social subscale remained significant (b = 0.10, p = .008). In fact, the most conservative model explaining the most variance only included the social curiosity predictor (b = 0.09, p = .002) and sex as a control variable (*b* = 0.05, *p* = .187), together explaining 29% of the variance in the data (*F*(2, 28) = 5.82, *p* = .008).

Together, these findings indicate that more curious infants tended to switch more between sampling from either of the two available information sources. This relationship was, however, mainly driven by their social curiosity scores.

4.5.4 Relationship between trait curiosity and category entropy

Visual inspection of the data suggested no systematic relationship between trait curiosity and infants' category entropy, that is, the extent to which they sampled from either or both available information sources (Figure 4.3, right column). After excluding two bivariate outliers from the cluster of balanced samplers based on Cook's distance, regression analyses on the remaining *n* = 32 observations (*M* = 11.2, *SD* = 0.47, 16 females, 16 males), controlling for age and sex, showed that curiosity did not significantly predict category entropy (*b* = 0.07, *p* = .262) and could only explain 12% of the variance in the data (*F*(3, 28) = 1.31, *p* = .290). Additional analyses on the ITCQ's three curiosity subscales could not disentangle nor explain any additional variance either (all *p*s > .05). Together, these findings indicate that the extent to which infants focused their sampling towards one or both available information sources was not directly related to their trait curiosity.

4.6 Discussion

The current study aimed to test whether early trait curiosity could explain variance in infants' active exploration patterns, specifically, how they weighted exploration against exploitation when freely sampling from two novel categories. Trait curiosity here was captured by the Infant and Toddler Curiosity Questionnaire (ITCQ, Altmann et al., 2024; Chapter 3) generating an overall curiosity score as well as scores for three subscales of sensory (e.g., scanning the environment and interacting with a wide variety of objects), investigative (e.g., focusing on an object's functions), and social (e.g., requesting information from social others through pointing) curiosity. Active exploration, on the other hand, was captured in the Curious Choices paradigm (Altmann et al., 2023; Chapter 2) in which infants' self-generated exploration sequences grouped into three clusters based on their overall engagement, switch proportion, and systematicity of sampling from either or both sources: *brief/explorers, balanced samplers,* and *exploiters*. While the largest cluster of balanced samplers recorded the most variance in their sampling, the other two clusters were substantially smaller – especially that of explorers – and recorded much more homogenous sampling at either end of the explore-exploit spectrum.

We found no significant differences in caregiver reported trait curiosity between these clusters, which may have been due to the varying cluster sizes leading to unreliable estimates. By investigating the specific exploration variables across the whole sample, we found that the relationship between trait curiosity and overall engagement was best described as an inverted U-shape but could not explain significant variance in the data. Indeed, these results reiterated the limitation by the two smaller clusters, as their homogenous behaviours introduced floor and ceiling effects. Also regarding the other exploration variables, this led to the overall relationships being present but not explaining enough of this variance to reach significance (reported in the supplementary materials). Thus, we focused on the cluster of balanced samplers (n=34) demonstrating this inverted u-shaped relationship more clearly and found that this relationship was mainly driven by scores on the sensory curiosity subscale. Furthermore, trait curiosity positively predicted switching behaviour, predominantly driven by scores on the social curiosity subscale. In contrast, we did not find any systematic relationships between trait curiosity or its subscales and the extent to which infants focused their sampling towards either or both categories.

The inverted U-shaped relation between trait curiosity and overall engagement indicates that up to a certain degree, curiosity predicts longer engagement (compare Lee et al., 2023). This could imply that infants lower in curiosity may struggled to perceive the learning opportunities offered by this study and were therefore not intrinsically motivated to engage more exploitatively. In contrast, infants very high in curiosity engaged less long, perhaps due to perceiving learning opportunities throughout their environment. This would have led them to disengage from the task earlier and explore the wider environment to discover new sources of information worth exploiting. Alternatively, earlier disengagement can also reflect faster information processing speed (Cao et al., 2023; Poli et al., 2023; Rose et al., 1982), leading to faster depletion of the available information associated reward. Unfortunately, we did not control for cognitive development in this study. However, the main driver of this relationship being the infants' sensory curiosity would speak in favour of the former interpretation, supported by similar results recently found for language development (Chapter 5). Additionally, Piccardi et al. (2020) showed that infants high in visual sensation-seeking tended to disengage prematurely compared to the learning potential further engagement would have offered them. Nevertheless, curiosity seemed to also have a protective function in infants from the two more extreme clusters, as it was associated with engaging longer compared to the other brief explorers but also disengaging earlier compared to the other exploiters (supplementary materials). However, these findings were non-significant and should be interpreted cautiously.

Furthermore, the positive relation between curiosity and higher levels of switching between the two categories may indicate a more gradual shift from exploitation towards exploration as a function of curiosity. One explanation for this effect could be that, when considering the cost associated with making such exploratory switches (Daw et al., 2006; Hayden et al., 2011; Pelz et al., 2015), more curious infants experience a lower switch cost and may possess more cognitive flexibility (Caruso, 1993). This is especially plausible when bearing in mind that this relationship was predominantly driven by the balanced-samplers' social curiosity. This subscale included behaviours such as pointing and interacting with social others to request information, which, as indicated by lower mean scores for this subscale, was not yet a skill developed and widely employed by all participating infants who were 10-12-months-old at the time. Thus, in this age group, higher scores might be especially predictive of more switching due to reflecting advanced cognitive development in line with previous research on the onset of joint attention and use of pointing gestures (Colonnesi et al., 2010; Mundy & Jarrold, 2010). Indeed, in older children, higher levels of curiosity have been linked to shorter exploration durations but also better learning outcomes (van Schijndel et al., 2018), suggesting more efficient and flexible information sampling abilities in line with both of our main findings.

However, curiosity was not related to the systematicity with which infants sampled from either or both categories. This aspect of their self-generated sequences may consequently indicate infants' individual reward-experience leading to personal preferences for *specific* encountered information sources (compare Tummeltshammer et al., 2014; Zettersten, 2020) rather than a general tendency to explore and exploit *all* available sources. Concurrently, previous studies have observed that infants and toddlers showed personal, but not systematic, preferences for the toys they explored and repeatedly engaged with (Karmazyn-Raz & Smith, 2023).

It is to be noted, however, that these interpretations are based on relationships which were present in the full sample but mainly driven by the sub-sample of balanced samplers. While this cluster represented more than half of the full sample, its size is still comparatively small. Thus, our findings may serve as suggestions for how infant trait curiosity may affect the balance between exploration and exploitation within infants' dynamic information sampling, but also call for additional research controlling for their cognitive development and information processing speed (e.g., Piccardi et al., 2020; Poli et al., 2023). Only then can specific mechanisms of trait curiosity be disentangled more robustly. For instance, more switching and earlier disengagement as the outcome of higher curiosity interacting with faster processing speed would lead to a balance between exploration and exploitation and, thus, optimised knowledge construction. The alternative would suggest a high level of distractibility in the absence of robust information encoding, representing the over-prioritisation of exploration at the expense of exploitation. Consequently, this early behaviour could have cascading implications for infants' further development (e.g., Reio, 2024; Shah et al., 2018; Smith et al., 2018), highlighting the importance of better understanding this intricate dynamic.

To summarise, this study presents, for the first time, systematic relationships between caregiver-reported trait curiosity in infants and the infants' observed exploration behaviours in an interactive, computerised task. Specifically, the relation between curiosity and overall engagement with the task was best described as an inverted U-shape, whereas higher levels of curiosity linearly predicted more switching between available information sources. In other words, higher curiosity shifted the balance from a general exploitative tendency towards more exploration within the constrained environment (switching) as well as the exploration of the wider environment through earlier disengaging from the task. Yet, these results were mainly driven by a sub-sample of infants and certain types of curiosity. In conclusion, these findings offer new and important insights regarding curiosity's role in how infants weigh exploration against exploitation when dynamically sampling information.

4.7 References

Ackermann, L., Hepach, R., & Mani, N. (2020). Children learn words easier when they are interested in the category to which the word belongs. *Developmental Science*, *23*(3). https://doi.org/10.1111/desc.12915

Altmann, E. C., Bazhydai, M., Karadağ, D., & Westermann, G. (2024). *The Infant and Toddler Curiosity Questionnaire: A validated caregiver-report measure of curiosity in children from 5 to 24 months*. OSF. https://doi.org/10.31234/osf.io/9swaf

Altmann, E. C., Bazhydai, M., & Westermann, G. (2023). *Curious Choices: Infants' moment-to-moment information sampling is driven by their exploration history*. PsyArXiv. https://doi.org/10.31234/osf.io/7d28k

Averbeck, B. B. (2015). Theory of Choice in Bandit, Information Sampling and Foraging Tasks. *PLOS Computational Biology*, *11*(3), e1004164. https://doi.org/10.1371/journal.pcbi.1004164

Barry, T. J., Griffith, J. W., De Rossi, S., & Hermans, D. (2014). Meet the Fribbles: Novel stimuli for use within behavioural research. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.00103

Bazhydai, M., Twomey, K., & Westermann, G. (2021). Curiosity and Exploration. In J. B. Benson (Ed.), *Encyclopedia of Infant and Early Childhood Development* (2nd ed; Issue 2nd ed). Elsevier. https://eprints.lancs.ac.uk/id/eprint/136590/

Bazhydai, M., Westermann, G., & Parise, E. (2020). "I don't know but I know who to ask": 12-month-olds actively seek information from knowledgeable adults. *Developmental Science*, *23*(5), e12938. https://doi.org/10.1111/desc.12938

Begus, K., Gliga, T., & Southgate, V. (2014). Infants Learn What They Want to Learn: Responding to Infant Pointing Leads to Superior Learning. *PLoS ONE*, *9*(10), e108817. https://doi.org/10.1371/journal.pone.0108817

Blanco, N. J., & Sloutsky, V. M. (2020). Attentional mechanisms drive systematic exploration in young children. *Cognition*, *202*, 104327. https://doi.org/10.1016/j.cognition.2020.104327

Blanco, N. J., & Sloutsky, V. M. (2021). Systematic exploration and uncertainty dominate young children's choices. *Developmental Science*, *24*(2), e13026. https://doi.org/10.1111/desc.13026

Bornstein, M. H., Hahn, C.-S., & Suwalsky, J. T. D. (2013). Physically Developed and Exploratory Young Infants Contribute to Their Own Long-Term Academic Achievement. *Psychological Science*, *24*(10), 1906–1917. https://doi.org/10.1177/0956797613479974

Cao, A., Raz, G., Saxe, R., & Frank, M. C. (2023). Habituation Reflects Optimal Exploration Over Noisy Perceptual Samples. *Topics in Cognitive Science*, *15*(2), 290–302. https://doi.org/10.1111/tops.12631

Caruso, D. A. (1993). Dimensions of quality in infants' exploratory behavior: Relationships to problem-solving ability. *Infant Behavior and Development*, *16*(4), 441–454. https://doi.org/10.1016/0163-6383(93)80003-Q

Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, *9*(2), 129–136. https://doi.org/10.1016/0040-5809(76)90040-X

Chen, X., Twomey, K. E., & Westermann, G. (2022). Curiosity enhances incidental object encoding in 8-month-old infants. *Journal of Experimental Child Psychology*, *223*, 105508. https://doi.org/10.1016/j.jecp.2022.105508

Colombo, J., Mitchell, D. W., Coldren, J. T., & Freeseman, L. J. (1991). Individual Differences in Infant Visual Attention: Are Short Lookers Faster Processors or Feature Processors? *Child Development*, *62*(6), 1247–1257. https://doi.org/10.2307/1130804

Colonnesi, C., Stams, G. J. J. M., Koster, I., & Noom, M. J. (2010). The relation between pointing and language development: A meta-analysis. *Developmental Review*, *30*(4), 352–366. https://doi.org/10.1016/j.dr.2010.10.001

Daw, N. D., O'Doherty, J. P., Dayan, P., Seymour, B., & Dolan, R. J. (2006). Cortical substrates for exploratory decisions in humans. *Nature*, *441*(7095), Article 7095. https://doi.org/10.1038/nature04766

Engel, S. (2011). Children's Need to Know: Curiosity in Schools. *Harvard Educational Review*, *81*(4), 625–645. https://doi.org/10.17763/haer.81.4.h054131316473115

Fortner-wood, C., & Henderson, B. B. (1997). Individual Differences in Two-Year-Olds' Curiosity in the Assessment Setting and in the Grocery Store. *The Journal of Genetic Psychology*, *158*(4), 495–497. https://doi.org/10.1080/00221329709596686

Franchak, J. M., Heeger, D. J., Hasson, U., & Adolph, K. E. (2016). Free Viewing Gaze Behavior in Infants and Adults. *Infancy*, *21*(3), 262–287.

https://doi.org/10.1111/infa.12119

Gottlieb, J., & Oudeyer, P.-Y. (2018). Towards a neuroscience of active sampling and curiosity. *Nature Reviews Neuroscience*, *19*(12), 758–770. https://doi.org/10.1038/s41583-018-0078-0

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of Curiosity Modulate Hippocampus-Dependent Learning via the Dopaminergic Circuit. *Neuron*, *84*(2), 486–496. https://doi.org/10.1016/j.neuron.2014.08.060

Hayden, B. Y., Pearson, J. M., & Platt, M. L. (2011). Neuronal basis of sequential foraging decisions in a patchy environment. *Nature Neuroscience*, *14*(7), Article 7. https://doi.org/10.1038/nn.2856

Hunter, M. A., & Ames, E. W. (1988). A multifactor model of infant preferences for novel and familiar stimuli. *Advances in Infancy Research*, *5*, 69–95.

Jepma, M., Verdonschot, R. G., van Steenbergen, H., Rombouts, S. A. R. B., & Nieuwenhuis, S. (2012). Neural mechanisms underlying the induction and relief of perceptual curiosity. *Frontiers in Behavioral Neuroscience*, *6*. https://doi.org/10.3389/fnbeh.2012.00005

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T., & Camerer, C. F. (2009). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. *Psychological Science*, *20*(8), 963–973. https://doi.org/10.1111/j.1467-9280.2009.02402.x

Kaplan, F., & Oudeyer, P.-Y. (2007). In search of the neural circuits of intrinsic motivation. *Frontiers in Neuroscience*, *1*. https://www.frontiersin.org/articles/10.3389/neuro.01.1.1.017.2007

Karmazyn-Raz, H., & Smith, L. B. (2023). Sampling statistics are like story creation: A network analysis of parent–toddler exploratory play. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *378*(1870), 20210358. https://doi.org/10.1098/rstb.2021.0358

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks Effect: Human Infants Allocate Attention to Visual Sequences That Are Neither Too Simple Nor Too Complex. *PLoS ONE*, *7*(5), e36399. https://doi.org/10.1371/journal.pone.0036399

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks Effect in Infant Auditory Attention. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12263

Kosie, J., Zettersten, M., Abu-Zhaya, R., Amso, D., Babineau, M., Baumgartne, H., Belia, M., Benavides, S., Bergmann, C., & Berteletti, I. (2023). *ManyBabies 5: A large-scale investigation of the proposed shift from familiarity preference to novelty preference in infant looking time*.

Lapidow, E., & Bonawitz, E. (2023). What's in the Box? Preschoolers Consider Ambiguity, Expected Value, and Information for Future Decisions in Explore-Exploit Tasks. *Open Mind*, *7*, 855–878. https://doi.org/10.1162/opmi_a_00110

Lee, N., Lazaro, V., Wang, J. J., Şen, H. H., & Lucca, K. (2023). Exploring individual differences in infants' looking preferences for impossible events: The Early Multidimensional Curiosity Scale. *Frontiers in Psychology*, *13*. https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1015649

Liszkowski, U., Carpenter, M., & Tomasello, M. (2007). Pointing out new news, old news, and absent referents at 12 months of age. *Developmental Science*, *10*(2), F1–F7. https://doi.org/10.1111/j.1467-7687.2006.00552.x

Lucca, K., & Wilbourn, M. P. (2018). Communicating to Learn: Infants' Pointing Gestures Result in Optimal Learning. *Child Development*, *89*(3), 941–960. https://doi.org/10.1111/cdev.12707

Lucca, K., & Wilbourn, M. P. (2019). The what and the how: Information-seeking pointing gestures facilitate learning labels and functions. *Journal of Experimental Child Psychology*, *178*, 417–436. https://doi.org/10.1016/j.jecp.2018.08.003

Mandler, J. M., Fivush, R., & Reznick, J. S. (1987). The development of contextual categories. *Cognitive Development*, *2*(4), 339–354. https://doi.org/10.1016/S0885-2014(87)80012-6

Meder, B., Wu, C. M., Schulz, E., & Ruggeri, A. (2021). Development of directed and random exploration in children. *Developmental Science*, *24*(4), e13095. https://doi.org/10.1111/desc.13095

Muentener, P., Herrig, E., & Schulz, L. (2018). The efficiency of infants' exploratory play is related to longer-term cognitive development. *Frontiers in Psychology*, *9*, 635.

Mundy, P., & Jarrold, W. (2010). Infant joint attention, neural networks and social cognition. *Neural Networks*, *23*(8), 985–997. https://doi.org/10.1016/j.neunet.2010.08.009

Oudeyer, P.-Y., Kaplan, F., & Hafner, V. V. (2007). Intrinsic Motivation Systems for Autonomous Mental Development. *IEEE Transactions on Evolutionary Computation*, *11*(2), 265–286. https://doi.org/10.1109/TEVC.2006.890271

Oudeyer, P.-Y., & Smith, L. B. (2016). How Evolution May Work Through Curiosity-Driven Developmental Process. *Topics in Cognitive Science*, *8*(2), 492–502. https://doi.org/10.1111/tops.12196

Pelz, M., Piantadosi, S. T., & Kidd, C. (2015). The dynamics of idealized attention in complex learning environments. *2015 Joint IEEE International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob)*, 236–241. https://doi.org/10.1109/DEVLRN.2015.7346147

Piaget, J. (1976). Piaget's Theory. In B. Inhelder, H. H. Chipman, & C. Zwingmann (Eds.), *Piaget and His School: A Reader in Developmental Psychology* (pp. 11–23). Springer. https://doi.org/10.1007/978-3-642-46323-5_2

Piccardi, E. S., Johnson, M. H., & Gliga, T. (2020). Explaining individual differences in infant visual sensory seeking. *Infancy*, *25*(5), 677–698. https://doi.org/10.1111/infa.12356

Poli, F., Ghilardi, T., Beijers, R., de Weerth, C., Hinne, M., Mars, R. B., & Hunnius, S. (2023). *Individual differences in processing speed and curiosity explain infant habituation and dishabituation performance*.

Poli, F., Serino, G., Mars, R. B., & Hunnius, S. (2020). Infants tailor their attention to maximize learning. *Science Advances*, *6*(39), eabb5053. https://doi.org/10.1126/sciadv.abb5053

Reio Jr., T. G. (2024). Individual Differences in Curiosity. *The Oxford Handbook of Individual Differences in Organizational Contexts*, 43.

Rose, S. A., Gottfried, A. W., Melloy-Carminar, P., & Bridger, W. H. (1982). Familiarity and novelty preferences in infant recognition memory: Implications for information processing. *Developmental Psychology*, *18*(5), 704–713. https://doi.org/10.1037/0012-1649.18.5.704

Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2016). Sources of developmental change in the efficiency of information search. *Developmental Psychology*, *52*(12), 2159–2173. https://doi.org/10.1037/dev0000240

Schulz, E., Wu, C. M., Ruggeri, A., & Meder, B. (2019). Searching for Rewards Like a Child Means Less Generalization and More Directed Exploration. *Psychological Science*, *30*(11), 1561–1572. https://doi.org/10.1177/0956797619863663

Şen, H. H., Kiefer, S. L., Aksu, E., & Lucca, K. (2024). Developmental differences in children and adults' enforcement of explore versus exploit search strategies in the United States and Turkey. *Developmental Science*, e13520.

Shah, P. E., Weeks, H. M., Richards, B., & Kaciroti, N. (2018). Early childhood curiosity and kindergarten reading and math academic achievement. *Pediatric Research*, *84*(3), Article 3. https://doi.org/10.1038/s41390-018-0039-3

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Singh, A., & Manjaly, J. A. (2022). Using Curiosity to Improve Learning Outcomes in Schools. *Sage Open*, *12*(1), 21582440211069392. https://doi.org/10.1177/21582440211069392

Singh, L., Barokova, M. D., Baumgartner, H. A., Lopera-Perez, D. C., Omane, P. O., Sheskin, M., Yuen, F. L., Wu, Y., Alcock, K. J., & Altmann, E. C. (2023). A unified approach to demographic data collection for research with young children across diverse cultures. *Developmental Psychology*.

Slone, L. K., Smith, L. B., & Yu, C. (2019). Self-generated variability in object images predicts vocabulary growth. *Developmental Science*, *22*(6), e12816. https://doi.org/10.1111/desc.12816

Smith, L. B., Jayaraman, S., Clerkin, E., & Yu, C. (2018). The Developing Infant Creates a Curriculum for Statistical Learning. *Trends in Cognitive Sciences*, *22*(4), 325–336. https://doi.org/10.1016/j.tics.2018.02.004

Smith, L. B., & Yu, C. (2013). Visual Attention Is Not Enough: Individual Differences in Statistical Word-Referent Learning in Infants. *Language Learning and Development*, *9*(1), 25–49. https://doi.org/10.1080/15475441.2012.707104

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*(6230), 91–94. https://doi.org/10.1126/science.aaa3799

Suarez-Rivera, C., Smith, L. B., & Yu, C. (2019). Multimodal parent behaviors within joint attention support sustained attention in infants. *Developmental Psychology*, *55*(1), 96–109. https://doi.org/10.1037/dev0000628

Tamis-LeMonda, C. S., Kuchirko, Y., & Tafuro, L. (2013). From Action to Interaction: Infant Object Exploration and Mothers' Contingent Responsiveness. *IEEE Transactions on Autonomous Mental Development*, *5*(3), 202–209. https://doi.org/10.1109/TAMD.2013.2269905

Tummeltshammer, K. S., Mareschal, D., & Kirkham, N. Z. (2014). Infants' Selective Attention to Reliable Visual Cues in the Presence of Salient Distractors. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12239

Twomey, K. E., & Westermann, G. (2018). Curiosity-based learning in infants: A neurocomputational approach. *Developmental Science*, *21*(4), e12629. https://doi.org/10.1111/desc.12629

van Schijndel, T. J., Jansen, B. R., & Raijmakers, M. E. (2018). Do individual differences in children's curiosity relate to their inquiry-based learning? *International Journal of Science Education*, *40*(9), 996–1015.

Wang, Q., Bolhuis, J., Rothkopf, C. A., Kolling, T., Knopf, M., & Triesch, J. (2012). Infants in Control: Rapid Anticipation of Action Outcomes in a Gaze-Contingent Paradigm. *PLoS ONE*, *7*(2), e30884. https://doi.org/10.1371/journal.pone.0030884

Wass, S. V., & Smith, T. J. (2014). Individual Differences in Infant Oculomotor Behavior During the Viewing of Complex Naturalistic Scenes. *Infancy*, *19*(4), 352–384. https://doi.org/10.1111/infa.12049

Yu, C., Suanda, S. H., & Smith, L. B. (2019). Infant sustained attention but not joint attention to objects at 9 months predicts vocabulary at 12 and 15 months. *Developmental Science*, *22*(1), e12735. https://doi.org/10.1111/desc.12735

Zettersten, M. (2020). *Seeking New Words: Active Word Learning in Infants and Children* [Ph.D., The University of Wisconsin - Madison]. https://search.proquest.com/docview/2408896456/abstract/E02DABE6983D46B2PQ/1

S4 Supplementary Materials

Table S4.1. Mean scores (and Standard Deviations) for each curiosity subscale and cluster.

	Exploration Clusters		
Exploration Facets	**Brief/Explorers**	**Balanced Samplers**	**Exploiters**
Sensory	6.63 (.34)	6.23 (.57)	6.33 (.37)
Investigative	6.50 (.60)	6.24 (.58)	6.10 (.64)
Social	5.17 (.71)	4.87 (.74)	4.82(.85)

S4.2 Additional Results on the whole sample

S4.2.1 Relationship between overall engagement and curiosity subscales

Regression analyses on the whole sample but with the three subscales as independent variables indicated that this relationship was mainly driven by infants' sensory curiosity. Separately adding a quadratic term for this subscale (b = -8.58, p = .030) but not for either of the other subscales nor all three combined significantly improved model fit ($\Delta F(1, 53) = 4.97$, p = .030). In fact, the most conservative model explaining the most variance only included the sensory terms (linear: b = -3.77, p = .206, quadratic: b = -8.05, p = .030) as well as sex as a control variable (b = -3.75, p = .130), together explaining 12% of the variance in the data ($F(3,56) = 2.64$, p = .059).

Yet, it seemed that the more curious exploiters tended to disengage earlier than the less curious cluster members (reiterated by negative slopes estimated for this cluster in an exploratory mixed effect analysis: y=31.25–0.75x; Table S4.2).

Table S4.2. Random slope coefficients of overall trait curiosity per cluster and dependent variable. Terms marked in bold indicate the cluster-specific slopes with opposite polarity compared to the other two clusters.

	Exploration Clusters		
DV/behavioural exploration variable	**Brief/Explorers**	**Balanced Samplers**	**Exploiters**
Overall Engagement	-13 + 2.76x	18.25 + 0.28x	**31.25 – 0.75x**
Switch-Prediction	**1.21 – 0.07x**	0.19 + 0.02x	-0.22 + 0.05x
Category Entropy	0.95 – 0.02x	0.89 – 0.02x	0.36 – 0.03x

Note. None of these terms, nor the model itself reached significance.

S4.2.2 Relationship between switch proportion and trait curiosity and its subscales

Multiple regression analysis on the whole sample, controlling for age and sex, estimated curiosity to positively predict switching ($b = 0.13$, $p = .071$) together explaining 11% of the variance in the data, however, not significantly so ($F(3, 56) = 2.16$, $p = .103$). Visual inspection of this relation by cluster indicated that the exploiters introduced floor effects by seldomly switching regardless of their curiosity scores, while brief/explorers introduced ceiling effects as the majority tended to switch at every sampling trigger they made. Yet it seemed that the more curious explorers tended to switch less (reiterated by negative slopes estimated for this cluster in an exploratory mixed effect analysis: y = 1.21–0.07x; full table in supplementary materials, Table S4.2). Additional regression analyses with the three subscales as independent variables could not explain any additional variance in the data (all *p*s > .05).

S4.2.3 Relationship between category entropy and trait curiosity

Multiple regression analysis on the whole sample, controlling for age and sex, indicated no systematic relationship between trait curiosity and category entropy, as curiosity did not significantly predict a change in category entropy ($b = .01$, $p = .894$) and the model could only explain 3% of the variance in the data ($F(3,56)=0.60$, $p=.619$).

5 TRAIT CURIOSITY & LANGUAGE DEVELOPMENT

5.1 Linking Statement

In this last experimental chapter, I describe an investigation into how infants' trait curiosity can predict language development one year later. Previous research indicated predictive links between specific exploration behaviours and vocabulary size (e.g., Colonnesi et al., 2010; Muentener et al., 2018), but could not establish a comprehensive account of how explorative or exploitative tendencies, or trait curiosity holistically, explained these links. In this short report, we examined the longitudinal relationship between trait curiosity at 10 to 12 months of age and vocabulary size about one year later. However, due to the novelty of this conceptualisation, the direction of this link was uncertain. For instance, a more curious baby with tendencies to explore broadly might discover a multitude of objects and, thereby, has the opportunity to learn more labels. However, a more curious baby with tendencies to explore more specifically (exploitatively) might encode the language-related information more robustly. Consequently, the analyses in this chapter were generally exploratory in nature.

This correlational study aimed to explore how best to describe the specific predictive relationships between trait curiosity and vocabulary size, and to test whether they could explain meaningful variance in the data. The results of this study have substantial theoretical implications for the role of trait curiosity in shaping infants' language development trajectories.

This chapter is currently prepared for submission in First Language.

Altmann, E. C., Bazhydai, M., & Westermann, G. (in preparation). Subscales of infants' trait curiosity differentially predict their productive vocabulary one year later. *Target submission: First Language.*

Subscales of infants' trait curiosity differentially predict their productive vocabulary one year later

Elena C. Altmann, Marina Bazhydai, and Gert Westermann

Funding Statement: This research was supported by the Doctoral Research Program in the Department of Psychology at Lancaster University and the Economic and Social Research Council (ESRC) International Centre for Language and Communicative Development (LuCiD) [ES/S007113/1 and ES/L008955/1].

Acknowledgements: We thank all families and babies who participated at both timespoints one year apart and made this study possible.

Materials and analysis scripts presented in this manuscript are available from the OSF. The authors have no conflicts of interest to declare.

Research highlights:

- For the first time, infants' trait curiosity was longitudinally related to trajectories of language development.
- Curiosity subscales differentially predicted productive vocabulary, with subscales capturing tendencies to explore information more deeply (investigative and social curiosity) predicting larger vocabularies one year later.
- Broader exploration tendencies (sensory curiosity), however, formed an inverted u-shaped relationship.
- The results highlight infant curiosity's benefits, but also suggest a risk of too much exploration if it comes at the expense of information exploitation.

5.2 Abstract

Infants are capable information processors who construct their language by detecting regularities in their environment but also by creating learning opportunities themselves. However, little is known about how infants' trait curiosity, manifested in their exploration tendencies, impacts the trajectories of their language development. We related infants' trait curiosity measured by the Infant and Toddler Curiosity Questionnaire (ITCQ) at 10-12 months of age to their vocabulary size at 24 months. Longitudinal data from $N = 30$ British infants (13 female, 17 male) showed no direct predictive link between overall curiosity and vocabulary; however, it revealed that curiosity subscales did differentially predict infants' productive vocabulary size one year later. Specifically, higher levels of investigative (e.g., inspecting an object's functions or a container's contents) and social (e.g., requesting information from social others by pointing) curiosity were positively predictive, whereas sensory curiosity (e.g., scanning the environment and interacting with a wide variety of objects) formed an inverted U-shaped relationship with productive vocabulary size. Similar patterns were found regarding toddlers' receptive vocabulary, however not explaining a significant amount of the variance in the data. These findings offer first insights into infant trait curiosity's role within language development.

Keywords: infant curiosity, language development, vocabulary development, individual differences

5.3 Introduction

Infants rapidly develop a plethora of new skills across the first two years of life with which they explore and interact with their surroundings, constructing their own understanding of the world (Berlyne, 1960; Piaget, 1976). From the second half of the first year, the development of language is an integral aspect of this process (for review see Mani & Ackermann, 2018). Such active learning is largely thought to be driven by children's curiosity, that is, their exploration and learning for its own sake (Bazhydai et al., 2021; Begus & Southgate, 2018; Gottlieb et al., 2013; Grossnickle, 2016; Kidd & Hayden, 2015; Reio et al., 2006) and associated with an intrinsically rewarding experience (Gruber et al., 2014; Jepma et al., 2012; Kang et al., 2009; Oudeyer et al., 2007). Numerous studies in adults have shown positive associations between trait curiosity and developmental outcomes such as academic success, job performance, innovation, and creativity (Grossnickle, 2016; Hardy et al., 2017; Kashdan et al., 2020; Kashdan & Yuen, 2007; Mussel, 2013; Reio & Callahan, 2004; Reio & Wiswell, 2000; Schutte & Malouff, 2020). Similar developmental benefits of trait curiosity are plausible in infancy, yet, up until recently there was no validated trait measure for this target group. Therefore, this is the first study to examine this, by linking infants' trait curiosity to their language development.

5.3.1 Exploration and language development

Emerging research demonstrates that infants explore in ways that allow them to improve their representation of the world by, for example, engaging with stimuli that are neither too predictable nor too unpredictable relative to their exploration history (Altmann et al., 2023 (Chapter 2); Chen et al., 2022; Kidd et al., 2012, 2014; Poli et al., 2020; Stahl & Feigenson, 2015) and with those that can reduce uncertainty (e.g., Bazhydai et al., 2020; Zettersten, 2020). Infants also use their developing motor skills to widen their explorable environment (Adolph & Hoch, 2019; Thurman & Corbetta, 2017), request information from social others through active non-verbal communication (Bazhydai et al., 2020; Begus et al., 2014; Iverson & Goldin-Meadow, 2005; Liszkowski et al., 2004; Tomasello et al., 2007) and later through verbal requests (e.g., Chouinard et al., 2007). Furthermore, young children engage in exploratory play to gain information (Bonawitz et al., 2012; Cook et al., 2011; Legare, 2012, 2014; Schulz et al., 2008; Schulz & Bonawitz, 2007) and thrive when given the opportunity to engage with what they are curious about (Engel, 2011; Singh & Manjaly, 2022; Watson et al., 2018). For instance, being in a state of curiosity was linked to information-encoding benefits in infants (Chen et al., 2022) and toddlers (Ackermann et al., 2020), with Begus et al. (2014) showing that toddlers learned the function of an object better when they had previously pointed at it to express their interest. Together, this research shows that children express their curiosity from infancy onward, actively shaping their own learning experiences and benefitting from it in the form of improved learning and enjoyment of learning (Alan & Mumcu, 2024; Engel, 2011; Gruber & Fandakova, 2021; Singh & Manjaly, 2022; Watson et al., 2018).

Similarly, language development throughout the first two years of life is also not a passive process based solely on external input. Instead, input interacts with the child's selective request for and engagement with it (e.g., Mani & Ackermann, 2018). As such, early manual exploration (Karmazyn-Raz & Smith, 2023) and visual experience in naturalistic contexts (Smith et al., 2018) seem to be dominated by a small, selective cluster of objects, also largely overlapping with the first acquired nouns. This suggests that infants control their own learning curriculum and that repeated engagement with a selection of information is beneficial if not necessary for early word learning. Additionally, concerning curiosity's role in language acquisition, recent experimental studies have shown that toddlers' interest in an object category led to better learning as well as retention of newly learned labels for these objects (Ackermann et al., 2020, 2023). Likewise, curiosity expressed through pointing (Begus et al., 2014; Colonnesi et al., 2010; Lucca & Wilbourn, 2019) and object-directed vocalisations (Goldstein et al., 2010) was also found to predict better word learning. Considering the importance of early language on children's general developmental prospects (e.g., Jago et al., 2023; McKean & Reilly, 2023), a better understanding of the differences in their trait curiosity and their self-generated learning opportunities (Smith et al., 2018) could help identify new points for intervention.

5.3.2 Trait Curiosity and Language Development

While the emergent body of research summarised above generally points towards the beneficial role of curiosity on word learning in infancy, these studies are mainly concerned with state curiosity, i.e., the infants' specific interest in the objects for which labels were learned. Little is known, however, about individual differences in young children's trait curiosity and how they may shape the trajectories of their language development. Yet, some studies have shown links between this developmental outcome and individual differences in specific exploration behaviours. For instance, one study found that infants who showed more efficient exploration, that is, who engaged at a higher rate with more functions of a novel object, developed larger vocabularies than their less efficient peers nine months later (Muentener et al., 2018). Additionally, a meta-analysis found that the onset and frequency of pointing were shown to longitudinally predict language development (Colonnesi et al., 2010). Such studies, however, notably focused on a limited number of specific manifestations of curiosity, rather than curiosity as a trait, observed a large amount of unexplained variability in the data, and reported some inconclusive findings (Ackermann et al., 2020b; Bazhydai et al., 2022; Nicoladis & Barbosa, 2024). Furthermore, the temporal stability of specific exploration behaviours including manual exploration, visual exploration and investigative pointing was largely found to be inconsistent (Aureli et al., 2013; Bornstein et al., 2020; Camaioni et al., 1991, 1991; Carranza Carnicero et al., 2000; Colombo et al., 1987; Gaertner et al., 2008) likely reflecting developmental shifts towards employing newly acquired exploration skills. Consequently, adopting a more holistic approach to measuring infants' trait curiosity, expressed through multiple and varied observable behaviours across their early life, might offer novel and unifying insights into its role in language learning.

Trait curiosity in adults and older children has been the subject of research for a long time (Grossnickle, 2016; Jirout & Klahr, 2012; Reio, 2024), for instance, showing that children's trait curiosity predicted better information and knowledge acquisition (Inagaki, 1978) even after controlling for intelligence (van Schijndel et al., 2018). In contrast, trait curiosity in infants has only recently gained more rigorous scientific attention. This emergence coincides with a generally increasing awareness that to better understand a psychological construct and its development we also need to acknowledge and understand the extent of its variability between individuals (Pérez-Edgar et al., 2020). The correspondingly recent research on early trait curiosity has already shown great potential to explain additional variance in, for instance, looking time towards surprising events (Lee et al., 2023) and academic success in kindergarten (Shah et al., 2018).

Altmann et al. (2024; Chapter 3) developed and validated a caregiver report questionnaire and showed that it was able to reliably measure infants' trait curiosity as the general tendency to actively explore one's immediate surroundings. In this scale, the pool of items targeting observable exploration behaviours grouped into three subscales of sensory (e.g., scanning and interacting with a wide variety of objects), investigative (e.g., inspecting an object's functions or a container's contents), and social (e.g., using pointing to request information from social others) curiosity. Altmann and colleagues also demonstrated that overall curiosity scores, as well as the three curiosity subscales, were related yet distinct from early measures of temperament, altogether providing evidence for a valid measure of infants' trait curiosity. Considering the impact such differences in trait curiosity could have on shaping developmental trajectories from infancy onward, it is crucial to address this construct holistically throughout development in order to reconcile trait curiosity research across the ages.

5.3.3 The current paper

The current paper aimed to, for the first time, establish the link between trait curiosity and developmental language outcomes by employing the newly validated Infant and Toddler Curiosity Questionnaire (ITCQ; Altmann et al., 2024, Chapter 3). We thereby sought to address (i) whether infant trait curiosity is predictive of language development and (ii) whether curiosity subscales (namely sensory, investigative, and social curiosity) can explain additional variance in the data. We expected trait curiosity to positively predict vocabulary outcomes but did not have specific hypotheses regarding the predictive patterns for each subscale. To answer these questions in a longitudinal study, we measured curiosity in infants at 10-12 months of age to predict their vocabulary size about a year later at 24 months of age. Due to the novelty of the scale and its subscales, however, this study was generally exploratory in nature.

5.4 Methods

5.4.1 Participants

The final sample consisted of N = 30 responses from primary caregivers of normally developing, English-learning, white children from the north-west of England, who completed measures at two timepoints (T1: children's age in months at T1: M = 11.2, SD = 0.5, range: 10.2 – 12.0; T2: M = 23.9, SD = 0.3, range: 23.5 – 24.7; 13 females, 17 males). Four additional responses were excluded due to the child's age exceeding the age range at timepoint two (n=1), caregiver-indicated concerns for the child's language development (n=1) and being univariate (mean curiosity; n=2) outlies. Caregivers were recruited from the University Babylab's database initially to take part in an in-person study (T1), for which caregivers received £5 for their travel to the Babylab, and the child received a small gift (book or t-shirt) for participating. Those who were happy to complete the follow-up survey about one year later received an additional £5 online gift voucher of their choice (via express.giftpay.com). The study was approved by the University's Faculty of Science and Technology research ethics committee.

5.4.2 Materials

5.4.2.1 Curiosity

As a measure of curiosity, caregivers completed the Infant and Toddler Curiosity Questionnaire (ITCQ; Altmann et al., 2024; Chapter 3) for which they indicated their agreement with 23[6] items asking about observable behaviours regarding their child's early exploration tendencies on a 7-point Likert-Scale from 1 ("Strongly disagree") to 7 ("Strongly agree") with an option of "Not applicable (NA)" indicating behaviours not yet or not recently observed. An overall mean score, as well as mean scores for the three subscales of sensory, investigative, and social curiosity, were computed across applicable items, with all scales indicating good internal consistency (overall: omega total = .89; Cronbach's $\alpha = .87$; sensory: $\alpha = .78$; investigative $\alpha = .74$; social: $\alpha = .81$) and test-retest reliability (ICC(A, 1) = .82, $p < .001$).

5.4.2.2 Vocabulary

Caregivers completed the Oxford-CDI (Hamilton et al., 2000) consisting of 416 items and indicated their child's comprehension and production for each word. Based on the responses, we computed the number of understood words for their receptive vocabulary, and the number of understood and said words for their productive vocabulary.

5.4.3 Procedure

At both time points, the questionnaires were completed online via the secure platform Qualtrics (Qualtrics, Provo, UT). Prior to the in-person appointment during which the infants participated in the gaze-contingent eye-tracking study (previously reported in Altmann et al., 2023; Chapter 2), caregivers were asked to complete the ITCQ (Altmann et al., 2024; Chapter 3) and provide demographic information, and were then

[6] Note: caregivers responded to all initial 36 items, however, based on analyses reported in Altmann et al. (2024; Chapter 3), the final set of reliable and valid items included the 23 items referred to here.

contacted shortly before their child's second birthday and invited to complete the follow-up survey, including the Oxford CDI as well as the Ages-and-Stages problem-solving subscale (not further reported here due to the paper's focus on language development). Participants read an information sheet and provided informed consent before answering any of the survey questions.

5.4.4 Analyses

Prior to analyses, curiosity mean scores were inspected for univariate outliers based on the IQR method and pairs of repeated measures were examined for influential bivariate (overall curiosity) and multivariate (across subscales) outliers via scatter plot inspection and Cook's distance. Curiosity mean scores (overall and per subscale) were centred after outlier exclusion to allow for non-linear terms while avoiding multicollinearity (e.g., Iacobucci et al., 2016). Age at T2 was centred as well to allow for more direct interpretation of the intercept indicting vocabulary size at the sample's mean age. To address research question 1, we conducted regression analyses with receptive and productive vocabulary as dependent variables, controlling for sex and age at T2, and overall curiosity as the independent variable. To address research question 2, we conducted the same analyses using the three curiosity subscales instead of overall curiosity to disentangle additional variance in the data. Model fit comparisons based on an ANOVA tested whether including quadratic predictor terms led to significant fit improvements. Residuals were inspected to be approximately normally distributed.

As curiosity subscales are correlated (from Altmann et al., 2024; Chapter 3) and thus might lead to multicollinearity, we addressed this by computing variance inflation factor (VIF) scores for each predictor variable. VIF scores of 1 indicate no correlation between the predictors whereas higher scores indicate a correlation and scores above 5-10 are generally seen as severely problematic (e.g., Thompson et al., 2017). Here, the VIF values were of no concern as all scores were close to 1 (maximal for sensory curiosity with VIF = 2.19).

As these analyses depended upon results from a previous study (Altmann et al., 2024; Chapter 3), they could not be pre-registered. Furthermore, this study was the first to relate trait curiosity to infants' language development and was therefore generally exploratory in nature. Nevertheless, variables were pre-planned before inspecting specific relations and R scripts as well as raw data are available on the OSF.

5.5 Results

5.5.1 Productive vocabulary

To explore the relationship between trait curiosity and productive vocabulary one year later we first excluded one bivariate outlier based on Cook's distance. Regression analyses on the remaining n = 29 participants (Figure 5.1, top left), controlling for sex (13 females, 16 males) and age at T2 (M = 23.9 SD = .31), found that productive vocabulary was not directly predicted by overall curiosity (b = 34.10, p = .522) and curiosity could only explain 4% of variance in the data ($F(3, 25) = 0.39$, p = .763). As visual inspection suggested a possibly inverted u-shaped relationship, we tested whether adding a quadratic term for overall curiosity could explain any additional variance and improve model fit, which it did not ($\Delta F(1, 24) = 1.14$, p = .296).

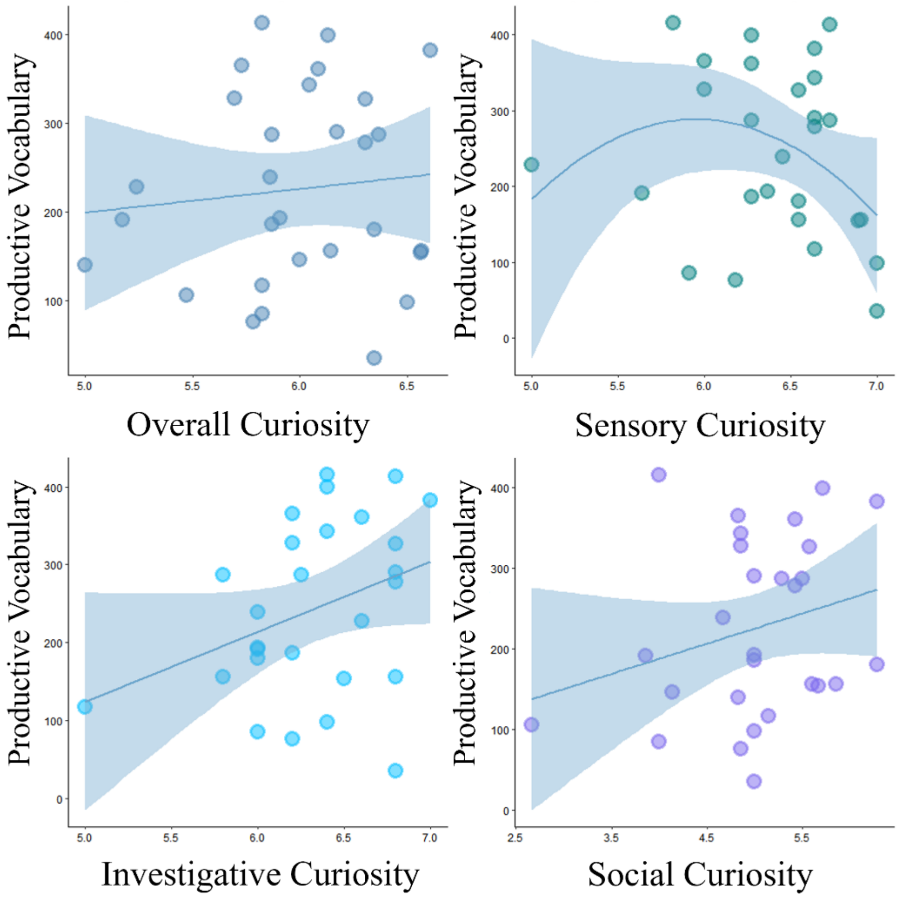


Figure 5.1. Relations between productive vocabulary size and curiosity scores. Separately presented for (top left) overall curiosity (n = 29), (top right) sensory curiosity, (bottom left) investigative curiosity and (bottom right) social curiosity (n = 28) after outlier exclusion.

To explore the relationship between the subscales of trait curiosity and productive vocabulary one year later we first excluded two multivariate outliers based on Cook's distance. Regression analyses on the remaining $n = 28$ (Figure 5.1), controlling for sex (12 females, 16 males) and age at T2 ($M = 23.9$ $SD = .30$), found significant linear relations between productive vocabulary and the subscales (sensory: $b = -136.79$, $p = .025$; investigative: $b = 112.96$, $p = .023$) with the model explaining 33% of the variance in the data, but non-significantly so ($F(5, 22) = 2.14$, $p = .099$). However, as visual inspection suggested the relationship between sensory curiosity and vocabulary to follow an inverted u-shape, we tested whether including a quadratic term for this subscale could explain any additional variance and improve model fit, which it did ($\Delta F(1, 21) = 7.99$, $p = .010$). Indeed, by adding this term, the model could now explain 51% of the variance in the data ($F(6, 21) = 3.68$, $p = .012$) with each of the subscale predictors reaching significance. Specifically, infants who had higher scores on the investigative subscale ($b = 107.68$, $p = .014$) and on the social subscale ($b = 57.80$, $p = .034$) at 10-12 months had reportedly larger productive vocabularies at 24 months. The inverted u-shaped relationship between sensory curiosity and productive vocabulary indicated that infants with comparatively intermediate curiosity scores reportedly formed the largest productive vocabulary by 24 months (linear term: $b = -211.40$, $p = .001$; quadratic term: $b = -165.03$, $p = .010$). Neither sex ($b_{male} = -13.12$, $p = .708$) nor age at T2 ($b = -20.57$, $p = .740$), however, were significant predictors.

5.5.2 Receptive vocabulary

To explore the relationship between trait curiosity and receptive vocabulary one year later we first excluded one bivariate outlier based on Cook's distance. Regression analyses on the remaining $n = 29$ participants (Figure 5.2, top left), controlling for sex (12 females, 17 males) and age at T2 ($M = 23.9$ $SD = .30$), found that receptive vocabulary was not directly predicted by overall curiosity ($b = -21.08$, $p = .449$) and could only explain 3% of variance in the data ($F(3, 25) = 0.27$, $p = .844$). As visual inspection suggested an inverted u-shaped relationship, we tested whether adding a quadratic term for overall curiosity could explain any additional variance and improve model fit, which it did not ($\Delta F(1, 24) = 0$, $p = .996$).

To explore the relationship between the subscales of trait curiosity and receptive vocabulary one year later we first excluded three multivariate outliers based on Cook's distance. Regression analyses on the remaining $n = 27$ (Figure 5.2), controlling for sex (11 females, 16 males) and age at T2 ($M = 23.9$ $SD = .26$), found that receptive vocabulary was not linearly predicted by the subscales either (all predictors' *ps* $> .05$) with the model explaining 13% of the variance in the data, but non-significantly so ($F(5, 21) = 0.64$, $p = .671$). However, as visual inspection suggested the relationship between sensory curiosity and vocabulary to follow an inverted u-shape, we tested whether including a quadratic term for this subscale could explain any additional variance and improve model fit, which it did ($\Delta F(1, 20) = 4.33$, $p = .050$). By adding this term, which itself reached significance ($b = -73.86$, $p = .050$), investigative curiosity became a significantly positive predictor of receptive vocabulary ($b = 59.06$, $p = .024$) and the model could now explain 29% of the variance in the data. However, the model itself did not show a significant fit ($F(6, 20) = 1.34$, $p = .285$).

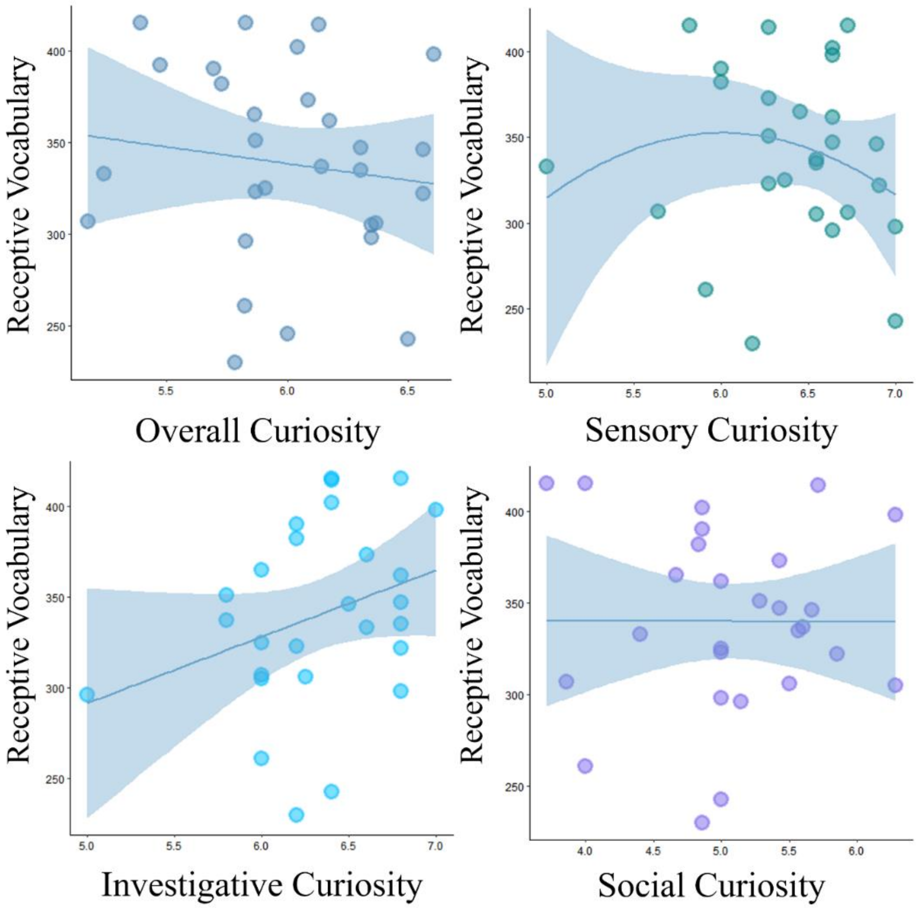


Figure 5.2. Relations between receptive vocabulary size and curiosity scores. Separately presented for (top left) overall curiosity ($n = 29$), (top right) sensory curiosity, (bottom left) investigative curiosity and (bottom right) social curiosity ($n = 27$) after outlier exclusion.

5.6 Discussion

The current longitudinal study tested whether differences in infants' trait curiosity at 10-12 months of age were predictive of vocabulary at 24 months. While overall trait curiosity did not significantly predict vocabulary about a year later, we found that the curiosity subscales did differentially predict this developmental outcome – however, only regarding productive vocabulary. Specifically, infants with higher levels of investigative (e.g., inspecting an object's functions or a container's contents) and social (e.g., using pointing to request information from social others) curiosity were found to develop larger productive vocabularies, whereas sensory curiosity (e.g., scanning and interacting with a wide variety of objects) formed an inverted U-shaped relationship with productive vocabulary size. Similar patterns were found regarding the receptive vocabulary, however, the model itself could not explain a significant amount of variance in the data.

That both infants' tendencies to employ investigative and social curiosity were predictive of a larger productive vocabulary is in line with previous observational studies on specific exploration behaviours. For instance, it has been found that more efficient exploration of an object's functions (Muentener et al., 2018), sustained attention (Yu et al., 2019), as well as the onset and frequency of pointing behaviours (Camaioni et al., 1991; Colonnesi et al., 2010; Fenson et al., 1994; Rowe et al., 2008) predicted larger vocabularies (but note Nicoladis & Barbosa, 2024). However, it was unexpected that sensory curiosity formed an inverted U-shape with vocabulary size. This finding could be explained by previously shown benefits of early exploitative tendencies focused on a small selection of objects with repeated language-related information being linked to earlier and more robust word learning (Karmazyn-Raz & Smith, 2023; Slone et al., 2019; Smith et al., 2018). Furthermore, solidified information encoding requires such exploitative engagement (Jalongo & Sobolak, 2011) and the learning of word-object mappings has been shown to be a slow and gradual process (Horst & Samuelson, 2008; McMurray et al., 2012). Given that the ITCQ's sensory curiosity subscale captures infants' broader exploration, at the extreme end, such explorative tendencies might be detrimental to effective word learning if it comes at the expense of deeper engagement with the encountered information.

From this discussion it also becomes clear that the non-significant result regarding overall curiosity can be explained by the differential impact of sensory curiosity. While higher levels of investigative and social curiosity plausibly lead to the beneficial exploitative engagement, too much sensory curiosity might negate this benefit if it manifests in distractibility. Alternatively, both vocabulary scores as well as scores on the former two subscales in this young age group are likely linked to the infant's cognitive development (Mundy & Jarrold, 2010; Tomasello et al., 2007) and processing speed (e.g., Poli et al., 2023), which were not measured in this study. Consequently, controlling for individual differences in these domains might reveal a positive effect of overall curiosity as well, meaning that as long as the infant is an effective and fast information processor (see also Lany, 2018; Lany et al., 2018b), more curiosity overall, including a stronger explorative tendency, would predict larger vocabularies.

Of note are the null findings regarding curiosity's role in predicting receptive vocabulary, as even though certain predictors reached significance in line with the above pattern, the model itself did not. However, as most studies on infants from around 24 months of age tend to not report receptive vocabulary and neither do studies on links with exploration behaviours (Muentener et al., 2018; Rantalainen et al., 2021), this finding does not stand in contrast to the literature. There have been previous suggestions of receptive vocabulary scores being noisy due to a risk of overestimating children's early word comprehension (compare Lany et al., 2018a). This is because caregiver reports of their children's understanding require assumptions and inferences about their abilities, whereas word production is directly observable and thus more reliable (e.g., Fenson et al., 1994). Indeed, it has been shown that infants as young at 6 months know the meanings of words that caregivers fail to report (Bergelson & Swingley, 2012, 2015). We therefore propose to treat this result with caution and suggest testing this with a word recognition task instead (e.g., Reznick, 1990).

In conclusion, this brief report presented a longitudinal study that found three distinct exploration tendencies of trait curiosity at 10-12 months of age to predict productive vocabulary at 24 months. These findings offer new insights regarding the benefits but also the potential pitfalls of infant curiosity, indicating that language development requires exploration but not to the degree that it comes at the cost of exploitation of learning opportunities. This is the first time this association has been established via a holistic approach, capturing various exploration tendencies as manifestations of infants' trait curiosity. Considering how trait curiosity has been linked to occupational trajectories and positive developmental outcomes in adults (Grossnickle, 2016; Reio, 2024) while also highlighting the developmental importance of early language abilities (e.g., McKean & Reilly, 2023), our findings help better understand the intricate yet wide-reaching impact trait curiosity might already have from infancy onward.

5.7 References

Ackermann, L., Förster, M., Schaarschmidt, J., Hepach, R., Mani, N., & Eiteljoerge, S. (2023). The role of interest in young children's retention of words. *Infant and Child Development*, e2466.

Ackermann, L., Hepach, R., & Mani, N. (2020). Children learn words easier when they are interested in the category to which the word belongs. *Developmental Science*, *23*(3). https://doi.org/10.1111/desc.12915

Ackermann, L., Lo, C. H., Mani, N., & Mayor, J. (2020b). Word learning from a tablet app: Toddlers perform better in a passive context. *PLOS ONE*, *15*(12), e0240519. https://doi.org/10.1371/journal.pone.0240519

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*, 141–164.

Alan, S., & Mumcu, I. (2024). Nurturing Childhood Curiosity to Enhance Learning: Evidence from a Randomized Pedagogical Intervention. *American Economic Review*, *114*(4), 1173–1210. https://doi.org/10.1257/aer.20230084

Altmann, E. C., Bazhydai, M., Karadağ, D., & Westermann, G. (2024). *The Infant and Toddler Curiosity Questionnaire: A validated caregiver-report measure of curiosity in children from 5 to 24 months*. OSF. https://doi.org/10.31234/osf.io/9swaf

Altmann, E. C., Bazhydai, M., & Westermann, G. (2023). *Curious Choices: Infants' moment-to-moment information sampling is driven by their exploration history*. PsyArXiv. https://doi.org/10.31234/osf.io/7d28k

Aureli, T., Perucchini, P., & Iverson, J. M. (2013). Motor acts and communicative gestures from 9 to 18 months of age in imperative and declarative context: Tracing the origin and development of pointing. *Rivista Di Psicolinguistica Applicata: XIII, 2, 2013*, 21–30.

Bazhydai, M., Jones, S. D., & Westermann, G. (2022, January 26). *Does curiosity enhance word learning in 18-month-old infants? A Registered Report.* [Other]. https://doi.org/10.31219/osf.io/bm5a9

Bazhydai, M., Twomey, K., & Westermann, G. (2021). Curiosity and Exploration. In J. B. Benson (Ed.), *Encyclopedia of Infant and Early Childhood Development* (2nd ed; Issue 2nd ed). Elsevier. https://eprints.lancs.ac.uk/id/eprint/136590/

Bazhydai, M., Westermann, G., & Parise, E. (2020). "I don't know but I know who to ask": 12-month-olds actively seek information from knowledgeable adults. *Developmental Science*, *23*(5), e12938. https://doi.org/10.1111/desc.12938

Begus, K., Gliga, T., & Southgate, V. (2014). Infants Learn What They Want to Learn: Responding to Infant Pointing Leads to Superior Learning. *PLoS ONE*, *9*(10), e108817. https://doi.org/10.1371/journal.pone.0108817

Begus, K., & Southgate, V. (2018). Curious Learners: How Infants' Motivation to Learn Shapes and Is Shaped by Infants' Interactions with the Social World. In M. M. Saylor & P. A. Ganea (Eds.), *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms* (pp. 13–37). Springer International Publishing. https://doi.org/10.1007/978-3-319-77182-3_2

Bergelson, E., & Swingley, D. (2012). At 6–9 months, human infants know the meanings of many common nouns. *Proceedings of the National Academy of Sciences*, *109*(9), 3253–3258.

Bergelson, E., & Swingley, D. (2015). Early word comprehension in infants: Replication and extension. *Language Learning and Development*, *11*(4), 369–380.

Berlyne, D. E. (1960). *Conflict, arousal, and curiosity* (pp. xii, 350). McGraw-Hill Book Company. https://doi.org/10.1037/11164-000

Bonawitz, E. B., van Schijndel, T. J. P., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive Psychology*, *64*(4), 215–234. https://doi.org/10.1016/j.cogpsych.2011.12.002

Bornstein, M. H., Putnick, D. L., Hahn, C.-S., Tamis-LeMonda, C. S., & Esposito, G. (2020). Stabilities of infant behaviors and maternal responses to them. *Infancy*, *25*(3), 226–245.

Camaioni, L., Castelli, M. C., Longobardi, E., & Volterra, V. (1991). A parent report instrument for early language assessment. *First Language*, *11*(33), 345–358. https://doi.org/10.1177/014272379101103303

Carranza Carnicero, J. A., Pérez-López, J., Del Carmen González Salinas, M., & Martínez-Fuentes, M. T. (2000). A longitudinal study of temperament in infancy: Stability and convergence of measures. *European Journal of Personality*, *14*(1), 21–37.

Chen, X., Twomey, K. E., & Westermann, G. (2022). Curiosity enhances incidental object encoding in 8-month-old infants. *Journal of Experimental Child Psychology*, *223*, 105508. https://doi.org/10.1016/j.jecp.2022.105508

Chouinard, M. M., Harris, P. L., & Maratsos, M. P. (2007). Children's questions: A mechanism for cognitive development. *Monographs of the Society for Research in Child Development*, i–129.

Colombo, J., Mitchell, D. W., O'Brien, M., & Horowitz, F. D. (1987). The stability of visual habituation during the first year of life. *Child Development*, 474–487.

Colonnesi, C., Stams, G. J. J. M., Koster, I., & Noom, M. J. (2010). The relation between pointing and language development: A meta-analysis. *Developmental Review*, *30*(4), 352–366. https://doi.org/10.1016/j.dr.2010.10.001

Cook, C., Goodman, N. D., & Schulz, L. E. (2011). Where science starts: Spontaneous experiments in preschoolers' exploratory play. *Cognition*, *120*(3), 341–349.

Engel, S. (2011). Children's Need to Know: Curiosity in Schools. *Harvard Educational Review*, *81*(4), 625–645. https://doi.org/10.17763/haer.81.4.h054131316473115

Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., Pethick, S. J., Tomasello, M., Mervis, C. B., & Stiles, J. (1994). Variability in Early Communicative Development. *Monographs of the Society for Research in Child Development*, *59*(5), i–185. https://doi.org/10.2307/1166093

Gaertner, B. M., Spinrad, T. L., & Eisenberg, N. (2008). Focused attention in toddlers: Measurement, stability, and relations to negative emotion and parenting. *Infant and Child Development: An International Journal of Research and Practice*, *17*(4), 339–363.

Goldstein, M. H., Schwade, J., Briesch, J., & Syal, S. (2010). Learning While Babbling: Prelinguistic Object-Directed Vocalizations Indicate a Readiness to Learn. *Infancy*, *15*(4), 362–391. https://doi.org/10.1111/j.1532-7078.2009.00020.x

Gottlieb, J., Oudeyer, P.-Y., Lopes, M., & Baranes, A. (2013). Information-seeking, curiosity, and attention: Computational and neural mechanisms. *Trends in Cognitive Sciences*, *17*(11), 585–593. https://doi.org/10.1016/j.tics.2013.09.001

Grossnickle, E. M. (2016). Disentangling Curiosity: Dimensionality, Definitions, and Distinctions from Interest in Educational Contexts. *Educational Psychology Review*, *28*(1), 23–60. https://doi.org/10.1007/s10648-014-9294-y

Gruber, M. J., & Fandakova, Y. (2021). Curiosity in childhood and adolescence—What can we learn from the brain. *Current Opinion in Behavioral Sciences*, *39*, 178–184. https://doi.org/10.1016/j.cobeha.2021.03.031

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of Curiosity Modulate Hippocampus-Dependent Learning via the Dopaminergic Circuit. *Neuron*, *84*(2), 486–496. https://doi.org/10.1016/j.neuron.2014.08.060

Hamilton, A., Plunkett, K., & Schafer, G. (2000). Infant vocabulary development assessed with a British communicative development inventory. *Journal of Child Language*, *27*(3), 689–705. https://doi.org/10.1017/S0305000900004414

Hardy, J. H., Ness, A. M., & Mecca, J. (2017). Outside the box: Epistemic curiosity as a predictor of creative problem solving and creative performance. *Personality and Individual Differences*, *104*, 230–237. https://doi.org/10.1016/j.paid.2016.08.004

Horst, J. S., & Samuelson, L. K. (2008). Fast mapping but poor retention by 24-month-old infants. *Infancy*, *13*(2), 128–157.

Iacobucci, D., Schneider, M. J., Popovich, D. L., & Bakamitsos, G. A. (2016). Mean centering helps alleviate “micro” but not “macro” multicollinearity. *Behavior Research Methods*, *48*(4), 1308–1317. https://doi.org/10.3758/s13428-015-0624-x

Inagaki, K. (1978). Effects of Object Curiosity on Exploratory Learning in Young Children. *Psychological Reports*, *42*(3), 899–908. https://doi.org/10.2466/pr0.1978.42.3.899

Iverson, J. M., & Goldin-Meadow, S. (2005). Gesture paves the way for language development. *Psychological Science*, *16*(5), 367–371.

Jago, L. S., Alcock, K., Meints, K., Pine, J. M., & Rowland, C. F. (2023). Language outcomes from the UK-CDI Project: Can risk factors, vocabulary skills and gesture scores in infancy predict later language disorders or concern for language development? *Frontiers in Psychology*, *14*. https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1167810

Jalongo, M. R., & Sobolak, M. J. (2011). Supporting Young Children’s Vocabulary Growth: The Challenges, the Benefits, and Evidence-Based Strategies. *Early Childhood Education Journal*, *38*(6), 421–429. https://doi.org/10.1007/s10643-010-0433-x

Jepma, M., Verdonschot, R. G., van Steenbergen, H., Rombouts, S. A. R. B., & Nieuwenhuis, S. (2012). Neural mechanisms underlying the induction and relief of perceptual curiosity. *Frontiers in Behavioral Neuroscience*, *6*.

https://doi.org/10.3389/fnbeh.2012.00005
Jirout, J., & Klahr, D. (2012). Children's scientific curiosity: In search of an operational definition of an elusive concept. *Developmental Review*, *32*(2), 125–160. https://doi.org/10.1016/j.dr.2012.04.002
Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T., & Camerer, C. F. (2009). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. *Psychological Science*, *20*(8), 963–973. https://doi.org/10.1111/j.1467-9280.2009.02402.x
Karmazyn-Raz, H., & Smith, L. B. (2023). Sampling statistics are like story creation: A network analysis of parent–toddler exploratory play. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *378*(1870), 20210358. https://doi.org/10.1098/rstb.2021.0358
Kashdan, T. B., Disabato, D. J., Goodman, F. R., & McKnight, P. E. (2020). The Five-Dimensional Curiosity Scale Revised (5DCR): Briefer subscales while separating overt and covert social curiosity. *Personality and Individual Differences*, *157*, 109836. https://doi.org/10.1016/j.paid.2020.109836
Kashdan, T. B., & Yuen, M. (2007). Whether highly curious students thrive academically depends on perceptions about the school learning environment: A study of Hong Kong adolescents. *Motivation and Emotion*, *31*(4), 260–270. https://doi.org/10.1007/s11031-007-9074-9
Kidd, C., & Hayden, B. Y. (2015). The Psychology and Neuroscience of Curiosity. *Neuron*, *88*(3), 449–460. https://doi.org/10.1016/j.neuron.2015.09.010
Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks Effect: Human Infants Allocate Attention to Visual Sequences That Are Neither Too Simple Nor Too Complex. *PLoS ONE*, *7*(5), e36399. https://doi.org/10.1371/journal.pone.0036399
Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks Effect in Infant Auditory Attention. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12263
Lany, J. (2018). Lexical-processing efficiency leverages novel word learning in infants and toddlers. *Developmental Science*, *21*(3), e12569. https://doi.org/10.1111/desc.12569
Lany, J., Giglio, M., & Oswald, M. (2018). Infants' Lexical Processing Efficiency is Related to Vocabulary Size by One Year of Age. *Infancy*, *23*(3), 342–366. https://doi.org/10.1111/infa.12228
Lany, J., Shoaib, A., Thompson, A., & Estes, K. G. (2018). Infant statistical-learning ability is related to real-time language processing. *Journal of Child Language*, *45*(2), 368–391. https://doi.org/10.1017/S0305000917000253
Lee, N., Lazaro, V., Wang, J. J., Şen, H. H., & Lucca, K. (2023). Exploring individual differences in infants' looking preferences for impossible events: The Early Multidimensional Curiosity Scale. *Frontiers in Psychology*, *13*. https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1015649

Legare, C. H. (2012). Exploring Explanation: Explaining Inconsistent Evidence Informs Exploratory, Hypothesis-Testing Behavior in Young Children. *Child Development*, *83*(1), 173–185. https://doi.org/10.1111/j.1467-8624.2011.01691.x

Legare, C. H. (2014). The Contributions of Explanation and Exploration to Children's Scientific Reasoning. *Child Development Perspectives*, *8*(2), 101–106. https://doi.org/10.1111/cdep.12070

Liszkowski, U., Carpenter, M., Henning, A., Striano, T., & Tomasello, M. (2004). Twelve-month-olds point to share attention and interest. *Developmental Science*, *7*(3), 297–307. https://doi.org/10.1111/j.1467-7687.2004.00349.x

Lucca, K., & Wilbourn, M. P. (2019). The what and the how: Information-seeking pointing gestures facilitate learning labels and functions. *Journal of Experimental Child Psychology*, *178*, 417–436. https://doi.org/10.1016/j.jecp.2018.08.003

Mani, N., & Ackermann, L. (2018). Why Do Children Learn the Words They Do? *Child Development Perspectives*, *12*(4), 253–257. https://doi.org/10.1111/cdep.12295

McKean, C., & Reilly, S. (2023). Creating the conditions for robust early language development for all: Part two: Evidence informed public health framework for child language in the early years. *International Journal of Language & Communication Disorders*, *58*(6), 2242–2264. https://doi.org/10.1111/1460-6984.12927

McMurray, B., Horst, J. S., & Samuelson, L. K. (2012). Word learning emerges from the interaction of online referent selection and slow associative learning. *Psychological Review*, *119*(4), 831.

Muentener, P., Herrig, E., & Schulz, L. (2018). The efficiency of infants' exploratory play is related to longer-term cognitive development. *Frontiers in Psychology*, *9*, 635.

Mundy, P., & Jarrold, W. (2010). Infant joint attention, neural networks and social cognition. *Neural Networks*, *23*(8), 985–997. https://doi.org/10.1016/j.neunet.2010.08.009

Mussel, P. (2013). Intellect: A theoretical framework for personality traits related to intellectual achievements. *Journal of Personality and Social Psychology*, *104*(5), 885–906. https://doi.org/10.1037/a0031918

Nicoladis, E., & Barbosa, P. G. (2024). Infants' pointing at nine months is associated with maternal sensitivity but not vocabulary. *Infant Behavior and Development*, *74*, 101923. https://doi.org/10.1016/j.infbeh.2024.101923

Oudeyer, P.-Y., Kaplan, F., & Hafner, V. V. (2007). Intrinsic Motivation Systems for Autonomous Mental Development. *IEEE Transactions on Evolutionary Computation*, *11*(2), 265–286. https://doi.org/10.1109/TEVC.2006.890271

Pérez-Edgar, K., Vallorani, A., Buss, K. A., & LoBue, V. (2020). Individual differences in infancy research: Letting the baby stand out from the crowd. *Infancy*, *25*(4), 438–457. https://doi.org/10.1111/infa.12338

Piaget, J. (1976). Piaget's Theory. In B. Inhelder, H. H. Chipman, & C. Zwingmann (Eds.), *Piaget and His School: A Reader in Developmental Psychology* (pp. 11–23). Springer. https://doi.org/10.1007/978-3-642-46323-5_2

Poli, F., Ghilardi, T., Beijers, R., de Weerth, C., Hinne, M., Mars, R. B., & Hunnius, S. (2023). *Individual differences in processing speed and curiosity explain infant habituation and dishabituation performance*.

Poli, F., Serino, G., Mars, R. B., & Hunnius, S. (2020). Infants tailor their attention to maximize learning. *Science Advances*, *6*(39), eabb5053. https://doi.org/10.1126/sciadv.abb5053

Rantalainen, K., Paavola-Ruotsalainen, L., Alakortes, J., Carter, A. S., Ebeling, H. E., & Kunnari, S. (2021). Early vocabulary development: Relationships with prelinguistic skills and early social-emotional/behavioral problems and competencies. *Infant Behavior and Development*, *62*, 101525.

Reio Jr., T. G. (2024). Individual Differences in Curiosity. *The Oxford Handbook of Individual Differences in Organizational Contexts*, 43.

Reio Jr., T. G., & Callahan, J. L. (2004). Affect, curiosity, and socialization-related learning: A path analysis of antecedents to job performance. *Journal of Business and Psychology*, *19*, 3–22.

Reio Jr., T. G., Petrosko, J., Wiswell, A., & Thongsukmag, J. (2006). The Measurement and Conceptualization of Curiosity. *The Journal of Genetic Psychology*, *167*(2), 117–135. https://doi.org/10.3200/GNTP.167.2.117-135

Reio Jr., T. G., & Wiswell, A. (2000). Field investigation of the relationship among adult curiosity, workplace learning, and job performance. *Human Resource Development Quarterly*, *11*(1), 5–30. https://doi.org/10.1002/1532-1096(200021)11:1<5::AID-HRDQ2>3.0.CO;2-A

Reznick, J. S. (1990). Visual preference as a test of infant word comprehension. *Applied Psycholinguistics*, *11*(2), 145–166.

Rowe, M. L., Özçalışkan, Ş., & Goldin-Meadow, S. (2008). Learning words by hand: Gesture's role in predicting vocabulary development. *First Language*, *28*(2), 182–199.

Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: Preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology*, *43*(4), 1045–1050. https://doi.org/10.1037/0012-1649.43.4.1045

Schulz, L. E., Standing, H. R., & Bonawitz, E. B. (2008). Word, thought, and deed: The role of object categories in children's inductive inferences and exploratory play. *Developmental Psychology*, *44*(5), 1266.

Schutte, N. S., & Malouff, J. M. (2020). A Meta-Analysis of the Relationship between Curiosity and Creativity. *The Journal of Creative Behavior*, *54*(4), 940–947. https://doi.org/10.1002/jocb.421

Shah, P. E., Weeks, H. M., Richards, B., & Kaciroti, N. (2018). Early childhood curiosity and kindergarten reading and math academic achievement. *Pediatric Research*, *84*(3), Article 3. https://doi.org/10.1038/s41390-018-0039-3

Singh, A., & Manjaly, J. A. (2022). Using Curiosity to Improve Learning Outcomes in Schools. *Sage Open*, *12*(1), 21582440211069392. https://doi.org/10.1177/21582440211069392

Slone, L. K., Smith, L. B., & Yu, C. (2019). Self-generated variability in object images predicts vocabulary growth. *Developmental Science*, *22*(6), e12816. https://doi.org/10.1111/desc.12816

Smith, L. B., Jayaraman, S., Clerkin, E., & Yu, C. (2018). The Developing Infant Creates a Curriculum for Statistical Learning. *Trends in Cognitive Sciences*, *22*(4), 325–336. https://doi.org/10.1016/j.tics.2018.02.004

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*(6230), 91–94. https://doi.org/10.1126/science.aaa3799

Thompson, C. G., Kim, R. S., Aloe, A. M., & Becker, B. J. (2017). Extracting the Variance Inflation Factor and Other Multicollinearity Diagnostics from Typical Regression Results. *Basic and Applied Social Psychology*, *39*(2), 81–90. https://doi.org/10.1080/01973533.2016.1277529

Thurman, S. L., & Corbetta, D. (2017). Spatial exploration and changes in infant–mother dyads around transitions in infant locomotion. *Developmental Psychology*, *53*(7), 1207–1221. https://doi.org/10.1037/dev0000328

Tomasello, M., Carpenter, M., & Liszkowski, U. (2007). A new look at infant pointing. *Child Development*, *78*(3), 705–722.

van Schijndel, T. J., Jansen, B. R., & Raijmakers, M. E. (2018). Do individual differences in children's curiosity relate to their inquiry-based learning? *International Journal of Science Education*, *40*(9), 996–1015.

Watson, L., Inan, I., Whitcomb, D., & Yigit, S. (2018). Educating for curiosity. *The Moral Psychology of Curiosity*, 293–309.

Yu, C., Suanda, S. H., & Smith, L. B. (2019). Infant sustained attention but not joint attention to objects at 9 months predicts vocabulary at 12 and 15 months. *Developmental Science*, *22*(1), e12735. https://doi.org/10.1111/desc.12735

Zettersten, M. (2020). *Seeking New Words: Active Word Learning in Infants and Children* [Ph.D., The University of Wisconsin - Madison]. https://search.proquest.com/docview/2408896456/abstract/E02DABE6983D46B2PQ/1

6 GENERAL DISCUSSION

Curiosity plays a pivotal role in our exploration, motivation to learn, and continued growth throughout development. Nevertheless, research has been largely neglecting its conceptualisation and mechanism during the early stages of development. This is due to the fact that even its existing, adult-oriented definitions have not yet formed a consensus and are challenging, if not impossible, to apply to infant behaviours. Consequently, the overarching objective of this thesis was to advance our comprehensive understanding of infant curiosity through pioneering research on both state and trait curiosity, as well as by establishing links between these constructs and important developmental outcomes.

6.1 What were the main findings?

Chapter 2 introduced a novel gaze-contingent eye-tracking paradigm to investigate the mechanisms underlying infants' active exploration. The study showed that infants structured their information sampling based on an epxloitative tendency to re-engage with a novel category, but that the self-generated sequences fell into clusters characterised by briefer more explorative, longer more exploitative, and intermediately long, overall more balanced sampling patterns. Furthermore, infants' engagement with a triggered exemplar at one trial was associated with their likelihood to re-engage or disengage from that information soure (here category) at the subsequent trial. Specifically, infants were more likely to switch from exploiting one category to exploring the other after spending less time looking at the presented stimulus, shifting their gaze more frequently to the untriggered side, and especially when it took them longer to trigger the subsequent trial. These behavioural measures interacted with the degree of similarity between the previously viewed stimuli, indicating that infants' moment-to-moment information sampling, as an indicator of their state curiosity, was not spontaneous but driven by their preceding engagement with the encountered information.

Chapter 3 introduced the Infant and Toddler Curiosity Questionnaire (ITCQ) as the first caregiver report measure designed to assess trait curiosity specifically in infants and toddlers aged 5 to 24 months. The final questionnaire comprised 23 items, each evaluating observable exploration behaviours on a 7-point Likert scale. The questionnaire was found to be unidimensional enough to allow for an overall curiosity score, with three emergent subscales (sensory, investigative, and social[7] curiosity) showing acceptable

[7] Note: *social* as in using social others as a means of gaining information, not curiosity about social others.

internal consistency as well. Two additional smaller studies demonstrated the ITCQ's test-retest reliability and that this measure of infants' trait curiosity was related to, yet distinct from, their temperamental dispositions.

Chapter 4 explored the correspondence between infants' trait and state curiosity by relating observations from the previous two studies. This study, driven by the cluster of *balanced samplers* (Chapter 2), found that infants with comparatively intermediate curiosity scores engaged with the paradigm the longest, while curiosity scores linearly predicted stronger tendencies to switch between the two novel categories. However, curiosity did not significantly relate to the extent to which infants focused on exploiting either or both categories. In this way, the findings suggest that trait curiosity affects infants' dynamic information sampling by shifting the balance from exploitation towards exploration. Together, they provided the first evidence of a caregiver report measure of trait curiosity relating to infants' experimentally captured patterns of exploration.

Finally, Chapter 5 explored the predictive link between trait curiosity and language development, one of the most extensively researched areas in developmental psychology. This longitudinal study found that while overall curiosity scores did not directly relate to vocabulary size, the ITCQ's three curiosity subscales did differentially predict productive vocabulary one year later. Specifically, infants rated by their caregivers to score higher in investigative and social curiosity were found to have larger productive vocabularies one year later. In contrast, infants with lower and higher reported levels of sensory curiosity were found to develop smaller productive vocabularies. This last finding implies potential limits to the benefits of curiosity, with infants' high levels of sensory curiosity potentially leading to overemphasising exploration of the wider environment at the cost of exploiting the encountered information sources to robustly construct their knowledge. Together, these findings also provided the first evidence of a longitudinal association between infants' trait curiosity and vocabulary development.

6.2 What are the methodological contributions for measuring curiosity?

Research specifically on infant curiosity has only recently gained more attention. Such research has mainly taken the form of looking-time studies, testing which information characteristics lead to infants' longest engagement as an indication of their state curiosity (e.g., Chen et al., 2022; Kidd et al., 2012, 2014; Poli et al., 2020). These studies are invaluable for a more nuanced understanding of curiosity from an information-processing perspective but cannot capture how curiosity guides infants' active exploration and information sampling in the real world. In contrast, there has been a lot of research on global patterns and on the development of infants' active exploration (e.g., Caruso, 1989, 1993; Hoch et al., 2019; Karmazyn-Raz & Smith, 2023; Schatz et al., 2022; Slone et al., 2019; Smith et al., 2018; Tamis-LeMonda et al., 2013). However, their conceptualisation and measurement were typically too broad to allow investigations on the underlying mechanisms of curiosity. Furthermore, until now, it was hypothesised but not empirically tested whether individual differences in infants' engagement and self-generated exploration patterns were linked to their underlying trait curiosity.

A significant contribution of this thesis was the development of methodological approaches that address the limitations of previous studies. First, the innovative Curious Choices paradigm, presented in Chapter 2, bridges the gap between structured looking-time studies and unstructured designs that observe infants' active exploration in more naturalistic settings. It also enables researchers to adapt their designs to test specific hypotheses regarding how characteristics of the environment (e.g., the number of available information sources, the degree of uncertainty) and the available information (e.g., varying the familiarity of or similarities between stimuli) influence infants' state curiosity and dynamically guide their re-engagement.

Secondly, the ITCQ presented in Chapter 3 is the first caregiver report measure of trait curiosity specifically developed and validated for infants and toddlers up to 24 months of age. Given the lack of research on infants' trait curiosity, the ITCQ marks a meaningful contribution to this emerging field. Due to the lack of applicable theoretical frameworks, we decided to avoid the implementation of any specific approach and instead followed a folk psychology definition of trait curiosity as *a keen desire or tendency to actively explore one's immediate surroundings*. This approach allowed the formulation of items about observable behaviours which can minimise potential social desirability due to curiosity's very positive connotation in Western cultures (e.g., Keller, 2016). Furthermore, it provided a foundation for future investigations into curiosity in cultures where the construct may be viewed less positively (e.g., Jukes et al., 2021; Chuang & Su, 2009).

The process of questionnaire development is an ongoing and time-consuming endeavour for which there is no gold standard (Downing, 2003; Dunn & McCray, 2020; Pett et al., 2003). It requires an extensive amount of data and the integration of theory in ways that generate large quantities of researchers' degrees of freedom. Consequently, it is subject to scrutiny from both psychometric and topic-specific research communities, which makes it an unpopular endeavour to embark on. This thesis, however, succeeded in developing a new questionnaire with a clear and logically accessible procedure while taking a neutral theoretical stance due to the elusiveness of the psychological construct. Chapters 4 and 5 additionally demonstrated that the ITCQ could explain variance in infants' active exploration and even their language development trajectories, making it informative and meaningful, albeit a reliable and cost-effective measure of trait curiosity.

Together, these two methodological innovations represent a substantial advancement in curiosity research in early development. It is also noteworthy that all data, analysis scripts, and materials have been made openly available to support not only the important trend of transparency and research integrity but also to enable other researchers to adapt and apply them for use in their own studies.

6.3 What were the theoretical contributions for conceptualising curiosity?

By solving two central methodological shortcomings in the measurement of infant curiosity this thesis was able to make meaningful contributions to its theoretical conceptualisations. The findings highlighted the complex nature of active exploration in the pursuit of knowledge construction, including the interplay between infants' engagement behaviour, environmental stimuli, and trait curiosity.

The findings of Chapter 2 emphasise the importance of integrating both the available information (Kidd et al., 2012, 2014; Poli et al., 2020) and the infants' actual engagement with this information (Hunter & Ames, 1988; Oakes et al., 1991; Rose et al., 1982) for conjointly predicting infants' active exploration as a manifestation of their state curiosity (compare Twomey & Westermann, 2018). Furthermore, they demonstrate that actively switching between information sources is effortful (Daw et al., 2006; Hayden et al., 2011; Pelz et al., 2015), but that this cost seems to decrease as the infants' state curiosity subsides. This was indicated, for instance, by the predictive association between shorter looking at an encountered stimulus which was very similar to the preceding one and shorter durations to subsequently trigger a switch. However, it is also important to acknowledge the vast amount of variance in exploration patterns, which indicate the possible influence of early trait curiosity.

The development of the ITCQ, as reported in Chapter 3, demonstrated that trait curiosity can be reliably measured in infants but also it also allowed the identification of potential facets of curiosity. These are indicated by the three subscales of exploration tendencies manifesting sensory, investigative and social curiosity. Sensory curiosity (e.g., e.g., "My child actively inspects a variety of objects, whether it be toys or ordinary household items.") seems to capture a tendency to prioritise the exploration of a wider learning space (e.g., a whole room; a spectrum of toys) over the exploitation of a smaller, more specific learning space (e.g., the functions of a single toy). Conversely, such exploitation would be more prevalent in infants who display higher levels of investigative (e.g., "When I open my bag in front of my child, they will come and peek into it.") and social (e.g., "When reading a picture book together, my child directs me (e.g., by pointing) towards what they want to know more about.") curiosity. Nevertheless, a general curiosity factor was evidenced to underly all three subscales. This indicates that a highly curious infant is likely to achieve a balance between exploration (broad/diversive, Berlyne, 1960; Caruso, 1993) and exploitation (deep/specific). This enables them to make new discoveries but importantly, also to robustly construct their knowledge.

Indeed, the findings of Chapters 4 and 5 have enriched this interpretation by demonstrating that overall curiosity, and in particular these subscales, could explain variance in observed exploration behaviours (Chapter 4) and predict knowledge construction in the form of vocabulary size (Chapter 5). Specifically, the results indicated that higher reported levels of curiosity, manifested in deeper and specific exploration tendencies (investigative and social curiosity), led to more switching between information sources within a constrained learning space (two novel categories on screen). This, in turn, may facilitate more robust information encoding through their comparison (Oakes et al., 2009). Furthermore, the same tendencies were also found to predict larger productive vocabularies one year later, consistent with observational studies demonstrating benefits for similar behaviours in terms of sustained attention and pointing gestures (Colonnesi et al., 2010; Smith et al., 2018; Yu et al., 2019).

Conversely, very high levels of sensory curiosity were found to predict earlier disengagement from the task, indicative of a tendency to explore the broader environment more quickly. This was accompanied by smaller productive vocabularies one year later. Similar tendencies in the form of visual sensation seeking were recently found to predict infants' premature disengagement from stimuli that could have still offered them substantial learning progress (Piccardi et al., 2020). It can be argued that there is a point at which sensory curiosity becomes maladaptive, whereby it leads to an excessive focus on exploring the broader environment, to the detriment of information exploitation. Such an imbalance would hinder the robust encoding of information, and in turn impair the construction of language-related knowledge.

Together, the findings presented in Chapters 4 and 5 are complementary, and collectively contribute to our understanding of infants' trait curiosity. They underscore the influence trait curiosity exerts on infants' evolving states of curiosity, including the potential for adverse consequences resulting from an imbalance between exploration and exploitation. This intricate interplay, however, has not yet been incorporated into any of the existing theoretical frameworks of curiosity reviewed in the general introduction. Thus, in the following section, I will briefly introduce our new, unifying framework to provide a more comprehensive and holistic picture of the mechanisms underlying curiosity-driven information sampling from infancy onward.

6.3.1 What could a holistic approach to conceptualising curiosity look like?

The framework upon which our unifying theory of curiosity is based, is learning progress maximisation driving dynamic information sampling (Gottlieb et al., 2013; Gruber et al., 2014; Kang et al., 2008; Kaplan & Oudeyer, 2007; Oudeyer et al., 2007). In the context of the exploration-exploitation framework, this would state that a curious learner engages with an information source (e.g., an object, a category, a topic) as long as it offers intrinsically rewarding learning progress, but disengages when learning progress subsides (e.g., available information is fully encoded). Subsequently, they turn to explore the broader environment in order to discover new information sources worth exploiting (Figure 6.1), in order to maximise learning progress across time and to construct their knowledge (Kaplan & Oudeyer, 2007; Oudeyer et al., 2007; Poli et al., 2020, 2022; Ten et al., 2021).

Then, changes in dynamic information sampling can be explained by considering which information sources are anticipated to provide maximal learning progress given the learner's exploration history and prior knowledge (Twomey & Westermann, 2018; Wade & Kidd, 2019). This can be achieved by either further engaging with the current source or exploring the broader learning space to discover a better option. In this way, previous dual-process approaches, such as Berlye's specific and diversive exploration (1960), can be unified by identifying a single underlying mechanism, eliminating the need for differential motivations through boredom and uncertainty. A learner with metacognitive abilities would be able to identify a gap in their knowledge if they anticipated maximal learning progress from a certain bit of information which is not immediately accessible (Loewenstein, 1994; Murayama et al., 2019). In the event of unsuccessful sampling in pursuit of that specific bit of information, the negative state of deprivation may be experienced (Litman & Jimerson, 2004).

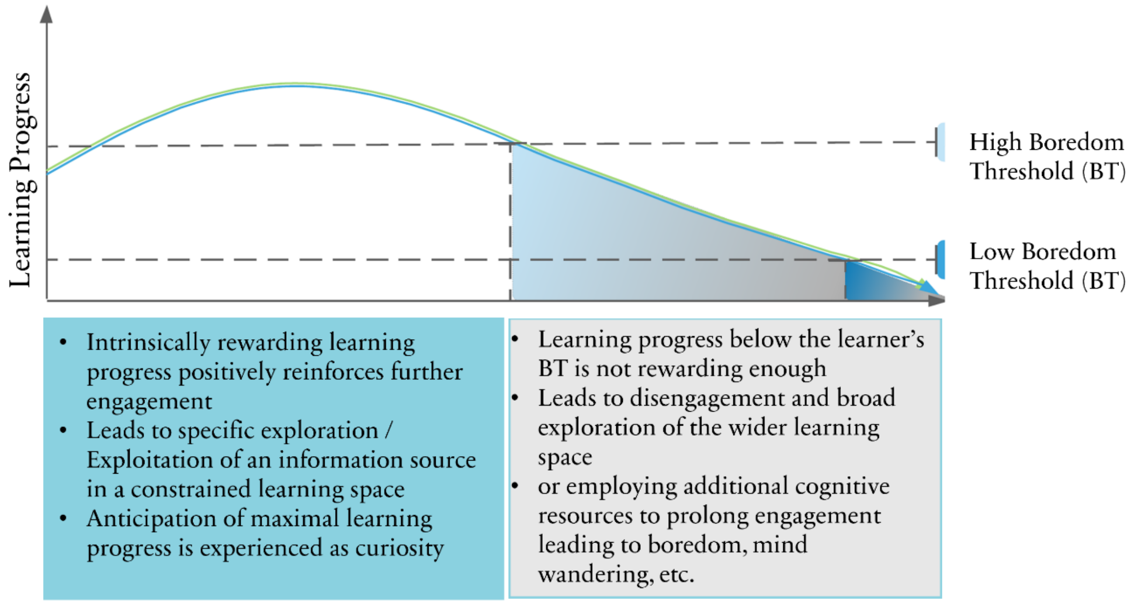


Figure 6.1. Illustration of the mechanism underlying dynamic information sampling in the new, unifying framework of curiosity.

We further expand this by proposing an individually varying parameter that can explain differences in more stable tendencies to weigh exploration against exploitation, namely the *boredom threshold* (Figure 6.1). In the absence of salient external information redirecting a learner's attention, this threshold determines the amount of learning progress that is *not* intrinsically rewarding enough to positively reinforce further engagement, and where the learner is likely to disengage from the current information source. We employed this term, not to reflect a boredom-based trigger mechanism (Berlyne, 1960), but because of the negative emotional state (Danckert, 2019) experienced when individuals are required to employ additional resources to continue engaging in an activity that does not challenge or satisfy them cognitively (Danckert & Merrifield, 2018; Eastwood et al., 2012).

This implies that given identical information and the same processing speed (Poli et al., 2023), a learner with a higher boredom threshold (reached sooner through declining learning progress, Figure 6.1) would disengage at an earlier stage (compare Piccardi et al., 2020) than a learner with a lower threshold. It can thereby reflect a more stable tendency to weigh exploration against exploitation and is likley manifested within trait curiosity, as observations from Chapters 4 and 5 would suggest. However, if the learner is still experiencing learning progress above this threshold, disengaging and switching to another information source then comes at a cost for inhibiting further, positively reinforced sampling behaviours (Daw et al., 2006).

These conceptualisations have potentially wide-reaching implications for research topics, including but not limited to interest formation (e.g., Murayama et al., 2019), boredom and the default mode network (e.g., Danckert, 2019), as well as the distinction between being curious or distractable (e.g., Chere, 2022). However, a discussion of these consequences would exceed the scope of this thesis.

6.4 Which are notable limitations of this thesis?

In regard to the experimental chapters of this thesis, it is necessary to acknowledge the challenges and limitations that were encountered. One consequence of giving infants an active role in the experimental studies was that the variance in the data increased and the observable effects decreased. Yet, this variance is nevertheless informative as infants do differ in their exploration and dynamic information sampling, so that it is important to acknowledge these differences. Demonstrating that we could explain some of that variance through trait curiosity further highlights the importance of such endeavours in the pursuit of a more holistic understanding of the construct (Pérez-Edgar et al., 2020).

Furthermore, gaze-contingent eye-tracking in infants may raise the question of *awareness*. Indeed, it is not possible to ensure that infants were *aware* of what they were doing or of the available information sources they could actively explore. Nevertheless, numerous studies have employed this methodology throughout infancy and robustly shown that infants rapidly learn this contingency (e.g., Bazhydai et al., 2022; Deligianni et al., 2011; Keemink et al., 2019; Tummeltshammer et al., 2014; Wang et al., 2012; Zettersten, 2020). Although this approach may not result in all infants discovering or engaging with all available information sources equally, it offers more ecologically valid and informative observations regarding infants' curiosity-driven, active exploration compared to predefined stimulus sequences. Nevertheless, this may have caused the necessarily reduced sample size in Chapter 4, as only the exploration patterns of infants who sampled from both categories in a more balanced way revealed the relationship to trait curiosity.

Furthermore, given the sensitivity of a gaze-contingent procedure to noisy sampling of infant gaze location, it is plausible that trials were not triggered appropriately due to missing data or low-quality calibration. However, in order to minimise this risk, an algorithm was implemented which was designed to ignore minor glitches in the data and only abort a gaze hit if a genuine look away from the screen occurred. Furthermore, a threshold of 700 ms was selected to minimise the probability of this occurring by chance, given that a look of such duration towards one location is unlikely to happen by chance when the infant is fussy. Finally, if the experimenter had any concerns about inappropriate triggering, the video recordings were inspected, which resulted in the reported exclusion of three infants. It is worth noting that analysing looking behaviour as a predictor of trigger choices, which were also based on infants' looking behaviour, could be perceived as circular. However, the behaviours during pre-trigger engagement and subsequent trigger phase were not identical. For instance, infants did not exhibit a greater tendency to shift their gaze or a decreased tendency to look during the trigger phase, which resulted in a switch.

Nevertheless, there is more to the paradigm that I had wished to explore, which I was unable to do due to the reduced testing time resulting from the COIVD-19 pandemic. Consequently, I needed to adapt my research plans and, instead, added the questionnaire development. Thus, I hope to address these limitations in the future. Based on the gained insights from my work, a more comprehensive version of these studies would include the following: To begin with, I would include a structured warm-up phase, with the aim of ensuring that each infant triggered each available information source for their "awareness" of these options, which could possibly support more balanced sampling across the sample. Furthermore, I would add a test phase to inform the depth of their information encoding and category formation, as well as a re-test to reflect whether patterns of exploration indeed captured more general tendencies or methodological artifacts. Lastly, I would control not only for their trait curiosity, but also for their temperament (van den Boom, 1994) and processing speed (Poli et al., 2023).

With regard to the development and validation of the questionnaire, one significant limitation of this thesis is the use of the same sample throughout all experimental chapters. On the one hand, this allowed us to measure the links between state and trait curiosity and explorative behaviours (Chapter 4) including a longitudinal study (Chapter 5) in the relatively short PhD time-frame. On the other hand, it is possible, that these findings could emerge only because the same data informed the factor structure in Chapter 3. To elaborate, questionnaire development is an iterative process that requires multiple independent samples to verify the reliability and validity of the established structures, and typically leads to adapted and revised versions (e.g., Putnam et al., 2014). Across their applications, findings might be inconsistent due to varying response patterns of caregivers from different socioeconomic backgrounds and cultures, which is why validation efforts are crucial. However, this was not possible in this thesis.

On a similar note, all data came from a rather homogenous WEIRD population (Western, Educated, Industrial, Rich, Democratic; Table 6.1) with a predominantly white ethnic background, which together, poses a clear need for additional studies in order to justify any generalisations (Putnam et al., 2024; Singh, 2024). Especially limiting in this

Table 6.1. Sample overview across the first two experimental chapters.

Chapters	**N**	**Age** (months)	**Sex** (m:f)	**Add. demo.**[a]	**Birth-order**	**Monoling. English**	**Maternal Education**
Chapter 2[b]	68	10-12	34:34	70%	1st: 42% 2nd: 49% ≥3rd: 9%	93%	**Postgraduate: 26%** **Higher Education: 54%** Practical skills/Trade studies: 9% Upper Secondary: 7% Lower Secondary: 4%
Chapter 3[c]	370	5-24 months	182:188	91%	1st: 50% 2nd: 40% ≥3rd: 10%	97%	**Postgraduate: 36%** **Higher Education: 46%** Practical skills/Trade studies: 7% Upper Secondary: 8% Lower Secondary: 2% No formal schooling: 0.3%

[a]Additional demographic data was optional so that not all participants indicated it. Percentages indicate full set of demographic data. Percentages for birth-order and maternal education are based on number of available responses per variable.
[b]Base-sample included throughout all experimental chapters (also in the full Chapter 3 sample). Chapter 4: representative subsample of n=60 and Chapter 5 of n=34. Not reported due to redundancies.
[c]Full sample reported of which the second and third within-chapter studies are comprised. Study 2: representative subsample of n=67 and Study 3 of n=75. Not reported due to redundancies.

regard is the predominantly high level of education. Even though the recruitment for the questionnaire study was largely conducted online via social media, and thus had the potential to reach a more representative population, the final sample ultimately reflects a self-selection bias. This bias alerts to the concern that the encouragement of curiosity likely is a privilege of those who have the time and resources, as well as, the environmental safety to allow it. Studies in Tanzanian and Chinese parents, for example, have indicated that despite cultural norms emphasizing obedience over independence and curiosity, parental education and financial security were strong predictors of more positive and encouraging attitudes (Jukes et al., 2021; Chuang & Su, 2009). However, such potential relations emerging from the ITCQ cannot reliably be established based on the here presented distributions, and thus, call for caution with regards to their generalisability.

Another limitation was that sample sizes in Chapters 4 and 5 were relatively limited due to experimental constraints and longitudinal attrition. Ideally, the samples would have overlapped more consistently to allow for a mediation analysis testing how infants' trait curiosity predicts language development via effects on their state curiosity. However, this was not possible given the available data, and the samples were therefore reported in two separate studies. Nevertheless, it can be contended that this approach facilitated a clearer report of two distinct constructs, active exploration and language development, also considering that the eye-tracking study did not specifically examine the relationship between exploration and word learning, nor did it assess any learning outcomes.

To conlcude, investigating the mechanisms underlying infants' active exploration is a complex process that necessitates a balance between making conservative decisions for stronger effects and aiming to explain the variance emerging from more ecologically valid observations. The reported findings, all of which are more exploratory in nature due to their novelty, nevertheless managed to lay an important foundation for future studies to build upon.

6.5 Where should we go from here?

A number of questions remain unanswered by this thesis, but it has opened up new avenues for future research. For instance, Chapters 2 and 4 suggested that exploration is a skill with cognitive development, processing speed, and the ability to overcome a switch cost being plausible parameters of individual differences, in addition to trait curiosity. Thus, future research should aim to differentiate the effects of state and trait curiosity from facets of cognitive development. Previously, it was demonstrated that infants' breadth of manual object exploration was linked to their problem-solving abilities (Caruso, 1993); thus, the Curious Choices paradigm in conjunction with the ITCQ and additional controls could be a novel approach to elucidate the underlying mechanisms that underpin this association. Finally, it would be beneficial to gather neurophysiological insights, for example by comparing the EEG activity during a passive and ative version of the paradigm, to enhance our understanding of the predictability of sampling choices, information encoding, and the possibility of an individually varying threshold to disengage (Piccardi et al., 2020).

Furthermore, recent research has shown that clustering (several repetitions close in time, reoccurring across the whole session) in parents' toddler-directed speech during free-play sessions resulted in superior word learning (Slone et al., 2023). However, little is known about the learning benefits of different timing schedules (clustered compared to massed together or spaced further apart; Goh & Barabási, 2008; Kim & Jo, 2016; Vázquez et al., 2006) early in development. The Curious Choices paradigm has recently inspired a collaboration to develop an adaptation to test which schedules lead to the best learning outcomes and which schedules toddlers actively generate themselves.

Additionally, the ITCQ thus far has been demonstrated to be reliable and informative in explaining variance in exploration behaviours and developmental trajectories via infants' trait curiosity. However, additional validation efforts are necessary to learn more about its value for research and its generalisability. For example, it could be investigated to what degree its expression and benefits are hindered by shyness (Hilton et al., 2019), and whether curiosity can be positively reinforced through caregiver nurturance (Alan & Mumcu, 2024; Merlo et al., 2007). Another important research question to address is whether trait curiosity corresponds to a neurophysiological marker such as greater theta oscillations (Begus & Bonawitz, 2020) or stronger activation of the reward circuits and hippocampus-dependent learning circuits (Gruber et al., 2014).

Furthermore, this work has already inspired new collaborations to translate and validate the ITCQ into several languages, including Dutch, German, and Italian, as well as an international collaboration for the development of its continuation into early childhood, the Early Child Curiosity Questionnaire (ECCQ; Altmann et al., 2023b). Both questionnaires could help control for additional variance in infants' engagement, thereby becoming a key measure throughout developmental research. Additionally, they could help reveal how the wide-reaching positive effects of trait curiosity in adulthood (review see, Reio, 2024) may find their origin already in infancy.

Finally, the ITCQ has made an important contribution by demonstrating that trait curiosity, as manifested in observable exploration tendencies, can be measured in pre-verbal infants, a population that, until recently, has been excluded from this research area.

Another population that has experienced such exclusion concerns animals, despite the ironic fact that the earliest curiosity studies investigated spontaneous exploration in rodents (Berlyne, 1955). As personality research also exists for animals (Stamps & Groothuis, 2010), the development of the ITCQ might inspire a similar approach to capture a curious trait and open new avenues for interdisciplinary, comparative research (Forss et al., 2024).

6.6 Conclusion

The importance of curiosity in infant development has been underestimated for too long. This is a significant gap in the literature, as infants represent the population possibly most reliant on curiosity to guide their exploration and knowledge construction. This thesis offers methodological innovations in the form of the Curious Choices paradigm and the ITCQ to measure the links between state and trait curiosity and patterns of active exploration. These innovations enabled theoretical contributions to this emerging research field, by conceptualising infants' state curiosity through dynamic information sampling choices and their trait curiosity as their tendencies to actively explore their immediate surroundings. Through my work, I was able to demonstrate that infants are active explorers whose individual information-sampling tendencies also impact their language development trajectories, showcasing curiosity's real-life importance. Collectively, this work emphasises the necessity to more comprehensively understand the interplay between state and trait curiosity from infancy onward, offering new tools and insights to do so. Importantly, this thesis confirms that infants are, in fact, in the driver's seat of their own development.

Consolidated Bibliography

Ackermann, L., Hepach, R., & Mani, N. (2020). Children learn words easier when they are interested in the category to which the word belongs. *Developmental Science*, *23*(3). https://doi.org/10.1111/desc.12915

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*, 141–164.

Aguirre, M., Brun, M., Couderc, A., Reboul, A., Senez, P., & Mascaro, O. (2022). Knowledge in Sight: Toddlers Plan Efficient Epistemic Actions by Anticipating Learning Gains. *Cognitive Science*, *46*(2), e13103. https://doi.org/10.1111/cogs.13103

Alan, S., & Mumcu, I. (2024). Nurturing Childhood Curiosity to Enhance Learning: Evidence from a Randomized Pedagogical Intervention. *American Economic Review*, *114*(4), 1173–1210. https://doi.org/10.1257/aer.20230084

Altmann, E. C., de Boer, E., Eiteljoerge, S., Bazhydai, M., Hunnius, S., Bounia-Mastrogianni, P., Meyer, M., Karadağ, D., Braithwaite, E. K., & Westermann, G. (2023, August 23). *The Development of the Early Child Curiosity Questionnaire (ECCQ)*. [Poster Presentation] 8th Lancaster Conference on Infant & Early Child Development, Lancaster, UK.

Altvater-Mackensen, N., Jessen, S., & Grossmann, T. (2017). Brain responses reveal that infants' face discrimination is guided by statistical learning from distributional information. *Developmental Science*, *20*(2), e12393. https://doi.org/10.1111/desc.12393

Baranes, A., & Oudeyer, P.-Y. (2013). Active learning of inverse models with intrinsically motivated goal exploration in robots. *Robotics and Autonomous Systems*, *61*(1), 49–73.

Bazhydai, M., Jones, S. D., & Westermann, G. (2022, January 26). *Does curiosity enhance word learning in 18-month-old infants? A Registered Report.* [Other]. https://doi.org/10.31219/osf.io/bm5a9

Bazhydai, M., Twomey, K., & Westermann, G. (2021). Curiosity and Exploration. In J. B. Benson (Ed.), *Encyclopedia of Infant and Early Childhood Development* (2nd ed; Issue 2nd ed). Elsevier. https://eprints.lancs.ac.uk/id/eprint/136590/

Bazhydai, M., Westermann, G., & Parise, E. (2020). "I don't know but I know who to ask": 12-month-olds actively seek information from knowledgeable adults. *Developmental Science*, *23*(5), e12938. https://doi.org/10.1111/desc.12938

Begus, K., & Bonawitz, E. (2020). The rhythm of learning: Theta oscillations as an index of active learning in infancy. *Developmental Cognitive Neuroscience*, *45*, 100810. https://doi.org/10.1016/j.dcn.2020.100810

Begus, K., Gliga, T., & Southgate, V. (2014). Infants Learn What They Want to Learn: Responding to Infant Pointing Leads to Superior Learning. *PLoS ONE*, *9*(10), e108817. https://doi.org/10.1371/journal.pone.0108817

Begus, K., & Southgate, V. (2018). Curious Learners: How Infants' Motivation to Learn Shapes and Is Shaped by Infants' Interactions with the Social World. In M. M.

Saylor & P. A. Ganea (Eds.), *Active Learning from Infancy to Childhood: Social Motivation, Cognition, and Linguistic Mechanisms* (pp. 13–37). Springer International Publishing. https://doi.org/10.1007/978-3-319-77182-3_2

Berg, C. A., & Sternberg, R. J. (1985). Response to novelty: Continuity versus discontinuity in the developmental course of intelligence. *Advances in Child Development and Behavior*, *19*, 1–47.

Berlyne, D. E. (1954). *A theory of human curiosity*.

Berlyne, D. E. (1955). The arousal and satiation of perceptual curiosity in the rat. *Journal of Comparative and Physiological Psychology*, *48*(4), 238–246. https://doi.org/10.1037/h0042968

Berlyne, D. E. (1960). *Conflict, arousal, and curiosity* (pp. xii, 350). McGraw-Hill Book Company. https://doi.org/10.1037/11164-000

Berridge, K. C. (1999). *Pleasure, pain, desire, and dread: Hidden core processes of emotion.*

Berridge, K. C., & Robinson, T. E. (1998). What is the role of dopamine in reward: Hedonic impact, reward learning, or incentive salience? *Brain Research Reviews*, *28*(3), 309–369.

Blanco, N. J., & Sloutsky, V. M. (2020). Attentional mechanisms drive systematic exploration in young children. *Cognition*, *202*, 104327. https://doi.org/10.1016/j.cognition.2020.104327

Blanco, N. J., & Sloutsky, V. M. (2021). Systematic exploration and uncertainty dominate young children's choices. *Developmental Science*, *24*(2), e13026. https://doi.org/10.1111/desc.13026

Bornstein, M. H., Hahn, C.-S., & Suwalsky, J. T. D. (2013). Physically Developed and Exploratory Young Infants Contribute to Their Own Long-Term Academic Achievement. *Psychological Science*, *24*(10), 1906–1917. https://doi.org/10.1177/0956797613479974

Bourgeois, K. S., Khawar, A. W., Neal, S. A., & Lockman, J. J. (2005). Infant Manual Exploration of Objects, Surfaces, and Their Interrelations. *Infancy*, *8*(3), 233–252. https://doi.org/10.1207/s15327078in0803_3

Caruso, D. A. (1989). Attachment and exploration in infancy: Research and applied issues. *Early Childhood Research Quarterly*, *4*(1), 117–132. https://doi.org/10.1016/S0885-2006(89)90129-4

Caruso, D. A. (1993). Dimensions of quality in infants' exploratory behavior: Relationships to problem-solving ability. *Infant Behavior and Development*, *16*(4), 441–454. https://doi.org/10.1016/0163-6383(93)80003-Q

Charnov, E. L. (1976). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, *9*(2), 129–136. https://doi.org/10.1016/0040-5809(76)90040-X

Chen, C., Houston, D. M., & Yu, C. (2021). Parent–Child Joint Behaviors in Novel Object Play Create High-Quality Data for Word Learning. *Child Development*, *92*(5), 1889–1905. https://doi.org/10.1111/cdev.13620

Chen, X., Twomey, K. E., & Westermann, G. (2022). Curiosity enhances incidental object encoding in 8-month-old infants. *Journal of Experimental Child Psychology*, *223*, 105508. https://doi.org/10.1016/j.jecp.2022.105508

Chere, B. (2022). *The impact of in-home noise on cognitive development*. Birkbeck, University of London.

Chuang, S. S., & Su, Y. (2009). Do we see eye to eye? Chinese mothers' and fathers' parenting beliefs and values for toddlers in Canada and China. *Journal of Family Psychology*, *23*(3), 331–341. https://doi.org/10.1037/a0016015

Clark, A. (2013). Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*(3), 181–204. https://doi.org/10.1017/S0140525X12000477

Colombo, J., Mitchell, D. W., Coldren, J. T., & Freeseman, L. J. (1991). Individual Differences in Infant Visual Attention: Are Short Lookers Faster Processors or Feature Processors? *Child Development*, *62*(6), 1247–1257. https://doi.org/10.2307/1130804

Colonnesi, C., Stams, G. J. J. M., Koster, I., & Noom, M. J. (2010). The relation between pointing and language development: A meta-analysis. *Developmental Review*, *30*(4), 352–366. https://doi.org/10.1016/j.dr.2010.10.001

Danckert, J. (2019). Boredom: Managing the Delicate Balance Between Exploration and Exploitation. In J. Ros Velasco (Ed.), *Boredom Is in Your Mind: A Shared Psychological-Philosophical Approach* (pp. 37–53). Springer International Publishing. https://doi.org/10.1007/978-3-030-26395-9_3

Danckert, J., & Merrifield, C. (2018). Boredom, sustained attention and the default mode network. *Experimental Brain Research*, *236*(9), 2507–2518. https://doi.org/10.1007/s00221-016-4617-5

Daw, N. D., O'Doherty, J. P., Dayan, P., Seymour, B., & Dolan, R. J. (2006). Cortical substrates for exploratory decisions in humans. *Nature*, *441*(7095), Article 7095. https://doi.org/10.1038/nature04766

De Eccher, M., Mundry, R., & Mani, N. (2024). Children's subjective uncertainty-driven sampling behaviour. *Royal Society Open Science*, *11*(4), 231283. https://doi.org/10.1098/rsos.231283

Deligianni, F., Senju, A., Gergely, G., & Csibra, G. (2011). Automated gaze-contingent objects elicit orientation following in 8-month-old infants. *Developmental Psychology*, *47*(6), 1499–1503. https://doi.org/10.1037/a0025659

Downing, S. M. (2003). Validity: On the meaningful interpretation of assessment data. *Medical Education*, *37*(9), 830–837.

Dunn, K. J., & McCray, G. (2020). The Place of the Bifactor Model in Confirmatory Factor Analysis Investigations Into Construct Dimensionality in Language Testing. *Frontiers in Psychology*, *11*. https://www.frontiersin.org/articles/10.3389/fpsyg.2020.01357

Eastwood, J. D., Frischen, A., Fenske, M. J., & Smilek, D. (2012). The Unengaged Mind: Defining Boredom in Terms of Attention. *Perspectives on Psychological Science*, *7*(5), 482–495. https://doi.org/10.1177/1745691612456044

Emberson, L. L., Richards, J. E., & Aslin, R. N. (2015). Top-down modulation in the infant brain: Learning-induced expectations rapidly affect the sensory cortex at 6 months. *Proceedings of the National Academy of Sciences*, *112*(31), 9585–9590. https://doi.org/10.1073/pnas.1510343112

Engel, S. (2011). Children's Need to Know: Curiosity in Schools. *Harvard Educational Review*, *81*(4), 625–645. https://doi.org/10.17763/haer.81.4.h054131316473115

Evans, N. S., Burke, R., Vitiello, V., Zumbrunn, S., & Jirout, J. J. (2023). Curiosity in classrooms: An examination of curiosity promotion and suppression in preschool math and science classrooms. *Thinking Skills and Creativity*, *49*, 101333. https://doi.org/10.1016/j.tsc.2023.101333

Eysenck, H. J. (1992). Four ways five factors are not basic. *Personality and Individual Differences*, *13*(6), 667–673. https://doi.org/10.1016/0191-8869(92)90237-J

Flake, J. K., & Fried, E. I. (2020). Measurement Schmeasurement: Questionable Measurement Practices and How to Avoid Them. *Advances in Methods and Practices in Psychological Science*, *3*(4), 456–465. https://doi.org/10.1177/2515245920952393

Fontenelle, S. A., Alexander Kahrs, B., Ashley Neal, S., Taylor Newton, A., & Lockman, J. J. (2007). Infant manual exploration of composite substrates. *Journal of Experimental Child Psychology*, *98*(3), 153–167. https://doi.org/10.1016/j.jecp.2007.07.001

Forestier, S., & Oudeyer, P.-Y. (2016). Modular active curiosity-driven discovery of tool use. *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 3965–3972.

Forss, S., Ciria, A., Clark, F., Galusca, C., Harrison, D., & Lee, S. (2024). A transdisciplinary view on curiosity beyond linguistic humans: Animals, infants, and artificial intelligence. *Biological Reviews*.

Fortner-wood, C., & Henderson, B. B. (1997). Individual Differences in Two-Year-Olds' Curiosity in the Assessment Setting and in the Grocery Store. *The Journal of Genetic Psychology*, *158*(4), 495–497. https://doi.org/10.1080/00221329709596686

Franchak, J. M., Heeger, D. J., Hasson, U., & Adolph, K. E. (2016). Free Viewing Gaze Behavior in Infants and Adults. *Infancy*, *21*(3), 262–287. https://doi.org/10.1111/infa.12119

Friston, K. (2010). The free-energy principle: A unified brain theory? *Nature Reviews Neuroscience*, *11*(2), 127–138.

Galli, G., Sirota, M., Gruber, M. J., Ivanof, B. E., Ganesh, J., Materassi, M., Thorpe, A., Loaiza, V., Cappelletti, M., & Craik, F. I. M. (2018). Learning facts during aging: The benefits of curiosity. *Experimental Aging Research*, *44*(4), 311–328. https://doi.org/10.1080/0361073X.2018.1477355

Gerken, L., Balcomb, F. K., & Minton, J. L. (2011). Infants avoid 'labouring in vain' by attending more to learnable than unlearnable linguistic patterns. *Developmental Science*, *14*(5), 972–979. https://doi.org/10.1111/j.1467-7687.2011.01046.x

Gerken, L., Dawson, C., Chatila, R., & Tenenbaum, J. (2015). Surprise! Infants consider possible bases of generalization for a single input example. *Developmental Science*, *18*(1), 80–89. https://doi.org/10.1111/desc.12183

Goh, K.-I., & Barabási, A.-L. (2008). Burstiness and memory in complex systems. *Europhysics Letters*, *81*(4), 48002.

Gottlieb, J., Oudeyer, P.-Y., Lopes, M., & Baranes, A. (2013). Information-seeking, curiosity, and attention: Computational and neural mechanisms. *Trends in Cognitive Sciences*, *17*(11), 585–593. https://doi.org/10.1016/j.tics.2013.09.001

Grossnickle, E. M. (2016). Disentangling Curiosity: Dimensionality, Definitions, and Distinctions from Interest in Educational Contexts. *Educational Psychology Review*, *28*(1), 23–60. https://doi.org/10.1007/s10648-014-9294-y

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of Curiosity Modulate Hippocampus-Dependent Learning via the Dopaminergic Circuit. *Neuron*, *84*(2), 486–496. https://doi.org/10.1016/j.neuron.2014.08.060

Hall, G. S., & Smith, T. L. (1903). Curiosity and interest. *The Pedagogical Seminary*, *10*(3), 315–358.

Hardy, J. H., Ness, A. M., & Mecca, J. (2017). Outside the box: Epistemic curiosity as a predictor of creative problem solving and creative performance. *Personality and Individual Differences*, *104*, 230–237. https://doi.org/10.1016/j.paid.2016.08.004

Hayden, B. Y., Pearson, J. M., & Platt, M. L. (2011). Neuronal basis of sequential foraging decisions in a patchy environment. *Nature Neuroscience*, *14*(7), Article 7. https://doi.org/10.1038/nn.2856

Hilton, M., Twomey, K. E., & Westermann, G. (2019). Taking their eye off the ball: How shyness affects children's attention during word learning. *Journal of Experimental Child Psychology*, *183*, 134–145.

Hoch, J. E., O'Grady, S. M., & Adolph, K. E. (2019). It's the journey, not the destination: Locomotor exploration in infants. *Developmental Science*, *22*(2), e12740. https://doi.org/10.1111/desc.12740

Hoicka, E., Powell, S., Rose, S. E., Reindl, E., & Tennie, C. (2023). The Early Independent Problem Solving Survey (EIPSS): Its psychometric properties in children aged 12–47 months. *Cognitive Development*, *68*, 101366. https://doi.org/10.1016/j.cogdev.2023.101366

Hunter, M. A., & Ames, E. W. (1988). A multifactor model of infant preferences for novel and familiar stimuli. *Advances in Infancy Research*, *5*, 69–95.

Inagaki, K. (1978). Effects of Object Curiosity on Exploratory Learning in Young Children. *Psychological Reports*, *42*(3), 899–908. https://doi.org/10.2466/pr0.1978.42.3.899

Inan, I. (2013). *The philosophy of curiosity*. Routledge.

Jago, L. S., Alcock, K., Meints, K., Pine, J. M., & Rowland, C. F. (2023). Language outcomes from the UK-CDI Project: Can risk factors, vocabulary skills and gesture scores in infancy predict later language disorders or concern for language development? *Frontiers in Psychology*, *14*. https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1167810

Jepma, M., Verdonschot, R. G., van Steenbergen, H., Rombouts, S. A. R. B., & Nieuwenhuis, S. (2012). Neural mechanisms underlying the induction and relief of perceptual curiosity. *Frontiers in Behavioral Neuroscience*, *6*. https://doi.org/10.3389/fnbeh.2012.00005

Jirout, J., & Klahr, D. (2012). Children's scientific curiosity: In search of an operational definition of an elusive concept. *Developmental Review*, *32*(2), 125–160. https://doi.org/10.1016/j.dr.2012.04.002

Jukes, M. C. H., Mgonda, N. L., Tibenda, J. J., Gabrieli, P., Jeremiah, G., Betts, K. L., Williams, J., & Bub, K. L. (2021). Building an assessment of community-defined social-emotional competencies from the ground up in Tanzania. *Child Development*, *92*(6), e1095–e1109. https://doi.org/10.1111/cdev.13673

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G. F., McClure, S. M., Wang, J. T., & Camerer, C. F. (2008). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1308286

Kang, M. J., Hsu, M., Krajbich, I. M., Loewenstein, G., McClure, S. M., Wang, J. T., & Camerer, C. F. (2009). The Wick in the Candle of Learning: Epistemic Curiosity Activates Reward Circuitry and Enhances Memory. *Psychological Science*, *20*(8), 963–973. https://doi.org/10.1111/j.1467-9280.2009.02402.x

Kaplan, F., & Oudeyer, P.-Y. (2007). In search of the neural circuits of intrinsic motivation. *Frontiers in Neuroscience*, *1*. https://www.frontiersin.org/articles/10.3389/neuro.01.1.1.017.2007

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2014). Crawling and walking infants elicit different verbal responses from mothers. *Developmental Science*, *17*(3), 388–395. https://doi.org/10.1111/desc.12129

Karmazyn-Raz, H., & Smith, L. B. (2023). Sampling statistics are like story creation: A network analysis of parent–toddler exploratory play. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *378*(1870), 20210358. https://doi.org/10.1098/rstb.2021.0358

Kashdan, T. B., Disabato, D. J., Goodman, F. R., & McKnight, P. E. (2020). The Five-Dimensional Curiosity Scale Revised (5DCR): Briefer subscales while separating overt and covert social curiosity. *Personality and Individual Differences*, *157*, 109836. https://doi.org/10.1016/j.paid.2020.109836

Kashdan, T. B., & Yuen, M. (2007). Whether highly curious students thrive academically depends on perceptions about the school learning environment: A study of Hong Kong adolescents. *Motivation and Emotion*, *31*(4), 260–270. https://doi.org/10.1007/s11031-007-9074-9

Kayhan, E., Meyer, M., O'Reilly, J. X., Hunnius, S., & Bekkering, H. (2019). Nine-month-old infants update their predictive models of a changing environment. *Developmental Cognitive Neuroscience*, *38*, 100680. https://doi.org/10.1016/j.dcn.2019.100680

Keemink, J. R., Keshavarzi-Pour, M. J., & Kelly, D. J. (2019). Infants' responses to interactive gaze-contingent faces in a novel and naturalistic eye-tracking paradigm. *Developmental Psychology*, *55*(7), 1362–1371.

https://doi.org/10.1037/dev0000736
Keller, H. (2016). Psychological autonomy and hierarchical relatedness as organizers of developmental pathways. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1686), 20150070. https://doi.org/10.1098/rstb.2015.0070
Kidd, C., & Hayden, B. Y. (2015). The Psychology and Neuroscience of Curiosity. *Neuron*, *88*(3), 449–460. https://doi.org/10.1016/j.neuron.2015.09.010
Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks Effect: Human Infants Allocate Attention to Visual Sequences That Are Neither Too Simple Nor Too Complex. *PLoS ONE*, *7*(5), e36399. https://doi.org/10.1371/journal.pone.0036399
Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2014). The Goldilocks Effect in Infant Auditory Attention. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12263
Kim, E.-K., & Jo, H.-H. (2016). Measuring burstiness for finite event sequences. *Physical Review E*, *94*(3), 032311.
Kosie, J., Zettersten, M., Abu-Zhaya, R., Amso, D., Babineau, M., Baumgartne, H., Belia, M., Benavides, S., Bergmann, C., & Berteletti, I. (2023). *ManyBabies 5: A large-scale investigation of the proposed shift from familiarity preference to novelty preference in infant looking time*.
Köster, M., Kayhan, E., Langeloh, M., & Hoehl, S. (2020). Making Sense of the World: Infant Learning From a Predictive Processing Perspective. *Perspectives on Psychological Science*, *15*(3), 562–571. https://doi.org/10.1177/1745691619895071
Lapidow, E., & Bonawitz, E. (2023). What's in the Box? Preschoolers Consider Ambiguity, Expected Value, and Information for Future Decisions in Explore-Exploit Tasks. *Open Mind*, *7*, 855–878. https://doi.org/10.1162/opmi_a_00110
Lau, J. K. L., Ozono, H., Kuratomi, K., Komiya, A., & Murayama, K. (2020). Shared striatal activity in decisions to satisfy curiosity and hunger at the risk of electric shocks. *Nature Human Behaviour*, *4*(5), 531–543. https://doi.org/10.1038/s41562-020-0848-3
Lee, N., Lazaro, V., Wang, J. J., Şen, H. H., & Lucca, K. (2023). Exploring individual differences in infants' looking preferences for impossible events: The Early Multidimensional Curiosity Scale. *Frontiers in Psychology*, *13*. https://www.frontiersin.org/articles/10.3389/fpsyg.2022.1015649
Lieder, F., & Griffiths, T. L. (2020). Resource-rational analysis: Understanding human cognition as the optimal use of limited computational resources. *Behavioral and Brain Sciences*, *43*, e1. https://doi.org/10.1017/S0140525X1900061X
Ligneul, R., Mermillod, M., & Morisseau, T. (2018). From relief to surprise: Dual control of epistemic curiosity in the human brain. *NeuroImage*, *181*, 490–500. https://doi.org/10.1016/j.neuroimage.2018.07.038
Liquin, E. G., & Gopnik, A. (2022). Children are more exploratory and learn more than adults in an approach-avoid task. *Cognition*, *218*, 104940. https://doi.org/10.1016/j.cognition.2021.104940

Liszkowski, U., Carpenter, M., & Tomasello, M. (2007). Pointing out new news, old news, and absent referents at 12 months of age. *Developmental Science*, *10*(2), F1–F7. https://doi.org/10.1111/j.1467-7687.2006.00552.x

Litman, J. A., Hutchins, T., & Russon, R. (2005). Epistemic curiosity, feeling-of-knowing, and exploratory behaviour. *Cognition & Emotion*, *19*(4), 559–582. https://doi.org/10.1080/02699930441000427

Litman, J. A., & Jimerson, T. L. (2004). The Measurement of Curiosity As a Feeling of Deprivation. *Journal of Personality Assessment*, *82*(2), 147–157. https://doi.org/10.1207/s15327752jpa8202_3

Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Development*, *71*(1), 137–144.

Loewenstein, G. (1994). The psychology of curiosity: A review and reinterpretation. *Psychological Bulletin*, *116*(1), 75.

Lucca, K., & Wilbourn, M. P. (2019). The what and the how: Information-seeking pointing gestures facilitate learning labels and functions. *Journal of Experimental Child Psychology*, *178*, 417–436. https://doi.org/10.1016/j.jecp.2018.08.003

Madhavan, R., Malem, B., Ackermann, L., Mundry, R., & Mani, N. (2024). An examination of measures of young children's interest in natural object categories. *Cortex*. https://doi.org/10.1016/j.cortex.2024.02.015

Mandler, J. M., Fivush, R., & Reznick, J. S. (1987). The development of contextual categories. *Cognitive Development*, *2*(4), 339–354. https://doi.org/10.1016/S0885-2014(87)80012-6

Mani, N., & Ackermann, L. (2018). Why Do Children Learn the Words They Do? *Child Development Perspectives*, *12*(4), 253–257. https://doi.org/10.1111/cdep.12295

Mather, E., & Plunkett, K. (2011). Same items, different order: Effects of temporal variability on infant categorization. *Cognition*, *119*(3), 438–447. https://doi.org/10.1016/j.cognition.2011.02.008

McKean, C., & Reilly, S. (2023). Creating the conditions for robust early language development for all: Part two: Evidence informed public health framework for child language in the early years. *International Journal of Language & Communication Disorders*, *58*(6), 2242–2264. https://doi.org/10.1111/1460-6984.12927

Meder, B., Wu, C. M., Schulz, E., & Ruggeri, A. (2021). Development of directed and random exploration in children. *Developmental Science*, *24*(4), e13095. https://doi.org/10.1111/desc.13095

Meltzoff, A. N., Waismeyer, A., & Gopnik, A. (2012). Learning About Causes From People: Observational Causal Learning in 24-Month-Old Infants. *Developmental Psychology*, *48*(5), 1215–1228. https://doi.org/10.1037/a0027440

Merlo, L. J., Bowman, M., & Barnett, D. (2007). Parental nurturance promotes reading acquisition in low socioeconomic status children. *Early Education and Development*, *18*(1), 51–69.

Muentener, P., Herrig, E., & Schulz, L. (2018). The efficiency of infants' exploratory play is related to longer-term cognitive development. *Frontiers in Psychology*, *9*, 635.

Murayama, K., FitzGibbon, L., & Sakaki, M. (2019). Process account of curiosity and interest: A reward-learning perspective. *Educational Psychology Review*, *31*, 875–895.

Mussel, P. (2013). Intellect: A theoretical framework for personality traits related to intellectual achievements. *Journal of Personality and Social Psychology*, *104*(5), 885–906. https://doi.org/10.1037/a0031918

Nicoladis, E., & Barbosa, P. G. (2024). Infants' pointing at nine months is associated with maternal sensitivity but not vocabulary. *Infant Behavior and Development*, *74*, 101923. https://doi.org/10.1016/j.infbeh.2024.101923

Oakes, L. M., Kovack-Lesh, K. A., & Horst, J. S. (2009). Two are better than one: Comparison influences infants' visual recognition memory. *Journal of Experimental Child Psychology*, *104*(1), 124–131. https://doi.org/10.1016/j.jecp.2008.09.001

Oakes, L. M., Madole, K. L., & Cohen, L. B. (1991). Infants' object examining: Habituation and categorization. *Cognitive Development*, *6*(4), 377–392. https://doi.org/10.1016/0885-2014(91)90045-F

Oudeyer, P.-Y., Kaplan, F., & Hafner, V. V. (2007). Intrinsic Motivation Systems for Autonomous Mental Development. *IEEE Transactions on Evolutionary Computation*, *11*(2), 265–286. IEEE Transactions on Evolutionary Computation. https://doi.org/10.1109/TEVC.2006.890271

Pelz, M., Piantadosi, S. T., & Kidd, C. (2015). The dynamics of idealized attention in complex learning environments. *2015 Joint IEEE International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob)*, 236–241. https://doi.org/10.1109/DEVLRN.2015.7346147

Pérez-Edgar, K., Vallorani, A., Buss, K. A., & LoBue, V. (2020). Individual differences in infancy research: Letting the baby stand out from the crowd. *Infancy*, *25*(4), 438–457. https://doi.org/10.1111/infa.12338

Pett, M. A., Lackey, N. R., & Sullivan, J. J. (2003). *Making sense of factor analysis: The use of factor analysis for instrument development in health care research*. sage.

Piaget, J. (1976). Piaget's Theory. In B. Inhelder, H. H. Chipman, & C. Zwingmann (Eds.), *Piaget and His School: A Reader in Developmental Psychology* (pp. 11–23). Springer. https://doi.org/10.1007/978-3-642-46323-5_2

Piccardi, E. S., Johnson, M. H., & Gliga, T. (2020). Explaining individual differences in infant visual sensory seeking. *Infancy*, *25*(5), 677–698. https://doi.org/10.1111/infa.12356

Piotrowski, J. T., Litman, J. A., & Valkenburg, P. (2014). Measuring Epistemic Curiosity in Young Children: Brief Report. *Infant and Child Development*, *23*(5), 542–553. https://doi.org/10.1002/icd.1847

Poli, F., Ghilardi, T., Beijers, R., de Weerth, C., Hinne, M., Mars, R. B., & Hunnius, S. (2023). *Individual differences in processing speed and curiosity explain infant habituation and dishabituation performance*.

Poli, F., Meyer, M., Mars, R. B., & Hunnius, S. (2022). Contributions of expected learning progress and perceptual novelty to curiosity-driven exploration. *Cognition*, *225*, 105119. https://doi.org/10.1016/j.cognition.2022.105119

Poli, F., Serino, G., Mars, R. B., & Hunnius, S. (2020). Infants tailor their attention to maximize learning. *Science Advances*, *6*(39), eabb5053. https://doi.org/10.1126/sciadv.abb5053

Pridham, K., Becker, P., & Brown, R. (2000). Effects of infant and caregiving conditions on an infant's focused exploration of toys. *Journal of Advanced Nursing*, *31*(6), 1439–1448. https://doi.org/10.1046/j.1365-2648.2000.01448.x

Putnam, S. P., Helbig, A. L., Gartstein, M. A., Rothbart, M. K., & Leerkes, E. (2014). Development and Assessment of Short and Very Short Forms of the Infant Behavior Questionnaire–Revised. *Journal of Personality Assessment*, *96*(4), 445–458. https://doi.org/10.1080/00223891.2013.841171

Putnam, S. P., Sehic, E., French, B. F., Gartstein, M. A., Luttges, B. L., & Peltola, M. (2024). The Global Temperament Project: Parent-Reported Temperament in Infants, Toddlers and Children from 59 Nations. *Developmental Psychology*.

Rabagliati, H., Ferguson, B., & Lew-Williams, C. (2019). The profile of abstract rule learning in infancy: Meta-analytic and experimental evidence. *Developmental Science*, *22*(1), e12704. https://doi.org/10.1111/desc.12704

Reber, R., Fazendeiro, T. A., & Winkielman, P. (2002). Processing fluency as the source of experiences at the fringe of consciousness. *Psyche*, *8*(10), 1–21.

Reio Jr., T. G. (2024). Individual Differences in Curiosity. *The Oxford Handbook of Individual Differences in Organizational Contexts*, 43.

Reio Jr., T. G., & Callahan, J. L. (2004). Affect, curiosity, and socialization-related learning: A path analysis of antecedents to job performance. *Journal of Business and Psychology*, *19*, 3–22.

Reio Jr., T. G., & Wiswell, A. (2000). Field investigation of the relationship among adult curiosity, workplace learning, and job performance. *Human Resource Development Quarterly*, *11*(1), 5–30.

Rose, S. A., Gottfried, A. W., Melloy-Carminar, P., & Bridger, W. H. (1982). Familiarity and novelty preferences in infant recognition memory: Implications for information processing. *Developmental Psychology*, *18*(5), 704–713. https://doi.org/10.1037/0012-1649.18.5.704

Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2016). Sources of developmental change in the efficiency of information search. *Developmental Psychology*, *52*(12), 2159–2173. https://doi.org/10.1037/dev0000240

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical Learning by 8-Month-Old Infants. *Science*, *274*(5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926

Saffran, J. R., & Kirkham, N. Z. (2018). Infant Statistical Learning. *Annual Review of Psychology*, *69*, 181–203. https://doi.org/10.1146/annurev-psych-122216-011805

Sakaki, M., Yagi, A., & Murayama, K. (2018). Curiosity in old age: A possible key to achieving adaptive aging. *Neuroscience & Biobehavioral Reviews*, *88*, 106–116. https://doi.org/10.1016/j.neubiorev.2018.03.007

Salomonsson, B., & Sleed, M. (2010). The Ages & Stages Questionnaire: Social–Emotional: A validation study of a mother-report questionnaire on a clinical mother–infant sample. *Infant Mental Health Journal*, *31*(4), 412–431. https://doi.org/10.1002/imhj.20263

Schatz, J. L., Suarez-Rivera, C., Kaplan, B. E., & Tamis-LeMonda, C. S. (2022). Infants' object interactions are long and complex during everyday joint engagement. *Developmental Science*, *25*(4), e13239. https://doi.org/10.1111/desc.13239

Schulz, E., Wu, C. M., Ruggeri, A., & Meder, B. (2019). Searching for Rewards Like a Child Means Less Generalization and More Directed Exploration. *Psychological Science*, *30*(11), 1561–1572. https://doi.org/10.1177/0956797619863663

Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: Preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology*, *43*(4), 1045–1050. https://doi.org/10.1037/0012-1649.43.4.1045

Schutte, N. S., & Malouff, J. M. (2020). A Meta-Analysis of the Relationship between Curiosity and Creativity. *The Journal of Creative Behavior*, *54*(4), 940–947. https://doi.org/10.1002/jocb.421

Şen, H. H., Kiefer, S. L., Aksu, E., & Lucca, K. (2024). Developmental differences in children and adults' enforcement of explore versus exploit search strategies in the United States and Turkey. *Developmental Science*, e13520.

Shah, P. E., Weeks, H. M., Richards, B., & Kaciroti, N. (2018). Early childhood curiosity and kindergarten reading and math academic achievement. *Pediatric Research*, *84*(3), Article 3. https://doi.org/10.1038/s41390-018-0039-3

Singh, A., & Manjaly, J. A. (2022). Using Curiosity to Improve Learning Outcomes in Schools. *Sage Open*, *12*(1), 21582440211069392. https://doi.org/10.1177/21582440211069392

Singh, L. (2024). Decolonizing and Diversifying Research in Cognitive Development. *Journal of Cognition and Development*, *25*(2), 175–179.

Slone, L. K., Abney, D. H., Smith, L. B., & Yu, C. (2023). The temporal structure of parent talk to toddlers about objects. *Cognition*, *230*, 105266.

Slone, L. K., Smith, L. B., & Yu, C. (2019). Self-generated variability in object images predicts vocabulary growth. *Developmental Science*, *22*(6), e12816. https://doi.org/10.1111/desc.12816

Smith, L. B., Jayaraman, S., Clerkin, E., & Yu, C. (2018). The Developing Infant Creates a Curriculum for Statistical Learning. *Trends in Cognitive Sciences*, *22*(4), 325–336. https://doi.org/10.1016/j.tics.2018.02.004

Smith, L. B., & Yu, C. (2013). Visual Attention Is Not Enough: Individual Differences in Statistical Word-Referent Learning in Infants. *Language Learning and Development*, *9*(1), 25–49. https://doi.org/10.1080/15475441.2012.707104

Spielberger, C. D., & Starr, L. M. (1994). Curiosity and Exploratory Behavior. In *Motivation: Theory and Research*. Routledge.

Stahl, A. E., & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, *348*(6230), 91–94. https://doi.org/10.1126/science.aaa3799

Stamps, J., & Groothuis, T. G. G. (2010). The development of animal personality: Relevance, concepts and perspectives. *Biological Reviews*, *85*(2), 301–325. https://doi.org/10.1111/j.1469-185X.2009.00103.x

Suarez-Rivera, C., Smith, L. B., & Yu, C. (2019). Multimodal parent behaviors within joint attention support sustained attention in infants. *Developmental Psychology*, *55*(1), 96–109. https://doi.org/10.1037/dev0000628

Sumner, E. S., Steyvers, M., & Sarnecka, B. W. (2019). It's not the treasure, it's the hunt: Children are more explorative on an explore/exploit task than adults. *CogSci*, 2891–2897.

Tamis-LeMonda, C. S., Kuchirko, Y., & Tafuro, L. (2013). From Action to Interaction: Infant Object Exploration and Mothers' Contingent Responsiveness. *IEEE Transactions on Autonomous Mental Development*, *5*(3), 202–209. https://doi.org/10.1109/TAMD.2013.2269905

Ten, A., Kaushik, P., Oudeyer, P.-Y., & Gottlieb, J. (2021). Humans monitor learning progress in curiosity-driven exploration. *Nature Communications*, *12*(1), 5972. https://doi.org/10.1038/s41467-021-26196-w

Tor, N., & Gordon, G. (2020). Digital Interactive Quantitative Curiosity Assessment Tool: Questions Worlds. *International Journal of Information and Education Technology*, *10*(8), 614–621. https://doi.org/10.18178/ijiet.2020.10.8.1433

Tummeltshammer, K. S., & Kirkham, N. Z. (2013). Learning to look: Probabilistic variation and noise guide infants' eye movements. *Developmental Science*, *16*(5), 760–771. https://doi.org/10.1111/desc.12064

Tummeltshammer, K. S., Mareschal, D., & Kirkham, N. Z. (2014). Infants' Selective Attention to Reliable Visual Cues in the Presence of Salient Distractors. *Child Development*, n/a-n/a. https://doi.org/10.1111/cdev.12239

Twomey, K. E., & Westermann, G. (2018). Curiosity-based learning in infants: A neurocomputational approach. *Developmental Science*, *21*(4), e12629. https://doi.org/10.1111/desc.12629

van den Boom, D. C. (1994). The Influence of Temperament and Mothering on Attachment and Exploration: An Experimental Manipulation of Sensitive Responsiveness among Lower-Class Mothers with Irritable Infants. *Child Development*, *65*(5), 1457–1477. https://doi.org/10.2307/1131511

Van der Horst, A. C., Klehe, U.-C., & Van der Heijden, B. I. (2017). Adapting to a looming career transition: How age and core individual differences interact. *Journal of Vocational Behavior*, *99*, 132–145.

van Heugten, M., & Shi, R. (2010). Infants' sensitivity to non-adjacent dependencies across phonological phrase boundaries. *The Journal of the Acoustical Society of America*, *128*(5), EL223–EL228. https://doi.org/10.1121/1.3486197

van Lieshout, L. L. F., Vandenbroucke, A. R. E., Müller, N. C. J., Cools, R., & de Lange, F. P. (2018). Induction and Relief of Curiosity Elicit Parietal and Frontal Activity. *The Journal of Neuroscience*, *38*(10), 2579–2588. https://doi.org/10.1523/JNEUROSCI.2816-17.2018

van Schijndel, T. J., Jansen, B. R., & Raijmakers, M. E. (2018). Do individual differences in children's curiosity relate to their inquiry-based learning? *International Journal of Science Education*, *40*(9), 996–1015.

Vázquez, A., Oliveira, J. G., Dezsö, Z., Goh, K.-I., Kondor, I., & Barabási, A.-L. (2006). Modeling bursts and heavy tails in human dynamics. *Physical Review E*, *73*(3), 036127.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive Sciences*, *8*(6), 266–272. https://doi.org/10.1016/j.tics.2004.04.002

Wade, S., & Kidd, C. (2019). The role of prior knowledge and curiosity in learning. *Psychonomic Bulletin & Review*, *26*(4), 1377–1387. https://doi.org/10.3758/s13423-019-01598-6

Wagstaff, M. F., Flores, G. L., Ahmed, R., & Villanueva, S. (2021). Measures of curiosity: A literature review. *Human Resource Development Quarterly*, *32*(3), 363–389. https://doi.org/10.1002/hrdq.21417

Waismeyer, A., & Meltzoff, A. N. (2017). Learning to make things happen: Infants' observational learning of social and physical causal events. *Journal of Experimental Child Psychology*, *162*, 58–71. https://doi.org/10.1016/j.jecp.2017.04.018

Walin, H., O'Grady, S., & Xu, F. (2016). *Curiosity and Its Influence on Children's Memory*.

Wang, Q., Bolhuis, J., Rothkopf, C. A., Kolling, T., Knopf, M., & Triesch, J. (2012). Infants in Control: Rapid Anticipation of Action Outcomes in a Gaze-Contingent Paradigm. *PLoS ONE*, *7*(2), e30884. https://doi.org/10.1371/journal.pone.0030884

Wang, S., Zhang, Y., & Baillargeon, R. (2016). Young infants view physically possible support events as unexpected: New evidence for rule learning. *Cognition*, *157*, 100–105. https://doi.org/10.1016/j.cognition.2016.08.021

Wass, S. V., & Smith, T. J. (2014). Individual Differences in Infant Oculomotor Behavior During the Viewing of Complex Naturalistic Scenes. *Infancy*, *19*(4), 352–384. https://doi.org/10.1111/infa.12049

Watson, L., Inan, I., Whitcomb, D., & Yigit, S. (2018). Educating for curiosity. *The Moral Psychology of Curiosity*, 293–309.

Yu, C., Suanda, S. H., & Smith, L. B. (2019). Infant sustained attention but not joint attention to objects at 9 months predicts vocabulary at 12 and 15 months. *Developmental Science*, *22*(1), e12735. https://doi.org/10.1111/desc.12735

Zettersten, M. (2020). *Seeking New Words: Active Word Learning in Infants and Children* [Ph.D., The University of Wisconsin - Madison]. https://search.proquest.com/docview/2408896456/abstract/E02DABE6983D46B2PQ/1

Glossary

- **State curiosity:** The response to encountered information in the environment, measured in infants typically via the duration (e.g., play or looking time) or latency of engagement.
- **Trait curiosity:** A holistic account of various exploration behaviours the infant generally employs to interact with their environment to construct their knowledge of the world.
- **Active exploration:** Infant-directed, self-guided, selective engagement with an information source which is captured dynamically across multiple information sampling events; includes both exploration and exploitation within a constrained environment.
- **Exploitation** (methodologically): Sustained engagement or active re-engagement with a specific information source in the environment; can be scaled to the size of the considered information/learning space (e.g., one stimulus, one category, one task, one topic, one room, etc.); comparable to the term of "specific exploration".
- **Exploration** (methodologically): Disengagement from current information, switching to another, not yet or not recently sampled information source in the environment; comparable to the term of "diversive exploration".
- **Learning Progress:** Updating one's internal representation, for example through prediction error reduction or connective weights eadjustments in one's knowledge network.